Chemical Changes at Impact-Induced Phase Transitions on the Lunar Surface

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Chemical changes at impact-induced phase transitions on the lunar surface

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Impact-induced melting and vaporization on the lunar surface generate products which are different in chemical composition from their parent materials.

By partial shock melting of plagioclase-pyroxene rocks, pure plagioclase melts can be formed because for a given shock pressure, the gain in entropy is higher in plagioclase than in pyroxene. Impact-induced melts of peritectic composition can only be produced if by some mechanism, shock heat is transferred to weakly or non-shocked rocks where partial melting can take place under equilibrium conditions. The formation of large masses of differentiates by partial shock-induced melting on the lunar surface is unlikely.

Distributions of the main chemical components have been determined for 744 lunar rocks and 971 lunar glasses. For glasses, the maxima of alkalies are shifted towards lower, and of aluminium towards higher, concentrations. These differences are attributed to selective vaporization from overheated shock melts.

It is supposed that some of the regular glass bodies and perhaps, also, of the chondrule-like particles in lunar soils and breccias are formed by condensation from shock-produced vapours. In this case they should be richer in magnesium, aluminium and calcium, and poorer in alkalis and silicon as compared with glasses of other origins.

1. INTRODUCTION

All rock fragments, mineral grains and glass particles from the Moon which have been investigated are constituents of the regolith, a layer of debris produced during a long period of bombardment of the lunar surface, which conceals the solid crust of the Moon from which it was formed. Information about the constitution of the lunar crust and the petrogenesis of its rocks must be deduced from data obtained by mineralogical, chemical and physical analyses of these regolith components. It has to be kept in mind in all such deductions that impact processes might not only have comminuted, deformed and physically transformed the primary rocks and minerals but that also, more-or-less profound changes in chemical composition might have been occurred.

2. IMPACT-INDUCED PHASE TRANSITIONS ON THE LUNAR SURFACE

Impact-induced phase transitions which occurred on the lunar surface include subsolidus transformations, shock melting, and shock vaporization.

2.1. *Subsolidus transformations*

The only known shock-induced subsolidus phase transformation on the lunar surface is the formation of diaplectic plagioclase glass from crystalline plagioclase by shock pressures in the range between 300 and 400 kbar (30 and 40 GPa). No chemical change is connected with this reaction. Whether the formation of various mineral assemblages with metallic iron (by subsolidus reduction of divalent iron), which have been observed in many lunar samples (El Goresy &

Ramdohr 1975, and references; Bell & Mao 1973; Sclar & Bauer 1975; and others), might in some cases be due to the direct action of shock waves seems not yet clear enough and should be further investigated.

2.2. *Selective melting*

The term impact or shock melting has been used in the literature for two different processes which are both generated by impacts but result in different products.

Shock melting in the proper sense occurs when a rock is shocked to such high peak pressures that after pressure release, the post-shock temperature is so high that the rock is partially or completely melted. In a shocked rock consisting of different mineral grains, the distribution of post-shock temperatures is inhomogeneous for two reasons. Impedance differences of the minerals cause multiple refractions and reflexions of the shock wave at grain boundaries so that local pressure spikes and hot spots are generated. Because of differences in the thermodynamic properties of the minerals, the gain in entropy achieved upon shocking is different in the individual phases so that after isentropic pressure release, the post-shock temperatures are different in individual mineral grains. If the net gain in internal energy is not high enough to melt the total rock, the inhomogeneous temperature distribution can lead to the formation of local melts or to the preferential fusion of those phases for which the shock-produced increase in energy exceeds the melt entropy. In this way, partial melts can be formed by the action of shock.

There are few known examples in which shock-produced melts are observed in direct contact with residual parent material. One example has been described by Engelhardt *et al.* (1971) in a mare basalt fragment of Apollo 12 (12057,14) consisting of 53 % clinopyroxene, 38 % plagioclase and 9 % opaques. All minerals show indications of strong shock deformations and transformations in the solid state. Within some restricted areas, about 1 mm^2 each, local stress concentrations resulted in the formation of shock-produced melts which were quenched to glasses, the compositions of which correspond to mixtures of different proportions of the rock-forming minerals. All observed areas of shock melting are situated adjacent to large ilmenite crystals. Apparently, pressure spikes and hot spots were preferentially produced at the grain boundaries of ilmenite which has the highest impedance of all minerals in the rock.

Whereas, in this example, local pressure concentrations caused local melting without chemical differentiation, there are other cases in which selective melting was generated by shock compression. Such an example is represented by the shocked norite 78235 from Apollo 17, consisting of bronzite ($\text{En}_{78}\text{Fs}_{19}\text{Wo}_3$) and plagioclase ($\text{An}_{95}$) in about equal amounts. Both minerals show indications of strong shock deformation and transformation in the solid state (Sclar & Bauer 1975; Goresy *et al.* 1976). The bronzite is fractured and shows deformation lamellae, and a large proportion of the plagioclase is transformed to diaplectic glass. Along grain boundaries against bronzite, the plagioclase has melted. The melt is colourless and has exactly the composition of the crystalline plagioclase. No bronzite was fused. In this case, selective melting of plagioclase occurred despite the fact that the melting point of anorthite is higher than that of bronzite, and a eutectic mixture of both components would melt at much lower temperatures.

These observations are in accordance with the calculations and experimental results of Ahrens *et al.* (1972, 1973) and of Gibbons *et al.* (1975). Ahrens and co-workers calculated the entropy along the Hugoniot of lunar plagioclase and pyroxenes and compared the resulting values of entropy increase with the entropies required to melt these minerals at low pressure and high temperatures. They could show that plagioclase from gabbroic anorthosite 15418 would melt on release from shock pressures lower than would clinopyroxene and orthopyroxene from the same rock. Plagioclase melts are formed by release from pressures between 500 and 600 kbar whereas pyroxene needs release from pressures between 700 and 850 kbar for melting. Similar results were obtained by Gibbons and co-workers from shock experiments with mineral powders; melting of plagioclase was observed to begin after compression at about 500 kbar, and melting of orthopyroxene at pressures above 800 kbar.

It follows from these observations, experiments and thermodynamic calculations that basaltic minerals behave under shock conditions quite differently than under normal melting processes which are governed by peritectic equilibria. If, in rocks consisting of pyroxene and plagioclase, partial melts are produced by shock, the first-formed melt will be of pure plagioclase or plagioclase-rich composition. Normal heating, on the other hand, produces from feldspathic lunar rocks a first-formed partial melt of peritectic composition which would correspond to aluminous 'kreep' basalt (Walker *et al.* 1973).

Partial melts of peritectic composition can be formed by another process which has also been called impact or shock melting. If, by some transport mechanism, heat produced by an impact is transferred from the shocked rocks where it has been generated to other rocks which are unshocked or only weakly shocked, partial melts can be formed under equilibrium conditions. On a small scale, such heat transport can be achieved by splashes of overheated melt. Such a case was described by Grieve & Plant (1973) in a basalt fragment from Apollo 16 (64455,35). This rock is covered by a crust of splash melt which supplied so much heat that within the rock an intergranular melt was formed, higher in TiO_2, Cr_2O_3, MgO and Na_2O, but lower in the refractory constituents Al_2O_3 and CaO than the parent rock (in contrast to the Ca-rich and Al-rich melts which are formed by shock melting *sensu stricto*).

It has been inferred by several authors (Taylor *et al.* 1972; Walker *et al.* 1973; Warner *et al.* 1974; and others) that large amounts of partial melts of peritectic composition were generated from primary rocks by thermal energy delivered by large impacts. Such a hypothesis has to overcome two difficulties: The heat for partial melting has to be transported from the shock-heated rocks to cooler rocks, and the partial melts have to be separated from the residues. We have the impression that both difficulties make it very unlikely that large amounts of partial melts have been formed in this way on the lunar surface. The mass of rocks which, at an impact, are exposed to shock pressures high enough to cause total melting are, under the conditions of bombardment of the Moon by extra-lunar bodies, about three times the mass of the projectile (Gault *et al.* 1972). A part of the shock-generated melt is overheated so that an excess of thermal energy is available through which, in surrounding rocks, some partial melting under equilibrium conditions could be caused, provided that the thermal energy could be transferred to these rocks. We suspect that even very large impacts can generate only minor amounts of peritectic partial melts. It is unlikely that thermal impact energy is a major factor in the chemical differentiation of lunar rocks by partial melting.

2.3. *Selective vaporization*

Fragments and regular bodies of glass form up to 60% of the regolith. It is now generally accepted that the overwhelming majority of glass particles in the regolith are quenched melts which were produced by impact melting of primary rocks or of the regolith.

If there are no inclusions of rocks or minerals with indications of shock, the chemical

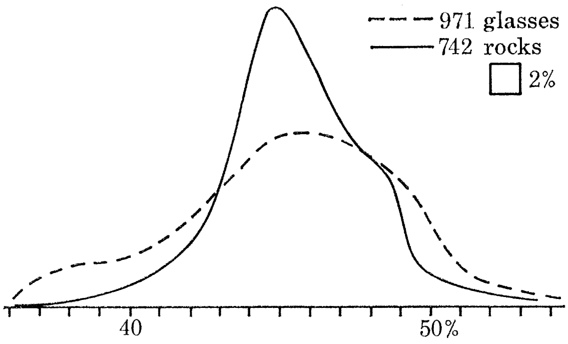

Figure 1. Distribution of SiO_2 in lunar rocks and glasses.

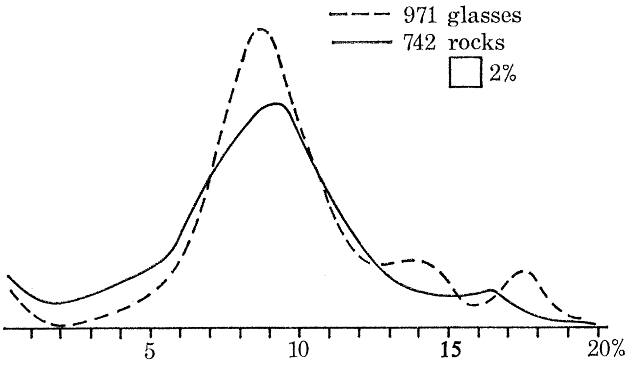

Figure 2. Distribution of MgO in lunar rocks and glasses.

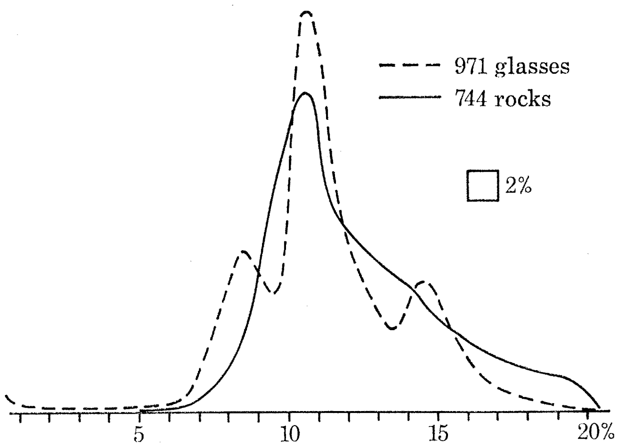

Figure 3. Distribution of CaO in lunar rocks and glasses.

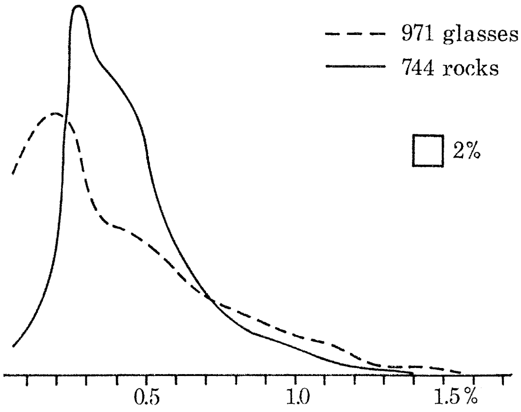

Figure 4. Distribution of Na_2O in lunar rocks and glasses.

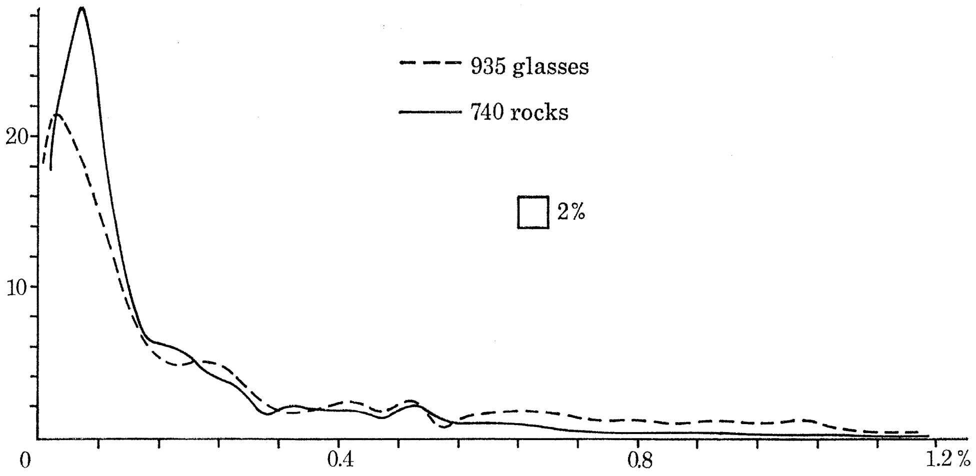

Figure 5. Distribution of K_2O in lunar rocks and glasses.

composition remains the only source of information on the origin of particular glasses. Glass fragments and bodies which show a very narrow range of compositions for which no rock counterparts are known, are very likely of volcanic origin. This has been assumed for the green glasses of Apollo 15 and the orange glasses of Apollo 17.

One basic difference between volcanic melts and melts of impact origin is the fact that volcanic melts were generally not heated to temperatures above their liquidus, whereas shock-produced melts may have been generated at all temperatures between the liquidus and the temperature of total vaporization. The overheating of silicate melts in the vacuum of the lunar surface should lead to a loss of the most volatile components. The degree of this selective vaporization should depend upon the specific surface area of the melt particles, the temperature of overheating, and the cooling history.

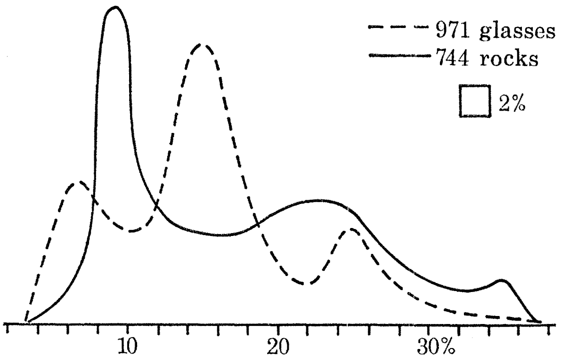

FIGURE 6. Distribution of Al_2O_3 in lunar rocks and glasses.

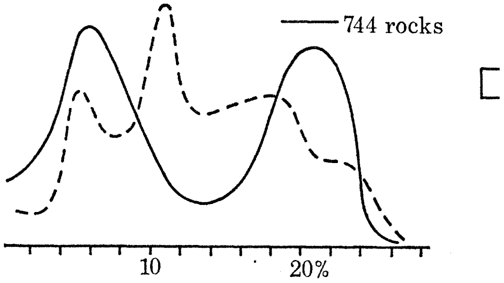

FIGURE 7. Distribution of FeO in lunar rocks and glasses.

Ivanov & Florensky (1975) have recently supposed that glasses of impact origin might be systematically depleted in the more volatile, main constituents as compared with the primary rocks from which they were formed. They supposed selective vaporization of alkalis, iron and silicon.

If the majority of glass particles in the regolith are of impact origin and if no changes took place during shock melting, the frequency distribution of the chemical components should be identical for glass and rock analyses provided that sufficiently large numbers of analyses of rock and glass particles, which were collected at random on the lunar surface, are considered. If, on the other hand, selective vaporization occurred due to overheating of shock-produced melt or if some glasses are quenched volcanic melts for which no rock counterparts exist, characteristic differences should exist between the average chemical composition of glasses and rocks.

In figures 1–7, frequency distributions are shown of the main chemical constituents in 744 lunar rocks and 971 lunar glass samples. The analyses are taken from the literature, mainly from the Proceedings of the Lunar Science Conferences. Table 1 shows the distribution of the analysed rock and glass samples among the individual Apollo and Luna sites.

For SiO_2 (figure 1), MgO (figure 2) and CaO (figure 3), the maxima of the frequency distributions are the same for rocks and glasses. The only difference is that the variation is larger for glasses than for rocks. For Na_2O (figure 4) and K_2O (figure 5), the maxima for the glasses are shifted towards lower concentrations as compared with the maxima for rocks. This can be explained by selective vaporization of alkalis from overheated shock melts. In addition there are, compared with the rocks, more sodium-rich and potassium-rich glasses. It might be that some of these alkali-rich glasses are magmatic differentiates. The distribution of Al_2O_3 (figure 6) is different for glasses and rocks: Main maxima of rocks are situated at 9 and 23 % Al_2O_3, respectively, to which the glass maxima at 15 and 25 % might correspond. The shift of the glass maxima to higher values might be explained by an enrichment of Al_2O_3 in overheated shock melts due to its extremely low volatility. There is an additional peak at 35 % Al_2O_3 for rocks which are very feldspathic and for which no glass counterparts exist. The glass maximum at about 7 % Al_2O_3 might represent glasses of volcanic origin.

Table 1. Origin of rock and glass samples represented in figures 1–7

	glasses		rocks	
site	number of analysed samples	in %	number of analysed samples	in %
Apollo 11	237	24.4	73	9.8
Apollo 12	276	28.4	151	20.3
Apollo 14	262	27.0	69	9.3
Apollo 15	153	15.8	166	22.3
Apollo 16	1	0.1	55	7.4
Apollo 17	0	0	10	1.3
Luna 16	38	3.9	33	4.5
Luna 20	4	0.4	187	25.1
total	971		744	

The distribution curves for iron are very strange (figure 7). There are two very distinct maxima for the rocks and a rather different distribution for the glasses. The glass maximum at 11 % FeO corresponds to glasses of 'kreep' composition with relatively high alkali contents. There are few rock counterparts of this composition.

The preliminary results of this statistical comparison will be completed by more data and detailed investigations, but two conclusions can already be deduced:

(1) The generation of melts by shock melting of primary rocks and already reworked material results in an overall loss of volatile components such as the alkalis and in an increase of stable components such as aluminium.

(2) Because of selective vaporization from overheated shock melts, the chemical composition of lunar glasses does not reflect the composition of their parent rocks.

2.4. *Selective condensation*

Another process by which the chemical composition of parent materials can be changed at impact-induced phase transitions is selective condensation. The amount of rock mass which is vaporized by an impact is about equal to the mass of the impacting body, and about half the mass of melted material (Gault *et al.* 1972). An appreciable amount of the target is, therefore, transformed into the gaseous state. Some proportion of these vapours may be dissipated into interplanetary space. Another fraction, depending on the cooling rate of the expanding gas cloud, will condense and form solid particles or fluid droplets.

It is not yet known whether some of the regular glass bodies, or even some of the crystalline chondrules which have been found in soils and breccias, are condensation products. If such particles are present in the regolith, the following prediction can be made: Condensation from impact-produced vapours will be selective. The more volatile elements and compounds will be lost and the condensates which return to within the regolith will be enriched in the less volatile components. If the condensation takes place at temperatures well above 1100 °C, the condensate will be strongly depleted in alkalis and correspond to mixtures of orthopyroxene with some anorthite (Larimer & Anders, 1967). This prediction has not yet been checked. From a preliminary review, we have the impression that regular glass bodies are indeed depleted in alkalis and silicon as compared with other glasses.

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