MODELING LUNAR VOLCANIC ERUPTIONS. R. M. Housley, Rockwell International Science Center, Thousand Oaks, California 91360.

From the time the first returned lunar samples were examined, it has been known that early in its history the moon underwent a period of volcanism, during which a large quantity of volatile poor basaltic magma was erupted. The nature of the volcanism and the influence of outgassing and volatile transport in the lunar vacuum have been extensively debated ever since.

Although photogeologists interpreted features on several areas of the moon as pyroclastic deposits, it was not until after the Apollo 17 mission that pyroclastic materials were convincingly identified in the returned lunar samples. The case for so identifying the Apollo 17 orange and black glasses and the Apollo 15 green glass has since been systematically argued by Heiken et al. (1) on the basis of chemical, petrographic and photogeologic evidence.

A plausible explanation for the puzzling fact that these glasses do not resemble terrestrial pyroclastic materials has been offered by O'Keefe (2). He pointed out that the frothy nature of terrestrial pyroclastics may depend on the fact that the surface tension of the melt increases as water is vaporized from it.

A plausible though modest source of volatiles that is compatible with the geochemical constraints imposed by the reduced nature of the lunar basalts has recently been suggested by Sato (3). He showed that all available data can be interpreted by assuming that about 100 ppm of finely divided graphite was present in the magma at depth. Above about 3 km, this graphite would react with the melt to form bubbles containing CO and CO\textsubscript{2} and leave finely divided grains of Fe metal in the melt. This avoids any problem associated with the nucleation of bubbles in a volatile poor magma and could help explain the different physical characteristics of lunar and terrestrial pyroclastics.

Thus, the stage is set for serious efforts to model lunar volcanic eruptions. We proceed in three steps, considering first, the transport of magma to the lunar surface; then the nature of the transient lunar atmosphere produced by the gas released; and finally, the processes that could occur in the vicinity of the point of eruption.

As a starting point for modeling magma transport, we assume that the volcanic plumbing is similar for lunar volcanos and for terrestrial oceanic volcanos. From a visual inspection of recent Hawaiian craters, by allowing for near surface flaring, we obtain an order of magnitude estimate of about 10 m for the typical diameter of terrestrial magma conduits.

It is important to note that in a conduit of this size any reasonable estimates of flow velocity and magma viscosity yield very high Reynolds numbers, implying that the flow must be highly turbulent. In this case, the average flow velocity depends strongly on the roughness of the conduit, but only weakly on the viscosity (4). Thus, we reach the surprising conclusion that the much lower viscosities of lunar magmas in comparison to their terrestrial counterparts will not lead to substantially increased eruption velocities.

In both lunar and terrestrial volcanos, the ultimate driving force responsible for magma migration is the difference in average density between the fluid and the rock through which it moves. Although the near surface
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Behavior of terrestrial magmas is complicated by the large volatile component present, we may roughly check whether our estimated conduit diameter is realistic by comparing calculated eruption characteristics with the recorded behavior of Hawaiian volcanos (5). Assuming the maximum reasonable density contrast of 10%, a viscosity of 145 poise (1), and an average surface roughness of 0.5 m in a 10 m diameter conduit, we can use the hydraulic engineering data graphically presented in (4) to calculate an average flow velocity of 16.5 m/sec, an eruption rate of $4.7 \times 10^6$ m$^3$/hr, and a Reynolds number of $3.4 \times 10^4$.

The eruption rate of $4.7 \times 10^6$ m$^3$/hr is about a factor of 5 high for typical recent Hawaiian eruptions (5), probably because the assumed effective pressure head is too large.

With the same conduit diameter and density contrast and a viscosity of 10 poise (1), the calculated lunar eruption rate is $1.9 \times 10^6$ m$^3$/hr, with a Reynolds number of $2 \times 10^5$ and a flow velocity of 6.8 m/sec.

From the Fe metal content of lunar basalts, we can calculate the amount of CO they must have evolved (3). Using 0.15 wt% Fe metal as determined by Morris and Gose (6) for 74001 glass, this is 0.075 wt%. Thus, our hypothetical eruption brings CO to the lunar surface at the rate of about $1.2 \times 10^6$ g/ml/sec.

As a first approximation, we assume that at modest distances from the source this gas expands hemispherically. A limiting velocity of about 1.5 km/sec will be reached when all the thermal energy is converted into kinetic energy of flow. The density $\rho$ and velocity $v$ at any radius $r$ and mass flow rate $m$ are related by

$$2\pi r^2 \rho v = m .$$

At distances where $v$ is close to its limiting value with the above mass flow rate

$$\rho = \frac{1.3 \times 10^{-4}}{R^2} \text{ gm/cm}^2 ,$$

where $R$ is the radius in m. The °C pressure corresponding to this $\rho$ is

$$P = \frac{1.04 \times 10^{-1}}{R^2} \text{ atoms, or } P = 7.9 \times 10^5 \text{ torr} .$$

Thus, we see that the pressure only falls off to $10^{-8}$ torr at about 100 km from the eruption site. Yet this formula suggests that pressure may remain quite modest near the eruption site, although a more complete calculation is needed to describe this region.

Fountaining during terrestrial volcanic eruptions appears to be caused by the evolution of gas from the magma in the conduit as it moves toward the surface. The observed fountaining, in fact, requires the evolution of only a fraction of the total gas present.

Our estimated molar abundance of CO in lunar magmas is about a factor of 10 lower than the volatile content of terrestrial magmas. However, it may more completely evolve in the conduit and on an equal molar basis will occupy 6 times the volume because of the lower pressure in the lunar conduit. Taking

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into account these facts, we have estimated that lunar magmas could reasonably fountain to a height of about 1 km.

At the point of eruption the gas would occupy considerably more than half the volume and would still be under sufficient pressure to expand violently separating much of the material into small droplets with velocities of the order of tens of m/sec.

This modeling effort clearly can be refined and extended in many ways. For example, the ability of the expanding gas cloud to transport solid particles and perhaps to generate lunar dust storms can be investigated.

At the present stage, it suggests several important experiments. The kinetics of graphite reaction with Fe silicate melts should be investigated. The partitioning of trace volatiles between gas and liquid should be studied. And the behavior of a dry vesicle laden melt on sudden decompression should be checked.

It also strongly suggests the following conclusions: 1) The difference in viscosity between lunar and terrestrial magmas is of minor importance in comparing their eruption characteristics. 2) Magma may fountain to heights of the order of 1 km during lunar eruptions. 3) Violent expansion of CO bubbles at the instant of surface arrival can lead to the formation of abundant ~ 100 μm glass balls and their distribution over a radius of hundreds of meters. 4) A major fraction of the more volatile elements in the magma may be in the bubbles and, hence, escape into the transient atmosphere. 5) The expansion of the transient atmosphere will distribute volatile elements essentially over the entire moon.