ASCENT AND EMPLACEMENT OF BASALTIC MAGMA ON THE EARTH AND MOON.

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Geological and physical observations and constraints have been applied to the development of a model of the ascent and emplacement of basaltic magma on the Earth and Moon[1] and the results are summarized below. Relatively simple mathematical models of the motion of gas/liquid mixtures[2] are adequate to treat basaltic eruptions provided that allowance is made for the coalescence of gas bubbles and that realistic geological and petrochemical constraints are applied to the numerical values of the variables involved. Gas exsolution from magmas on the Earth and Moon (and Mars) only occurs at relatively shallow depths (commonly less than 2 km for terrestrial and lunar basalts). As a result it is generally convenient to consider separately the rise of bubble-free magmatic liquid at depth in a planetary crust and the more complex motions which occur near the surface as gas is exsolved. A lower limit is set to the width of the dike or conduit up which a magma can rise from a given depth, either by the presence of a finite yield strength in the magma or by the need to avoid excessive cooling of the magma during its ascent. The latter constraint is controlled mainly by the magma viscosity. For a wide range of magma types it is found that if the yield strength at depth is greater than a few hundred N/m^2, then yield strength rather than viscosity will limit the ability of the magma to erupt. Bubble coalescence, leading to intermittent explosive activity of strombolian style, will occur in any magma near the surface if the rise speed is sufficiently slow or the viscosity (and yield strength) are sufficiently small. For the commonly occurring basalts on both the Earth and Moon, the rise speed in the crust must be greater than 0.5 to 1 m/s if strombolian activity is to be avoided and relatively steady fire fountaining is to take place.

Earth - For terrestrial basalts commonly having viscosities not less than 10^2 Pa s and negligible yield strengths, dike or conduit widths in the range 0.2 to 0.6 m are needed to allow eruptions from depths between 500 m and 20 km. Corresponding minimum mass eruption rates lie in the range 10 to 300 kg/s for isolated central conduits and in the range 30 to 500 kg/s per meter length of fissure for elongate vents. To accommodate the output rates of 3×10^4 kg $s^{-1}m^{-1}$ for the Columbia River flood basalt eruptions, fissures up to about 4 m wide would be needed. Fire fountain height is dictated by the vertical velocity of the magma/gas dispersion emerging through the vent, and both quantities increase with increasing magma gas content, increase with increasing mass eruption rate, and decrease with increasing magma viscosity. Fire fountains up to 500 m high imply the release of up to about 0.4 wt% of water from the magma, corresponding to initial water contents up to about 0.6 wt%.

Moon - Lunar basaltic eruptions differed from their current terrestrial counterparts in that the magmatic liquids were produced at relatively great depths and were relatively dense compared to the upper lunar crust; however, consideration of the topography of mare basins[3] shows that the effective density contrast driving lunar eruptions was similar to the actual density contrast driving terrestrial basaltic eruptions. The main volatile released from lunar magmas was probably carbon monoxide, produced in amounts[4] up to several hundred ppm--proportionately less by more than an order of magnitude than is common in terrestrial magmas. However, the much greater energy release per unit mass from this gas as it is decompressed to the near-zero ambient lunar

atmospheric pressure, coupled with the fact that both vertical and horizontal expansion of the gas must have occurred, imply a much more efficient use of the avilaable gas on the Moon than on the Earth. The gas volume fraction would reach 0.75, leading to magma disruption, at depths of 14 and 41 m for CO contents of 250 and 750 ppm, respectively; some measure of magma disruption must always have taken place in lunar eruptions unless either the gas content were truly zero or the magma possessed an appreciable yield strength. The differences between terrestrial and lunar magma rheologies and crustal environments do not lead to gross differences between the effusion rates expected on these two planets through fissures or conduits of a given size. Consequently, the recognition of high effusion rate features such as long lava flows and sinuous rilles on the Moon implies only that the tectonic and other forces associated with the onset of some lunar eruptions were such as to allow wide fissures or conduits to form. It is possible that the common occurrence of high effusion rate eruptions could explain the apparent absence of large lunar basaltic shield volcanoes: recognizable individual shields can only be built up when the mean distance flowed by lavas from one source area is substantially less than the mean spacing between sources. The surface widths of elongate fissure vents need be no wider than 10 m to permit the occurrence of mass eruption rates up to ten times larger than those proposed for terrestrial flood basalt eruptions; effusion rates one hundred times larger could be accommodated by 25 m wide vents. As a result, elongate fissure-like structures with widths of many tens to hundreds of meters commonly identified as lunar vents are rarely likely to represent the true vent sizes directly. These structures may be the results of collapse around a vent after eruption ceases or may be produced by accumulation of pyroclastic debris in some circumstances.

Considerations of the details of basaltic eruption processes on the Moon lead to the prediction of several types of volcanic landforms. We discuss elsewhere the correlation of these landforms with specific lunar features.[5]
a) Circular pyroclastic blankets formed around a central vent. These should be low and wide relative to terrestrial counterparts (but the ratio height/width is proportional to eruption duration for fixed M, mass eruption rate and n, released gas content). Blankets which are relatively thick both near the vent and near the maximum range (dome- or shield-like) and which have a well-defined outer edge would be the products of eruptions in which most of the magma was disrupted into sub-mm droplets and in which M lay in the range 10^2 to 10^5 kg/s; blanket radii up to 2.4 km would be expected for released gas contents, n, up to 750 ppm. Blankets which are relatively thick only near the vent (low cone shape) and have radii up to 300 m would be products of eruptions in which all the magma was disrupted into clots larger than several mm, in which n was less than about 200 ppm and in which M lay in the range 10^2 to 10^7 kg/s; such low, cone-like features could be wider (up to 1.5 to 2 km radius for M up to 10^6 kg/s) if magma fragments were concentrated into the size range 1 to 10 mm. In all the above cases, lava flows could easily be absent; flows would be formed, however, if either M or n became small at any stage during the eruption.
b) Circular "regions" up to 3 km radius around a central vent which are the sources of major laval flows. These would be formed for M greater than 10^5 kg/s if most of the magma were disrupted into sub-mm droplets or for M greater than 10^7 kg/s if the magma disrupted mainly into clots larger than a few mm. We explore elsewhere the possibility that these "regions" are the circular depressions that appear to be the sources of some sinuous rilles.[6]

c) Circular pyroclastic cones, commonly less than 50 m in radius, acting as the sources of minor lava flows. These would mark sites of low-effusion rate conduit eruptions. Values of M would have been nominally less than about 100 kg/s, but taking account of the uncertainties in the calculations may have been up to a few hundred kg/s. Such features should commonly be surrounded by very thin pyroclastic blankets of sub-mm droplets extending out to many tens of km.

d) Elongate cinder or spatter ridges. These should be very rare unless they are narrower than about 1 km. Ridges up to 150 m wide and highest near their outer edges could be formed by steady fissure eruptions in which magma was disrupted mainly into clots larger than a few mm provided M/L was less than 3×10^4 kg $s^{-1}m^{-1}$ and n was less than about 100 ppm. Wider ridges up to 1 km wide could be formed for the same ranges of values of M/L and n if magma were disrupted mainly into clasts in the 1 to 10 mm size range. In both the above cases, lava flows would commonly be absent. However, ridges up to about 500 m wide with associated lava flows could be formed by strombolian activity with M/L less than a few hundred kg $s^{-1}m^{-1}$ provided the explosions disrupted the magma into clots mainly in the 1 to 10 mm size range. Otherwise, strombolian activity from fissure sources would build very narrow spatter ridges (up to about 40 m wide) from coarse ejecta and distribute a thin blanket of sub-mm droplets for distances up to tens of km.

e) Elongate regions up to 4 km wide which are the sources of major lava flows. These would be associated with the great majority of high effusion rate eruptions from fissures. The direction of drainage of lava flows away from these source regions would depend on local topography. Where such drainage was along the direction of the controlling fissure, a pyroclastic rampart could be built up parallel to the fissure at the maximum range of the ejected material due to deposition of relatively cool clasts in the optically thin outermost part of the ejecta cloud. Where lava drainage was at right angles to the fissure direction, any cool clasts would be rafted away on the flow.

f) Dark mantle deposits. These should take the form of very extensive but thin deposits; diameters could commonly be up to 50 km and might be as large as 200 km. Sources would either be vents from which steady eruptions occurred at high effusion rates but only a small fraction (of the order of 1%) of the magma disrupted into sub-mm droplets or low effusion rate eruptions in which strombolian activity occurred. Thus, dark mantle deposits are not particularly diagnostic of high or low effusion rates, high or low magma gas contents or geometric shape of source vent. It can, however, be asserted that the total mass of material ejected into a dark mantle deposit must consist of sub-mm droplets and must be much less than the mass of material ejected into near-vent flows or pyroclastic structures: by a factor of order 100 in the case of high effusion rate eruptions and by a factor of order 1000 in the case of strombolian explosions. Dark-halo craters of the Alphonsus type appear to be produced by a different eruption process, one analogous to terrestrial vulcanian explosive activity.[7]

g) Hybrid sources. We stress the fact that where a vent region is fissure controlled but only parts of the fissure system are wide enough at depth to allow rapid magma rise, the result will be a series of relatively isolated vents aligned along the fissure. In these cases, and in any other cases where the typical ranges of ejecta are much greater than the active length of an elongate vent, it will be much more accurate to treat the system as one or more central conduit sources rather than a fissure source.

References: [1]Wilson L. and Head J.W. (1980) To be submitted to J. Geophys. Res. [2]McGetchin T.R. and Ullrich W.C. (1973) J. Geophys. Res. 78, 1833; Pal S.I. et al (1978) PLPSC 9, 1485. [3]Solomon S.C. (1975) PLSC 6, 1021. [4]Housley (1978) PLSC 9, 1473. [5]Head J.W. and Wilson L. (1980) Characteristics and eruption conditions of lunar volcanic features: I,II (in preparation). [6]Wilson L. and Head J.W. (1980) this vol. [7]Head J.W. and Wilson L. (1979) PLPSC10, 2861-2897.