**MARE BASALT VOLCANISM: GENERATION, ASCENT, ERUPTION AND HISTORY OF EMPLACEMENT OF SECONDARY CRUST ON THE MOON.** James W. Head[1] and Lionel Wilson[1,2]. [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA. (james_head@brown.edu) [2]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK.

We utilize a theoretical analysis of the generation, ascent, intrusion and eruption of basaltic magma on the Moon [1-2] to develop new insights into magma source depths, supply processes, transport and emplacement mechanisms via dike intrusions, and effusive and explosive eruptions. We make predictions about the intrusion and eruption processes and compare these with the range of observed styles of mare volcanism, related features and deposits and the geologic record [3-7] (Fig. 1,2).

**Generation:** Density contrasts between the bulk mantle and regions with a greater abundance of heat sources will cause larger heated regions to rise as buoyant melt-rich diapirs that generate partial melts that can undergo collection into magma source regions; diapirs could rise to the base of the anorthositic crustal density trap (when the crust is thicker than the elastic lithosphere) or, later in history, to the base of the lithospheric rheological trap (when the thickening lithosphere exceeds the thickness of the crust) (Fig. 3).

**Ascent:** Residual diapiric buoyancy, and continued production and arrival of diapiric material, enhances melt volume and overpressurizes the source regions, producing sufficient stress to cause brittle deformation of the elastic part of the overlying lithosphere; a magma-filled crack (dike) initiates and propagates toward the surface as a convex upward, blade-shaped dike (Fig. 3-4). The volume of magma released in a single event is likely to lie in the range $10^2$ $km^3$ to $10^3$ $km^3$, corresponding to dikes with widths of 40-100 m and both vertical and horizontal extents of 60-100 km, favoring eruption on the lunar nearside. Shallower magma sources produce dikes that are continuous from the source region to the surface, but deeper sources will produce dikes that detach from the source region and ascend as discrete penny-shaped structures (Fig. 3). As the Moon cools with time, the lithosphere thickens, source regions become less abundant and rheological traps become increasingly deep; the state of stress in the lithosphere becomes increasingly contractional, inhibiting dike emplacement and surface eruptions.

**Intrusion:** In contrast to small dike volumes and low propagation velocities in terrestrial environments, lunar dike propagation velocities are typically sufficiently high that shallow sill formation is not favored; local low-density breccia zones beneath impact crater floors, however, may cause lateral migration to form laccoliths (e.g., Vitello Crater) and sills (e.g., Humboldt Crater) in floor-fractured craters. Dikes emplaced into the shallow crust (Fig. 4-5) may stall and produce crater chains due to active and passive gas venting (e.g., Mendeleev Crater Chain), or if sufficiently shallow, may create a near-surface stress field that forms linear and arcuate graben, often with pyroclastic and small-scale effusive eruptions (e.g., Rima Parry V).

**Effusive Eruptions:** Effusive eruptions are modulated by effusion rates, eruption durations, cooling and supply limitations to flow length, and pre-existing topography. Relatively low effusion rate, cooling-limited flows lead to small shield volcanoes (e.g., Tobias Mayer, Milicius); higher effusion rate, cooling-limited flows lead to compound flow fields (e.g., most mare basins) and even higher effusion rate, long-duration flows lead to thermal erosion of the vent, effusion rate enhancement, and thermal erosion of the substrate to produce sinuous rilles (e.g., Rimae Prinz). Extremely high effusion rate flows on slopes lead to volume-limited flow with lengths of many hundreds of kilometers (e.g., the young Imbrium basin flows).

**Explosive Eruptions:** Explosive, pyroclastic eruptions are common on the Moon. The low pressure environment in propagating dike crack-tips can cause gas formation at great depths and throughout dike ascent; at shallow crustal depths both the smelting reaction and the recently documented abundant magmatic volatiles in mare basalt

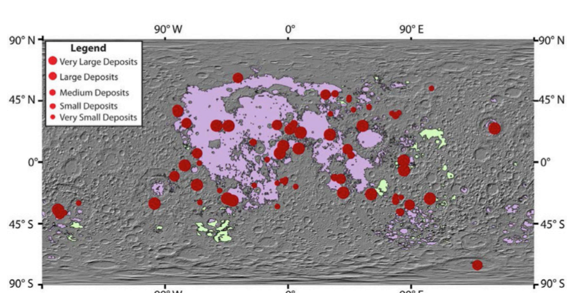

Fig. 1. Maria (purple), cryptomaria (green) [5-6] and pyroclastic deposits (red dots; [7]).

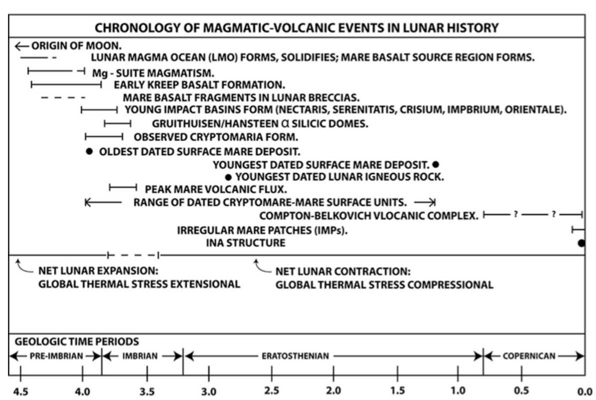

Fig. 2. Chronology of lunar magmatic-volcanic events.

magmas contribute to significant shallow degassing and pyroclastic activity associated with the dike as it erupts at the surface. Dikes penetrating to the surface produce a wide range of explosive eruption types whose manifestations are modulated by lunar environmental conditions: 1) terrestrial strombolian-style eruptions map to cinder/spatter cone-like constructs (e.g., Isis and Osiris); 2) hawaiian-style eruptions map to broad flat pyroclastic blankets (e.g., Taurus-Littrow Apollo 17 dark mantle deposits); 3) gas-rich ultraplinian-like venting can cause Moon-wide dispersal of gas and foam droplets (e.g., many isolated glass beads in lunar soils); 4) vulcanian-like eruptions caused by solidification of magma in the dike tip, buildup of gas pressure and explosive disruption, can form dark-halo craters with admixed country rock (e.g., Alphonsus Crater floor); 5) ionian-like eruptions can be caused by artificial gas buildup in wide dikes, energetic explosive eruption and formation of a dark pyroclastic ring (e.g., Orientale dark ring); 6) multiple eruptions from gas-rich fissures can form regional dark mantle deposits (e.g., Rima Bode, Sinus Aestuum); and 7) long duration, relatively high effusion rate eruptions accompanied by continuing pyroclastic activity cause a central thermally eroded lava pond and channel, a broader pyroclastic ‘spatter’ edifice, an even broader pyroclastic glass deposit and, if the eruption lasts sufficiently long, an associated inner thermally eroded vent and sinuous rille channel (e.g., Cobra Head and Aristarchus Plateau dark mantle).

**Global Distribution and History:** The asymmetric nearside-farside distribution of mare basalt deposits is most plausibly explained by crustal thickness differences; intrusion is favored on the thicker farside crust and extrusion is favored on the thinner nearside crust. Second-order effects include regional and global thermal structure (areal variations in lithospheric thickness as a function of time) and broad geochemical anomalies (the Procellarum-KREEP Terrain). Differences in mare basalt titanium content as a function of space and time is testimony to a laterally and vertically heterogeneous mantle source region. The rapidly decreasing integrated flux of mare basalts is a result of the thermal evolution of the Moon; continued cooling 1) decreased diapiric rise and mantle melting, 2) thickened the lithosphere, and 3) caused the global state of stress to be increasingly contractional, all progressively inhibiting the generation, ascent and eruption of basaltic magma. Late-stage volcanic eruptions are typically widely separated in time and characterized by high-volume, high-effusion rate eruptions producing extensive volume-limited flows, a predictable characteristic of deep source regions below a thick lithosphere late in lunar history.

**Summary:** Extrusive mare basalt volcanism (MBV) begins with regional cryptomaria emplacement (~4 Ga; earlier MB breccia fragments may be excavated dikes) and is initially globally distributed but much more abundant on the nearside. Peak MBV volcanism is also globally distributed but much more abundant on the nearside. Late stage MBV is concentrated on the western nearside/limb. We see no conclusive evidence for MBV activity in the last billion years. MBV composition/mineralogy changes with time: Early high-Ti, middle low Ti, late high-Ti. MBV distribution and mineralogy suggest heterogeneity of mantle source regions in space and time; we see no evidence for asymmetrical (e.g., nearside/farside) distribution of source regions and the major factor in MBV areal distribution appears to be crustal thickness. MBV eruption frequency decreases significantly with time (10-20 Ma to 40-100 Ma intervals). The major causes of the leptokurtic skewed-right MBV flux curve are: 1) rapid onset of MBV, 2) narrow peak flux, 3) relatively rapid decay due to global cooling, increasing depth of source regions, and increasingly compressional state of stress in the lithosphere. The total volume of lunar extrusive secondary crust is miniscule compared to primary crust. This improved paradigm for the generation, ascent, intrusion and eruption of basaltic magma provides the basis for the broader interpretation of the lunar volcanic record in terms of variations in eruption conditions in space and time, and their relation to mantle heterogeneity and a more detailed understanding of lunar thermal evolution.

**References:** [1] Wilson and Head (2015) *Icarus*, in press. [2] Head and Wilson (2016) *Icarus*, in review. [3] Hiesinger et al. (2011) *GSA SP 477*, 1. [4] Shearer et al. (2006) *RMG* 60, 365. [5] Whitten and Head (2015a) *Icarus* 247, 150. [6] Whitten and Head (2015b) *PSS* 106, 67. [7] Gaddis et al. (2003) *Icarus* 161, 262.

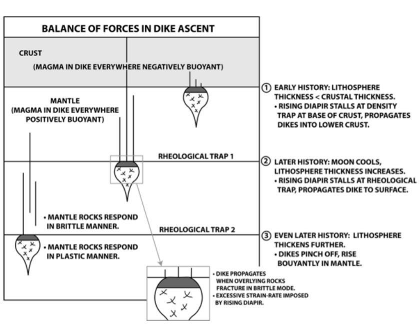


Fig. 3. Balance of forces in dike emplacement with time.

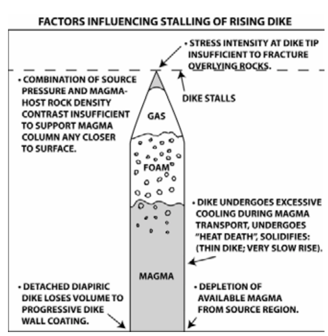


Fig. 4. Factors influencing stalling of rising dike.

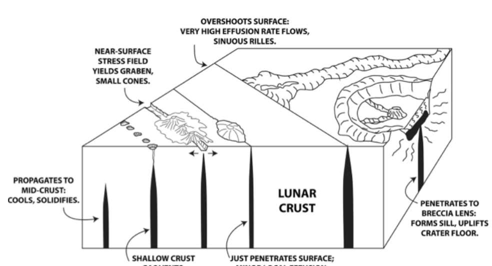


Figure 5. Dike near-surface intrusion/eruption processes.