LUNAR MARE DEPOSIT VOLUMES, COMPOSITION, AGE, AND LOCATION: IMPLICATIONS FOR SOURCE AREAS AND MODES OF EMPLACEMENT: R. Aileen Yingst and James W. Head, Dept. Geological Sciences, Brown University, Providence RI 02912 USA

Introduction: Analysis of lunar mare basalts has resulted in intense focus on the petrological aspects of rock characterization and led to a series of mare basalt petrogenetic models (e.g., 1). Analysis of high-resolution images of the mare surface documented the geomorphology of landforms and the stratigraphy of volcanic units (e.g., 2, 3). However, there have been only a handful of analyses focusing on documentation of processes operating between the source regions and the surface features (4, 5). This is particularly true with respect to both conceptual and quantitative assessments of the relation of source regions to surface features, and the interpretation of surface features in terms of the geometry of the conduits delivering magma from the source to the surface. In recent studies we have been working to bridge this gap by establishing the basic theoretical framework for considering the ascent and eruption of magma on the Moon (4), and then developing the principles of reservoir development at neutral buoyancy zones at the base of the highlands crust or at rheological boundaries, the overpressurization of reservoirs, and the general properties of dikes that would be propagated toward the surface from both a theoretical (6) and observational (7) point of view. In this contribution we report on an initial analysis of mare deposit volumes, compositions, ages, and locations, and investigate implications for modes of emplacement and nature of source regions.

Data: In the major lunar maria, analysis of volumes of mare deposits and linkage to their source vents is complicated by subsequent lava flow unit emplacement and burial. To minimize these problems, our intital analyses focus on deposits that occur in isolated patches in the highlands adjacent to the major maria. Although we cannot be sure without supporting evidence that each of these deposits represents a single eruption episode, this approach nonetheless represents better maximum estimates than the more complex deposits of the main maria. We have focused our analysis initially on the mare patches in the western limb and farside area because of the large numbers of patches there (8) and recent data on their composition and ages (9, 10). Although the presence and general characteristics of these mare patches have been known for years (2) recent Galileo multispectral data and impact crater size-frequency distribution data from Lunar Orbiter provide important new information to apply to this problem (9, 10). Mare volumes for 33 lava ponds in the Orientale area have been estimated by Gaddis and Head (8) by measuring flow scarp height, partially buried craters, pre-existing topography and ejecta blanket topography (Fig. 1). In order to examine the evolution of lunar volcanism in this region in space and time, we have placed some of these data in a stratigraphic column (Fig. 2).

Modes of Occurrence, Volumes, and Associated Features: Gaddis (8) found that of the 33 ponds analyzed, 11 occur in association with Orientale basin rings (BR), 10 on the floors of pre-existing craters (CF), and 12 in intercrater areas (IC). Only two of the 33 lava ponds exceed 1280 km^3 (Lacus Veris, 5755 and Grimaldi, 11,250 km^3), and these are likely to have multiple flow units. The remainder fall between 20-1280 km^3 and showed no major differences in average volume relative to mode of occurrence (BR = 385; CF = 250; IC = 542 km^3). Twenty-one ponds were 200 km^3 or less (Fig. 1); of these, the largest group (7 ponds) have volumes 20 km^3 or less, and the next largest (4 ponds) have volumes between 140-160 km^3. For comparison, the terrestrial Laki eruption was ~12 km^3, and the Roza Member of the Columbia River Basalts was ~1200 km^3 (11), approximately at the upper and lower ends of the range of values for the 31 ponds, and orders of magnitude higher than single eruptions associated with shallow magma reservoirs such as Hawaii. Sinuous rilles are associated with 27% of the ponds and linear rilles with 42%; 18% show both linear and sinuous rilles. Sinuous rilles are preferentially associated with basin ring occurrences (BR = 55%; CF = 20%; IC = 0%) and linear rilles show a slight preference for crater floor occurrences (BR = 45%; CF = 50%; IC = 33%).

Interpretation: Typical volumes for dikes bringing melt close to or out onto the lunar surface from source regions at about 100 km depth have been estimated to lie in the range of 200-600 km^3 (6). Thus, if such volumes are required even to establish pathways to the surface it is easy to understand why typical observed lunar volumes would fall more in the terrestrial flood basalt range than in a range typical of shallow magma reservoirs. Observation and analysis of the 31 pond volumes on the western nearside thought to represent single eruptive phases (10-1280 km^3) show that these values range from a small percentage up to about a factor of two of the total estimated dike volumes. In addition, Hulme (12) has estimated that extruded volumes required to erode sinuous rille channels lie in the range of 100 to at least 1000 km^3; 78% of the ponds with sinuous rilles fall in this range. The large number of ponds with associated linear rilles is also consistent with penetration of dikes to the near-surface environment (6,7). The lack of strong correlation of average pond volumes with mode of occurrence suggests that conditions at depth, not in the upper crust, are important. We thus conclude that these data are consistent with dikes that are propagating to the surface from overpressurized source regions at depth.

Stratigraphy: Fig. 2 shows the crater ages of mare deposits analyzed by Greeley *et al.* (9) on the western limb and farside and indicates that mare emplacement occurred over a period of ~1.8 billion years, between ~2.5 and

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System

3.8 b.y. ago. The earliest deposits occurred within ~140 my of the formation of the Orientale basin at ~3.84 Ga, and represent continuation of pre-Orientale mare, now cryptomaria (13), emplacement in the Schiller-Schickard region, and filling of the south-central Orientale basin. Later emplacement (~3.64 Ga) took place in the South Pole-Aitken basin (Apollo and Van de Graff) and following this phase, volcanism continued in Mare Orientale, Lacus Veris, and nearby Riccioli (~3.45-3.5 Ga). Basalts were emplaced in western Grimaldi at ~3.25 Ga. The most recent volcanic activity in this region of the Moon appears to have taken place in Lacus Autumni (~2.85 Ga) and in eastern Grimaldi (~2.49 Ga).

Interpretation: For the most part, there appears to be no strong correlation between time of large crater or basin formation and mare emplacement. Maria in Apollo, Van de Graff, South Pole-Aitken, and Grimaldi postdate these events by many hundreds of millions of years. Although maria began filling Orientale soon after its formation (within ~140 my) nearby deposits were already being emplaced in the Schiller-Schickard region prior to the Orientale event and continued subsequently, contemporaneous with the early Orientale basin fill. In addition, the separation in ages of fill is striking. Maria within Orientale appear to have been emplaced in three phases at ~3.7, ~3.45-3.5, and ~2.85. The total duration is 850 my and the spacing between these phases is 200 my to 650 my, an extremely long time period for a single continuous source region to remain active by terrestrial standards. A similar situation exists in the maria within the crater Grimaldi; on the basis of crater size-frequency distribution data (9) the western flow unit was formed more than 750 million years before the eastern unit and the two units have different TiO_2 abundances, suggesting that they may have different source regions. The age difference would seem to indicate different source regions since in 750 million years a diapir/reservoir would almost certainly have solidified. If this is true, the closeness of the two units in such a small basin (about 150 km diameter) suggests a diversity of reservoirs in the same region of the mantle at widely separated time intervals. An alternative is that these deposits represent the surface manifestations of reservoirs in the upper mantle derived from and replenished by long-lasting plume-like instabitities in the deeper mantle (14). We are presently building on this basic data set of individual volcanic episodes in space and time in order to address further the questions of areal extent, compositional variation, and temporal duration of mare basalt source regions.

References: 1) J. Longhi, *G&CA, 56*, 2235, 1992; C. Neal and L. Taylor, *G&CA, 56*, 2177, 1992. 2) D. Wilhelms, *USGS PP-1348*, 302 pp., 1987. 3) J. Head, *RGSP, 14*, 265, 1976; BVSP, Pergamon, 1981. 4) L. Wilson and J. Head, *JGR, 86*, 2971, 1981. 5) F. Spera, *G&CA, 56*, 2253, 1992. 6) J. Head and L. Wilson, *G&CA, 56*, 2155, 1992. 7) J. Head and L. Wilson *PSS*, in press, 1994. 8) L. Gaddis and J. Head, *LPSC XII*, 321, 1981; L. Gaddis, Brown Univ. MSc. Thesis, 1981. 9) R. Greeley *et al.*, *JGR, 98*, 17183, 1993. 10) A. McEwen *et. al.*, *ibid.*, 17207, 1993. 11) S. Reidel and P. Hooper, *GSA SP 239*, 1989. 12) G. Hulme, *Mod. Geol.*, *4*, 107, 1973. 13) J. Head *et al.*, *JGR, 98*, 17149, 1993. 14) P. Hess and E. M. Parmentier, *LPSC XXIV*, 651, 1993.

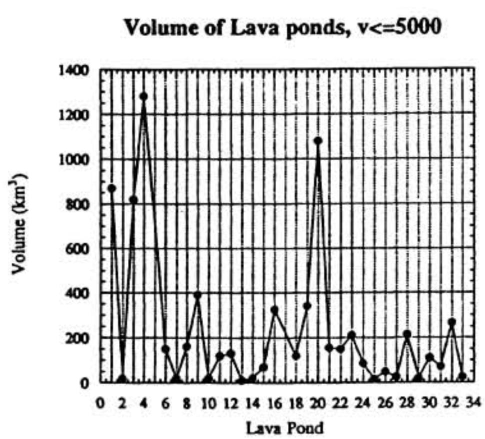

Figure 1.
Volume-frequency distribution for 31 lava ponds (8).

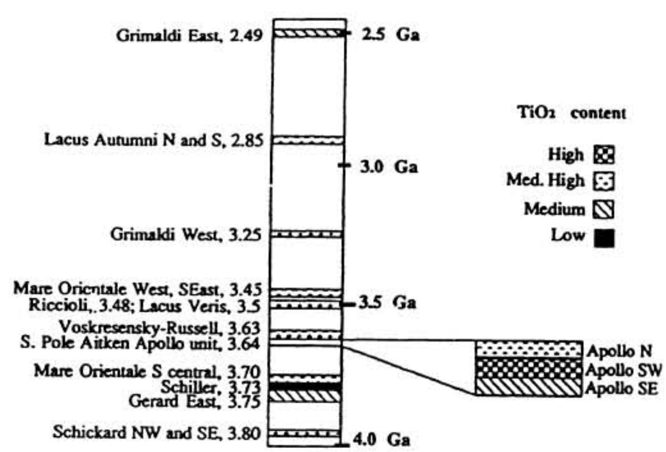

Figure 2.
Stratigraphic column for mare deposit emplacement (9).

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System