GEOLOGIC EVIDENCE FOR ONSET, DISTRIBUTION, DIVERSITY AND DURATION OF LUNAR MARE BASALT VOLCANISM: IMPLICATIONS FOR PETROGENETIC MODELS AND THERMAL EVOLUTION: James W. Head, III, Department of Geological Sciences, Brown University, Providence, RI 02912 USA

Introduction: Analysis of Apollo, Luna, and meteorite lunar mare basalt samples has provided an important basis for establishing chronology and petrogenetic derivation. Extensive geologic mapping and remote sensing data have provided a basis for understanding mare basalt distribution and volumetric significance. At the same time, recent analyses of mare basalt surface deposits and their mode of emplacement have provided a basis for models of the ascent and eruption of magmas from shallow subcrustal regions. No complete and satisfactory end-to-end model exists, however, for the formation and evolution of mare basalt source regions, the ascent and behavior of basaltic source materials, the melting and transport of mare basalt magmas, and the final emplacement of mare basalt magmas on the surface. The surface record of mare basalt volcanism represents one of the most fundamental constraints on such models and in this contribution the implications of this record, and outstanding problems in its interpretation, are outlined.

Onset: A major outstanding question in the petrogenesis of mare basalts is the source of heat required for their melting and their depth of origin. A key to the understanding of some types of models for the origin of mare basalt source regions is the onset of mare-type volcanism. Although estimates are made difficult by the obscuring effects of basin and crater deposits, the increasing detection of cryptomaria has clearly demonstrated that mare volcanism began and was areally extensive prior to the formation of Orientale, the last of the large impact basins, at about 3.8 Ga. Consistent with this, sample geochronology data show evidence of high-Ti basalts at 3.85 +/- 0.2 Ga in Mare Tranquillitatis. Unresolved is the actual age of onset and areal and volumetric significance of this early mare-type volcanism, and its relationship to the suite of aluminous basalts.

Diversity and Distribution in Space and Time: Early analyses emphasized the high-Ti nature of the Apollo 11 basalts and the low-Ti nature of the Apollo 12 basalts and hypothesized that melting of the mare basalt source region began at the ilmenite-rich residuum and deepened with time into the mantle. Remote sensing data from unsampled western maria showed, however, that young high-Ti basalts were widespread, if volumetrically small, and that they were largely of Eratosthenian age thus considerably complicating the simple model. These and subsequent analyses have shown that each of the mare basins are characterized by a diversity of mare basalt volcanic fill (summarized in 4-5) and that temporal heterogeneity is at least as important as sequential heterogeneity, from a remote sensing point of view.

There is abundant geologic evidence that the vast majority of observed volcanic deposits (over 90%, about 9.3 x 106 km3) were emplaced in the Late Imbrian Period, spanning 600 Ma from about 3.8 to 3.2 Ga. During this time, a wide range of basaltic compositions was being emplaced in virtually all the nearside mare basins, with earliest and intermediate deposits dominated by (but not confined to) high-Ti basalts; later deposits of this period are dominantly low-Ti and represent the major late fill of the nearside basins (e.g., Crisium, Serenitatis, Humorum, Imbrium, Nubium, Procellarum). Thus, if these volumes can be linked to processes of petrogenesis not unduly modified by the state of stress in the lithosphere and crustal density barrier filtration it means that the maximum period of production, ascent, and emplacement of mare basalts was between 3.8 and 3.2 Ga, and that magmas produced during this period were diverse in space and time, but dominated by an early phase of high-Ti basalts. The next phase of mare basalt volcanism occurred during the Eratosthenian Period, spanning 2.1 Ga, and less than 5% of the total volume of mare basalts was emplaced during this time. Some of these latest flows in Oceanus Procellarum may extend into the Copernican Period. This material was emplaced largely on the central and western nearside in Imbrium and Procellarum and is predominantly composed of high-Ti basalts. The low overall volumetric significance of these latest deposits and their extremely low average effusion rate (about 10^-5 km3/au) is certainly partly due to the general thermal evolution of the Moon and the increasingly compressional state of stress in the lithosphere with time, both factors minimizing production of basaltic magmas and their ascent to the surface. Nonetheless, the key points are that
the heat source for melting of parental material was operating for an additional 2 Ga, and that it was producing high-Ti basalts extruded over a limited portion of the lunar surface.

Duration: Evidence of abundant cryptomaria are testimony to the fact that mare volcanism began more prior to the end of 'heavy bombardment', and fragments in highland breccias have been cited as evidence for onset as early as 4.2 Ga. The age of the latest mare volcanic units is debated but most workers accept an age of 2.5 Ga for the youngest large Imbrium basin flows, although they may be as young as 1.5-2.0 Ga and evidence has been cited for flows of Copernican age, which would be younger than about 1.1 Ga. Thus, mare basalt volcanic deposits are testimony to the production and extrusion of mare basalts for a period of at least 2 Ga and perhaps as long as 3 Ga; however, surface volcanism has not been volumetrically significant on the Moon since about the late Archean on Earth.

Style of Emplacement: The presence of extensive lava flows, sinuous rilles attributable to thermal erosion, and lack of large shield volcanoes are some of the evidence that suggests that magmas are commonly delivered to the surface in large quantity, through dikes originating from depth. The low density of the lunar highlands crust provides a density barrier to the buoyant ascent of mantle melts and ascending dikes are likely to stall at a neutral buoyancy zone there, before reservoir overpressurization propagates dikes toward the surface. This density barrier means that intrusion to extrusion ratios may be very high and that the abundance of mare basalts on the surface cannot be equated directly to the amount of melting in the interior. Indeed, the nearside-farside asymmetry in mare basalt deposit occurrence has been interpreted to be due to thicker farside crust acting to inhibit ascent of dikes to the surface, and correlation of eruption volumes in individual mare patches with crustal thickness further supports this hypothesis.

Implications for Petrogenetic Models/Modes of Emplacement and Outstanding Problems: Can this heterogeneity in time and space be linked to vertical and/or horizontal diversity in the mantle source regions? At least four issues must be addressed before this is more confidently known: 1) Superposition of younger maria makes the establishment of early mare basalt ages more difficult, and more refined estimates are required. More sophisticated mixing models and higher resolution multispectral imaging and spectrometer data will aid in these determinations. 2) The low-density lunar crust likely acts as a density barrier to the buoyant ascent of mare basalt magmas and this may be responsible for much of the areal difference in distribution of mare basalt deposits, most notably in the nearside-farside asymmetry, but also in the volumes of individual deposits. 3) The style of emplacement of mare deposits (shallow near-surface dike emplacement versus flood basalts) differs sufficiently that volumes of individual eruption events vary widely depending on this factor, rather than on the significance of melting in the source region. More detailed models are required to quantitatively assess these two factors. 4) Thermal evolution is a very significant factor, rather than on the state of stress in the lithosphere and thus the ability of magma to reach the surface. Successful interpretation of the surface record of mare basalt volcanism in terms of petrogenesis must also factor in the influence of this filter.