EVIDENCE FOR CRYPTOMARE IN THE NORTHERN LIGHT PLAINS OF THE MOON

J. F. Mustard and J. W. Head, Dept. Geol. Sci., Brown University, Providence RI, 02912.

Introduction: The onset, distribution, and volumetric significance of earliest lunar mare basaltic volcanism is an important question in determining the overall thermal evolution of the Moon, but one made difficult to address by the lack of widespread sampling sites and the superposition of impact crater and basin deposits. Detection of pre-basin mare deposits (termed cryptomaria (1)) and development of criteria for their further delineation has led to increased knowledge of their distribution and significance. In this study, we use Galileo CCD data from the Earth-Moon 2 encounter (2) to assess the possible occurrence of cryptomaria underlying the extensive light plains units north of the Imbrium Basin and Mare Frigoris.

Regional Stratigraphy: Analysis of the stratigraphy of exposed basaltic deposits provides a setting for possible cryptomaria occurrences. The most significant regional event is the formation of the Imbrium Basin and the emplacement of the Fra Mauro Formation and related deposits (Alpes and Lineated units) (3). Prominent in the region are extensive light plains of two ages; Ip_1, located primarily within and W of Meton and equivalent in age to the Imbrium event (7), and Ip_2, concentrated in lows in a triangular-shaped area the corners of which are defined by W. Bond, Baillaud, and Atlas. On the basis of stratigraphy, these light plains are younger than the Imbrium event but older than the Imbrian-aged maria; an age equivalent to the Orientale basin event is interpreted on the basis of crater degradation and size-frequency distribution data (7). Regional mapping of these and the overlying mare deposits (3,4) indicate that the vast majority of Mare Frigoris are maria of Imbrian age, with Imbrian mare deposits also occurring in small patches to the N and E of Frigoris, just SE of Philolaus, just S of Baillaud, in and adjacent to Humboldtianum, and within and just W of Endymion. Smaller occurrences of Eratosthenian-aged maria occur to the west (part of the Procellarum basalts (5)) and along the margins of Mare Frigoris to the N and S.

Cryptomare? Two possible environments for cryptomaria exist: 1) Pre-Imbrian, underlying the Fra Mauro Formation and its facies, and 2) Pre-Orientale, overlying Imbrium basin deposits but obscured by influences from the Orientale basin event. In addition to the occurrence of Imbrian-aged mare patches in this area, the southern end of the younger light plains occurrence (the base of the triangle) is dominated by lack of highland topography, a very smooth plains surface, loss of highland crater rims in this direction (e.g. Gärtner), and the occurrence of mare ridges, all suggestive of the presence of mare fill. Hawke et al. (8) have determined that Gärtner D, a dark halo crater, excavates basalt from beneath the northern light plains. Initial analyses of SSI data from the Galileo EM-2 encounter indicate that this basalt ejecta has spectral affinities to med-high Ti basalts of the Imbrium basin, but that early and late Imbrium light plains are dominated by highland-like spectral properties (2). Belton et al. (2) conclude that cryptomare are unlikely to be present beneath the majority of these light plains. We have investigated this question further using the experience gained from analysis of the Schiller-Schickard region (9,10), the Procellarum shores (11), and criteria for identification of cryptomare (12).

Methods: Two approaches to analysis of the EM-2 SSI data were taken to assess the evidence for cryptomare in this region: color ratio images (0.41/0.756: 0.99/0.756: 0.76/0.41) and spectral mixture analysis. Areas highlighted from these analyses as important were then analyzed using the full spectral properties of the SSI instrument. We initially focus on Gärtner D and associated terrains, since this region contains the best evidence for cryptomare (2,8). An imaged-based linear spectral mixture model was performed using local endmembers representative of red mare, blue mare, highlands, and fresh crater ejecta (highland). The distribution and spectral abundance of these endmembers were calculated with an average rms error of $\approx$1.5%.

Results: The mixture maps correspond well with previous mapping of volcanic units in Mare Frigoris (4). The red basalt endmember image has high abundances in all areas mapped as red basalt, as does the blue basalt. Intermediate mare types are characterized by mixtures of red and blue mare endmembers. The ejecta blanket of Gärtner D exhibits high abundances of the blue mare endmember, consistent with previous analyses of EM-2 data (2). The plains surrounding Gärtner D do not exhibit any abundance patterns that distinguish them from nearby highlands. In contrast, there is a region (Zone A) mapped as light plains (3), approximately 100 km west of Gärtner D, that exhibits high abundances (60-90%) of the blue mare endmember. It also has characteristics in the color ratio composites similar to regions mapped as blue mare. An additional area with similar properties (Zone B) is also found in the light plains at the most eastern boundary of Mare Frigoris. 6-channel SSI spectra were obtained from known blue mare, Gärtner D ejecta, and Gärtner plains. These were compared to spectra taken from small fresh craters and surrounding anomalous plains in zones A and B. The crater spectra are comparable to the spectrum of Gärtner D ejecta in albedo, slope, and 1 μm band strength. Spectra from zones A and B are comparable to spectra from the blue mare, and distinct from Gärtner plains and nearby highlands.

The majority of the light plains N of Frigoris, however, do not exhibit such well defined spectral properties. From the mixture analysis we find that the light plains are slightly higher in mare abundance that the inter-plains terra. In addition, the plains are redder with a marginally greater 1 μm band depth in the color ratio composites. However these distinctions are subtle and do not uniquely identify cryptomare (e.g. 11). Also, the analyses are complicated by the fact that the incidence angle increases rapidly towards the pole and ejecta from the craters Anaxagoras and Thales criss-cross the region. There are, however, numerous small fresh craters in the region that sample both the light plains and inter-plains terra. To assess if the terrain has highland-like or mare-like spectral properties, spectra from fresh craters in representative mare and highland regions were assembled. Then spectra from small fresh craters in the region north of Frigoris were extracted, compared to the base spectra, and categorized as mare-like, highland-like, or ambiguous. When plotted on a base map, we find that all small fresh craters in the light plains between Mare Frigoris and the crater Kane are mare-like. Highland-like craters are found on all the small fresh craters on the inter-plains terra, as well as the young crater in the older light plains within the crater Meton. The fresh crater spectra farther from Mare Frigoris become increasingly ambiguous closer to the terminator due to decreasing light levels and the effects of compression noise.

Discussion: On the basis of this analysis we propose that there are cryptomare of med-high Ti basalts near Gärtner D and at the far eastern end of Mare Frigoris. They have spectral affinities to the young med-high Ti basalts in the region, but are clearly older. Thus it is evident that there was a period of early high-Ti volcanism in these areas, perhaps similar to other regions of the Moon such as Mare Tranquillitatis. It is also likely that the light plains (Ip_2) between Mare Frigoris and the crater Kane are underlain by volcanics with affinities to the red basalts of Mare Frigoris. It is possible that the young light plains farther to the north are also cryptomare, but new data are required to resolve this issue. Nevertheless, the older light plains (Ip_1) do not show evidence for cryptomaria predating the emplacement of Imbrium-aged plains and ejecta.

It is also possible that the Gärtner D impact excavated vertical dike material rather than flatlying cryptomare. We observe that the crater has impacted directly on a linear rille cutting the smooth plains. Elsewhere, the presence of linear rilles with associated volcanic cones and not related to loading and flexure has been attributed to shallow intrusion of dike material, with dikes being of the order of several hundred meters thick (13). In this interpretation, the dike underlying Gärtner D may be a feeder for the early blue deposits. Alternatively, it could be related to the later, youngest blue maria for which surface eruptive deposits are not exposed in this area.

In summary, at the resolution of the Galileo SSI data, we find no evidence for cryptomaria predating the emplacement of Imbrium-aged plains and ejecta. Evidence does exist, however, for cryptomaria of several compositional affinities north and east of Mare Frigoris and apparently postdating the Imbrium event, but predating the time of formation of the Orientale Basin. Although the Orientale basin is several thousand km distant, apparently contributions of highland ejecta from there and elsewhere obscured the basic mare signature to produce the cryptomaria.

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