Evidence for Cryptomare in the Northern Light Plains of the Moon

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; Ip1, located primarily within and W of Meton and equivalent in age to the Imbrium event (7), and Ip2, 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 is 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. Gärtnert), and the occurrence of mare ridges, all suggestive of the presence of mare fill. Hawke et al. (8) have determined that Gärtnert, 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 medium-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 Gärtnert 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 ~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 Gärtnert D exhibits high abundances of the blue mare endmember, consistent with previous analyses of EM-2 data (2). The plains surrounding Gärtnert 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 Gärtnert 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, Gärtn er D ejecta, and Gärtn er 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 Gärtn er 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 Gärtn er 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 cross-cross the region. There are, however, numerous small fresh craters in the region that
take both the light plains and inter-plains terra. To assess if the terrain has highland-like or
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 Gärtn er 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 Tranquilitatis. It is also likely that the light plains (Ip2) 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 (Ip1) do not show evidence for
cryptomaria predating the emplacement of Imbrium-aged plains and ejecta.

It is also possible that the Gärtn er 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 dike being of
the order of several hundred meters thick (13). In this interpretation, the dike underlying Gärtn er
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.

41, 719-727.