**EARTH-BASED RADAR AND ORBITAL REMOTE SENSING OBSERVATIONS OF MARE BASALT FLOWS AND PYROCLASTIC DEPOSITS IN MARE NUBIUM.** L. M. Carter[1], N. E. Petro[2], B. A. Campbell[3], D. M. H. Baker[2], and G. A. Morgan[3]. [1]University of Arizona (lmcarter@lpl.arizona.edu), [2]NASA Goddard Space Flight Center, [3]Smithsonian Institution.

**Introduction:** Nubium is a pre-Nectarian aged basin that is 690 km in diameter. Crater size-frequency distribution measurements show that lava flow units within the basin have a range of ages from Imbrian to Eratosthenian (2.8 to 3.8 Gya), with most units having formed in the Late Imbrian at 3.3-3.5 Gya [1]. Flow units have been mapped according to composition derived from spectral data [1, 2]. The flows show a range of estimated $TiO_2$ weight percent ranging from 1-5%, and Bugliolacchi et al. [2] find that the older flows are also less $TiO_2$ rich.

The source vents and morphology of most lunar mare basalts have remained elusive due to a thick regolith cover that has accumulated during billions of years of bombardment from bolides and micrometeorites. Radar remote sensing can penetrate through regolith and reveal buried terrains, but 12.6 cm wavelength (S-band) radar imaging of the Moon does not penetrate deep enough to see buried features in most places. Recent 200 m/pixel radar imaging at the deeper penetrating 70 cm wavelength (P-band) using the Arecibo Observatory radar system has revealed flow structures such as channels and flow lobes in Mare Serenitatis and Mare Imbrium [3, 4]. Here we use both S-band and P-band ground-based radar data (Figs. 1, 2), along with other spacecraft data sets, to shed new light on volcanism in Mare Nubium.

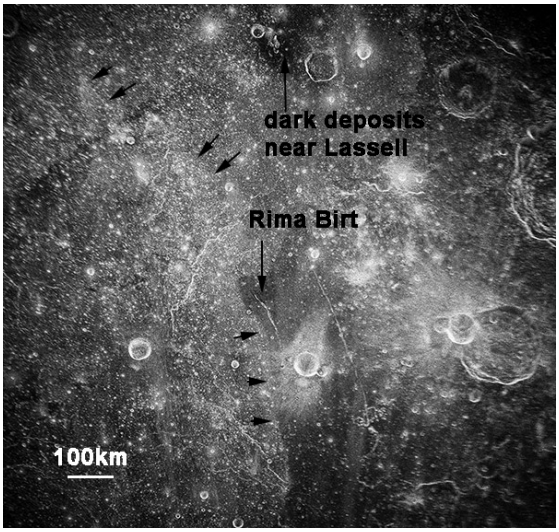


**Fig. 1:** S-band (12.6) cm radar backscatter image of Mare Nubium. Dark arrows highlight radar-bright flow boundaries (top) also visible in other data sets (Figs. 2,3) and a sharp boundary with a radar dark region on the eastern margin (bottom).

**Lava flow complexes:** Many of the previously mapped lava flow units [1, 2] are visible in one or both radar data sets. While P-band data samples a greater extent of the regolith column, and thus exaggerates subtle differences in ilmenite content, some boundaries are also visible in the S-band data. This suggests that the ilmenite differences across the Nubium unit boundaries are similar to Mare Imbrium, but greater than those in Mare Serenitatis, where none of the P-band

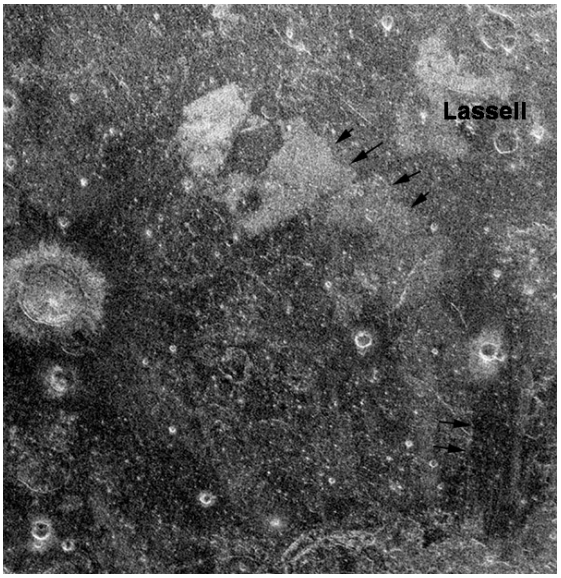


**Fig. 2:** P-band (70 cm) radar backscatter image of Mare Nubium. Dark arrows highlight radar-bright and dark flow boundaries from Fig. 1. This figure covers a larger area than Fig. 1, due to the larger beam size of the telescope at this wavelength. Radar-bright flows correspond to lower derived $TiO_2$ values and some are visible in the Clementine color ratio data (Fig. 3).

boundaries are seen in S-band data [3, 4]. In general, the radar-bright flows in the P-band data correspond to lower derived $TiO_2$ values (from method in [5]), and so the P-band map closely resembles some of the mapping done by [2] based on compositions, though it is not possible to delineate as many units from the radar data. Note that the circular photometric anomaly identified by [6] and visible in Clementine UV/VIS data (Fig. 3) does not appear in either radar data set, which suggest that it is either a thin surface effect, or that the composition is not different enough to cause a change in radar reflectivity. This feature does not appear on

$TiO_2$ maps, suggesting that if it represents a near-surface expression of highlands material as proposed [6], it has not sufficiently changed the relative ilmenite content to be detectable.

**Possible Pyroclastics:** Near the crater Lassell, there is a very low $TiO_2$ region that is also radar dark with very low radar CPR, especially in the S-band data (Fig. 1). The floor of Lassell has been previously identified as having spectral characteristics indicative of pyroclastics [7], but the radar data suggest a larger area of pyroclastics including Lassell and the highlands to the west. The Clementine color ratio data [8] show that the radar-dark region is also very red (Fig. 3), similar to many other pyroclastic deposits, including those associated with Rima Birt. While highland materials are also reddish in the Clementine composite images, they have much higher average CPR values than pyroclastics.

The S-band radar data show a very dark region surrounding Rima Birt (Fig. 1) and continuing to the east past Rupes Recta. This same dark region is visible in

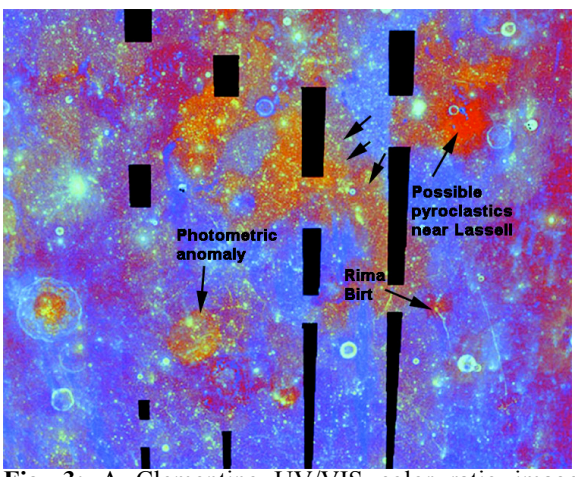


**Fig. 3:** A Clementine UV/VIS color ratio image shows some of the lava flow features seen in P-band data (Fig. 2), but does not show the eastern radar-dark region boundary. Clementine data show a photometric anomaly discussed by [5], which is not visible in the radar data. Note the red-colored pyroclastics associated with Rima Birt and the red area near Lassell crater.

P-band radar backscatter data but is not as low-return as the surrounding high titanium basalt regions. This eastern dark region was proposed as a possible large pyroclastic deposit [9], and pyroclastics could possibly explain the radar-dark character at both wavelengths. A small region of pyroclastics surrounding Rima Birt has been previously identified near the northern part of the rille [10, Fig. 3], but the larger dark area (arrows, Fig. 1) is significantly more extensive in the radar data. This sharp boundary is not visible in either the $TiO_2$ data or Clementine color ratio data.

This eastern radar-dark area is similar to the Tacquet Formation region on the southern part of Mare Serenitatis [11] that also has SC (same sense circular) backscatter cross section and Circular Polarization Ratio values less than would be expected based solely on the predicted $TiO_2$ content. The Tacquet region has also been suggested as a possible pyroclastic deposit due to mantling of the surface and lack of small craters with blocky ejecta. Both the Taquet and eastern Mare Nubium radar-dark regions lack spectral features associated with pyroclastics, such as a red UV/VIS signature and evidence of increased OH.

If this eastern dark region has been partially mantled by pyroclastics, it would be another example of a large regional pyroclastic deposit at the edge of a mare basin, similar to pyroclastics that ring the southern half of Mare Serenitatis. However, an alternate possibility is that the radar is more sensitive to changes in $TiO_2$ content than the spectroscopy, and that the dark, low CPR region has these characteristics because the surface is so attenuating that the radar does not detect as many buried regolith blocks. In this case, radar would possibly be a better delineator of modest ilmenite changes than spectroscopy. Note that young crater ejecta, including some Tycho rays, are still readily visible in the radar images as bright streaks on top of the dark deposit (Fig. 1); these rocks may be on the surface and therefore still visible to the radar.

**Conclusions:** Radar data of Mare Nubium point to a new extensive area of pyroclastics (Lassell) and suggest that the relationship between radar backscatter, CPR, and $TiO_2$ may be fairly complex. As has been observed before [3, 4], higher radar backscatter is associated with lower $TiO_2$, likely because the radar wave is less attenuated and can travel farther into the subsurface when the loss tangent is lower. The Mare Nubium basalt flows may also have less regolith cover than the Mare Serenitatis flows.

**References:** [1] Hiesinger et al., J. Geophys. Res., 108, E7, 5065, doi:10.1029/2002JE001985, 2003. [2] Bugliolacchi et al., Met, and Plan. Sci., 41, 2, 285, 2006. [3] Campbell et al., J. Geophys. Res., 119, 313, doi:10.1002/2013JE004486, 2014. [4] Morgan et al., J. Geophys. Res., 121(8), doi:10.1002/2016JE005041, 2016. [5] [6] Korokhin et al., Plan. Space Sci., doi:10.1016/j.pss.2016.01.011, 2016. [7] Gaddis et al., Icarus, 161, 262, 2003. [8] Pieters et al. 1999, Science, 266, 1844. [9] Gaddis et al., Icarus, 61, 461, 1985. [10] Gustafson et al., J. Geophys. Res., 117(E12), doi:10.1002/2011JE003893, 2012. [11] Carter et al., J. Geophys. Res., *114,* E11004, doi:10.1029/2009JE0034062009.