LUNAR DEBRIS SURGE AND SECONDARY CRATERS. K. S. Martin-Wells,[1] D. B. Campbell,[2] B. A. Campbell,[3] and L. M. Carter,[4] [1]Carleton College, 323 Olin Hall, Northfield, MN 55057 (kwells@carleton.edu), [2]Cornell University, 514 Space Sciences Building, Ithaca, NY 14853, [3]Center for Earth and Planetary Studies, National Air and Space Museum, [4]NASA Goddard Spaceflight Center.

Introduction: In recent work, radar circular polarization echo properties have been used to identify secondary craters without distinctive "secondary" morphologies.[1] Because of the potential for this method to improve our knowledge of secondary crater populations, it is important to understand the origin of the radar polarization signature associated with secondary impacts. We have combined Lunar Reconnaissance Orbiter Camera photographs and ground-based radar polarization data to examine the geomorphology of lunar secondary craters with radar circular polarization ratio enhancements.

Observations: Radar CPR is a measure of the ratio of power received in the "same" sense of circular polarization as transmitted to the power received in the "opposite" sense. It can be used as a proxy for roughness on the scale of the radar wavelength, with rough surfaces giving higher values of radar CPR.[2] The radar data used in this work were collected bi-statically, using the 305 m Arecibo Telescope as the transmitter and the 100 m Green Bank telescope as the receiver. LROC Wide Angle Camera (WAC) and Narrow Angle Camera (NAC) products were obtained through the NASA PDS.

Four regions containing Tycho (D = 86 km) secondary craters were selected for study: "Tycho", "Maginus", "Clavius," and "Lilius." Each of these four regions is located along the direction of the Tycho ray discussed in Wells et al. (2010), ranging in distance from the edge of the parent crater ejecta blanket to 27 Tycho-radii downrange.

The morphologies observed at the Tycho secondary craters in these regions are consistent with debris flows sweeping the region shortly after emplacement of the craters. Smooth material appears to have flowed over or around many of the secondary crater rims, resulting in rounded or subdued rim morphologies, well-developed uprange dunes, degraded downrange rims, deceleration dunes, and crater floors with hummocky textures. Braided terrains appear in the inter-crater regions of these clusters, extending from ridges and troughs down to fine lineations. The presence and location of isolated clusters of blocky material are also consistent with a debris flow interpretation.

The flow morphologies cited above are common in and around Tycho secondary crater clusters, out to distances of approximately 500 km (11 crater radii) from the parent crater. Some regions also exhibit flows of smooth, dark material with raised margins draping over the rims of secondary craters toward the crater floors. The raised margins of these flows are often accompanied by an increase of block-rich material compared to the surrounding smooth terrain. The flow units consistently overlay the bright, block-rich units, suggesting that the blocks are not eroding out of the margins, but may have been pushed along the surface by the flows to their current positions.

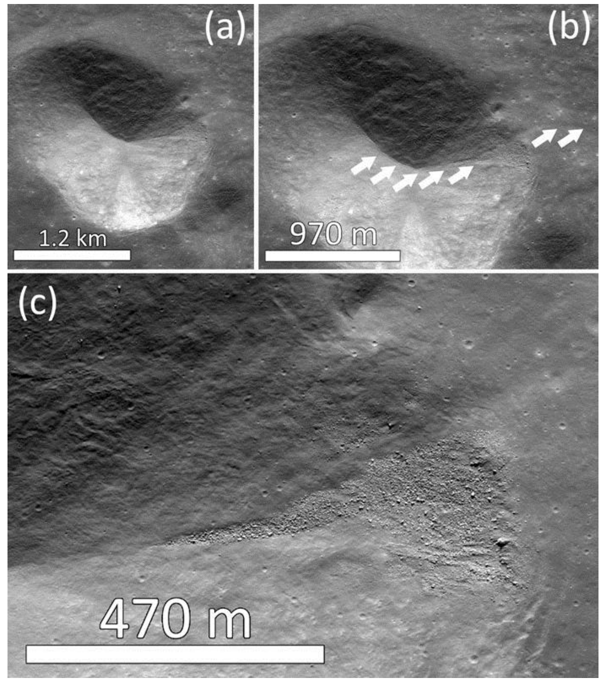

Figure 1. Example of a secondary-initiated debris flow breaching the rim of another secondary crater (from LROC NAC M109203644LC). (a) A large Tycho secondary crater near the tip of the Lilius Region 1 cluster. (b) Smooth material breaches the rim of this secondary crater from uprange. White arrows highlight the sharp downrange margin of this smooth flow. (c) A contact between the smooth material and bright, blocky material on the inside of the eastern rim.

In keeping with Morrison and Oberbeck (1973)'s debris surge hypothesis, we propose that primary ejecta from Tycho crater interacted with the surface in these regions, creating fast-moving surges of material traveling downrange just behind the Tycho ejecta curtain.[3] High-veolocity fragments transported large distances from Tycho likely experienced high levels of internal tension,[4] and may have broken into smaller fragments during flight. Because of the long travel times, and their velocities relative to one another after breakup, these fragments may have been less clustered at impact than ejecta fragments with lower velocities. These loosely clustered fragments would have then impacted at slightly different radial distances and slightly different times. Large, secondary-crater-forming fragments and smaller fragments (which may not have been large enough to form craters) would have been distributed at random along the radial direction in these clusters.

When the small fragments impacted the surface, they transferred momentum to loose material on the local surface. This transfer of momentum could initiate debris flow in the downrange direction, adding to any asymmetric ejection of material downrange due to excavation of the secondaries themselves. The velocity of this flow would have been less than that of the ejecta curtain,[4] so the debris flow would follow behind the formation of the secondary craters by the expanding curtain of ejecta. Where the debris flow encountered newly formed secondary crater rims, it could have either flowed over the rims, cut channels in the rims, or traveled partway up the rims, or been diverted around the them, depending on the flow velocity and rim height. We observed evidence of all of these morphologies in our survey of secondary crater clusters. Some smooth deposits "drape" over the rims of secondary craters and bury or partially bury the block-rich terrains, suggesting that the debris flows traveled up the uprange crater rims (Figure 1). V-shaped dunes, braiding, and lineations observed at these clusters show how debris is diverted around crater rims.

When the secondary craters in these clusters formed, they would have also ejected blocky material preferentially in the downrange direction. This material could have been entrained by the debris flow and transported even further in the downrange direction, explaining the extended downrange asymmetry of the elevated radar CPR features.

The presence of blocks protruding from these flows suggests that the smooth terrains are a thin layer covering a block-rich substrate of material excavated by the secondary craters. Small, pitted-craters observed on flow units also support this interpretation. This buried layer of block-rich material would contribute to the radar CPR enhancements at 13- and 70-cm wavelengths. At NAC resolution, it is unclear whether the 13-cm scatterers are located primarily on the surface or if they are buried by the smooth material, but 70-cm scatterers should be visible in the NAC images. Their absence, therefore, indicates they must be located in the sub-surface. Whether buried or on the surface, transportation of radar scatterers downrange by debris flow and asymmetric ejection of secondary material explains the source and orientation of the radar CPR enhancement observed at Tycho secondary crater clusters.

Summary: These observations provide evidence of debris flows not only in areas of clustered secondary craters, but also at relatively isolated craters revealed to be secondaries by the signature radar CPR enhancement distribution. Observations of debris flows associated with Tycho secondary craters are also relevant to theories of ray formation and preservation. The prevalence of ejecta-fragment-intiated debris flows, as revealed by this work, supports the findings of Pieters et al. (1985) that local material makes up a large percentage of ray material.[5] If this is the case, it may be very difficult to form long-lasting compositional rays, indicating that many lunar rays are likely maturity rays and therefore weather quickly. However, it should take longer for the small blocks that cause the CPR signature to weather than the maturation process that causes degradation of ray albedo in optical and UV-bands. This means that CPR enhancements can be used to map rays that no longer have albedo signatures. In addition to mixing primary and local material and excavating fresh material that forms high albedo lunar rays, these debris flows scour local highs and fill local lows over large portions of the lunar surface. The erosive power of debris surge was first discussed by Oberbeck (1975), but primarily in the context of basin ejecta. This work shows that even moderately-sized lunar craters like Tycho or Copernicus can significantly modify large parts of the lunar surface.[6]

References:

[1] Wells, K. S. et al. (2010) *J. Geophys. Res.*, *115*, E06008. [2] Campbell and Cambell (2006) *Icarus*, *180*. [3] Oberbeck and Morrison (1973) *Proc. Lunar Planet. Sci. Conf. 4th*. [4] Melosh (1989) *Impact Cratering: A Geologic Process, Oxford University Press*. [5] Pieters et al. (1985) *J. Geophys. Res.*, *90*. [6] Oberbeck (1975) *Rev. of Geophys. And Space Phys.*, *13*.