EXAMINATION OF THE SHAPE AND APPEARANCE OF HIGHLY OBLIQUE IMPACTS ON THE MOON, MARS, AND MERCURY. R. R. Herrick, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775-7320 (rrherrick@alaska.edu).

Introduction: Experimental work [1] and observations on planetary bodies [2,3,4] has shown that with decreasing impact angle first the ejecta blanket, and then the crater interior, becomes asymmetric. The asymmetries associated with highly oblique impact can yield important insights into the cratering process beyond what can be learned from axisymmetric near-vertical impacts. Using primarily Viking and Apollo-era imaging, previous work has characterized the appearance and shape of lunar and martian highly oblique craters [3,4,5]. In general terms, as impact angle decreases on these bodies, an uprange "forbidden zone" void of ejecta forms, and as the impact angle approaches horizontal a downrange forbidden zone forms and the crater becomes elliptical with the major axis along the direction of travel.

Since these early works an abundance of new planetary data has been collected, such that there is now near-global image coverage on both the moon and Mars at better than 20 m resolution, global laser altimetry data, and extensive stereo image coverage. There is also global image coverage on Mercury at resolutions ranging from ~10-200 m, laser altimetry in the northern hemisphere, and extensive stereo coverage. In this abstract I take advantage of this new data and have begun examining in detail some of the better preserved highly oblique impact crater forms over a wide range of sizes on the Moon, Mars, and Mercury. This trio of bodies presents an interesting basis for comparison: the Moon and Mercury are airless bodies with superficially similar surfaces but different gravity, while Mars and Mercury have similar surface gravity but different target properties. I focus particularly on the topography of these craters.

Figure 1 shows an example from each of the planetary bodies with a panchromatic image overlaid on color topography. In many cases I have supplemented existing publicly distributed topographic data sets with stereo-derived topography generated with the Ames Stereo Pipeline (ASP) or SOCET SET. Recent work [e.g., 6] has also illustrated the significant effect on crater morphology of intraplanetary variations in the target, so in my analysis I try to compare a crater with a similar-sized well-preserved axisymmetric crater in a similar geologic setting. So far I have examined a handful of craters on each planetary body. I first summarize the general observations that I have made, and then I present some specific observations regarding the lunar crater Messier and martian rampart craters.

General observations: The following observations are consistent across the three planetary bodies:

- For craters with only an uprange forbidden zone, and a circular rim planform, the uprange rim is lower than the crossrange and downrange rim heights (which are similar), typically about half the height.
- For elliptical craters with butterfly ejecta, there is

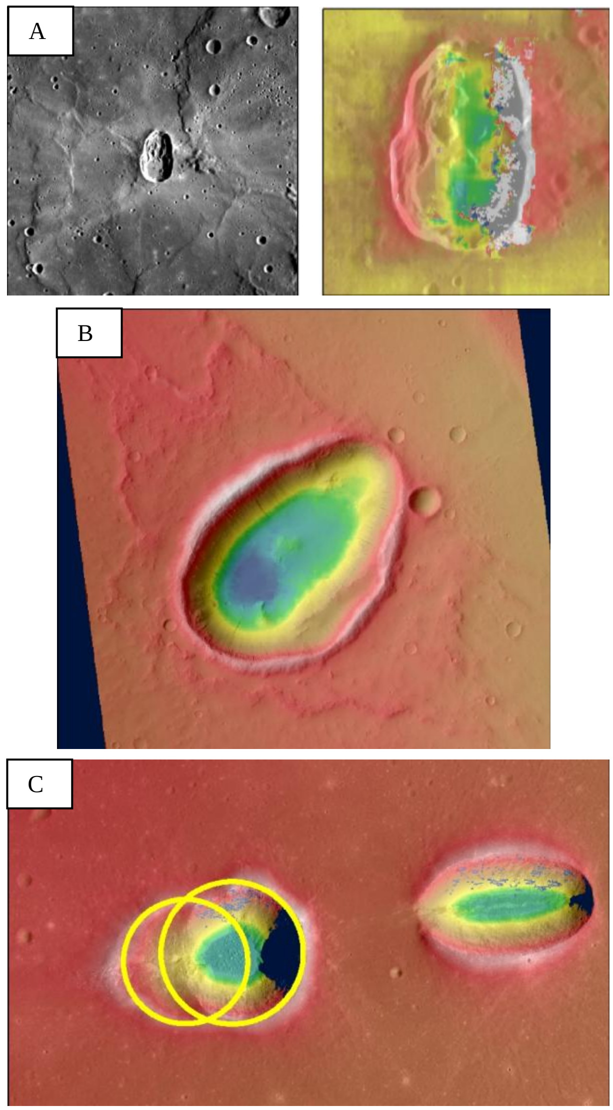

Figure 1 Examples of stereo-derived topography overlaid on images. A) Hovnatanian crater, Mercury, 34 x 22 km, ASP-derived topography spans 1500 m elevation. B) Martian crater at 21.6 N, 280.8 E, 7.9 x 5.3 km, SOCET SET derived topography from CTX pair spans 850 m elevation (courtesy UAF undergrad R. Bogardus). C) Messier (14.3 x 8.6 km, right) and Messier A from Kaguya TC image and topography. Elevations span 2300 m and circles are 11.4 and 9.9 km in diameter.

always at least a small uprange rim that rises above the surrounding terrain.

- For highly elliptical craters it is not uncommon for there to be no elevated downrange rim and for the rim to appear to have been "blown out" by a decapitated impactor.
- The crossrange rim heights and rim-floor depths for the highly oblique impact craters are consistent with simiar-sized fresh craters from near-vertical impact in a similar geologic setting.
- The deepest part of the crater floor is usually off-center towards the uprange end of the crater. For craters that are elliptical and have not experienced extensive terracing, the uprange wall slope is typically steeper than the downrange wall slope.
- For highly oblique craters that form in non-layered terrain, a low-relief medial ridge is a common feature in the crater interior.

An interesting crater form that is more common on Mars than the other planets are craters that are not strictly elliptical but instead more "tear-dropped" shaped, with a nearly hemispherical uprange end and an elongated downrange end with a lowered downrange rim, such as in Figure 1B. The crater Torricelli is a lunar analog and I have not identified an analog on Mercury.

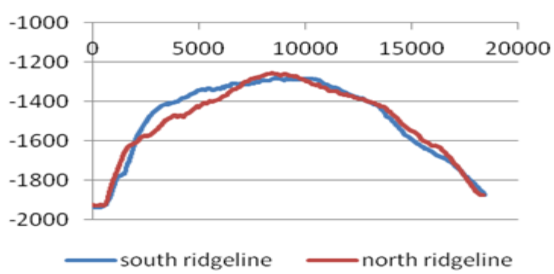

Figure 2. Profiles along the north and south rims of Messier.

Messier and Messier A: The improved image and topography resolution for Messier from the Kaguya and Lunar Reconnaissance Orbiter provide new information for this already well-studied crater. The new imaging, with its high resolution, shows melt in the floor of Messier, pooled downrange and embaying the eastern ejecta and rim of Messier A, scouring the western rim of Messier A, and pooling just west of Messier A. The rim height of the eastern part of Messier A and the north and south rims of the western extension of Messier A are consistent with circular mare craters of the diameters drawn in Figure1C. Based on superposition relationships and other observations, I interpret there to have been three separate impact events. First, an ~9-km simple crater formed (smaller circle in Figure 1C). Then Messier A formed, with its excavation altered by the preexisting crater and its ejecta largely filling that crater. Finally, Messier formed, and melted and decapitated impactor material went downrange and partially scoured out the western rim of the first crater form. The melt and downrange rays from Messier occur at nearly 5° off axis counterclockwise from the medial ridge and planform of Messier, perhaps as the result of a strangely shaped impactor. There is a 0.5° topographic slope to the preimpact surface dipping ESE. Figure 2 shows that the topographic profiles of the north and south rims of Messier are also slightly different.

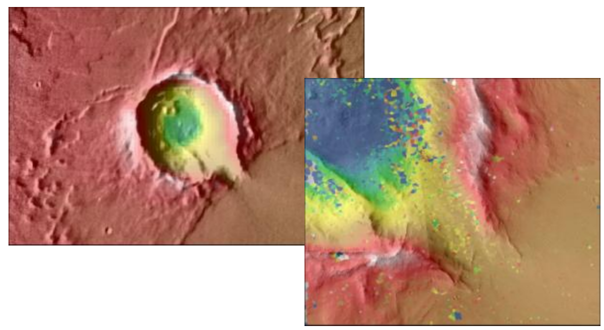

Figure 3. Martian crater 15 x 12 km at 9.2 N, 279.6 E with butterfly ejecta and ramparts directly intersecting rim. Left image shows MOLA gridded topography and right image shows stereo-derived topography from ASP with CTX pair.

Martian crater ramparts: Of particular interest is closely examining places where the rampart of a butterfly or forbidden-zone ejecta blanket intersects the crater rim (e.g., crater in Figure 3). My initial interpretation after examining high-resolution imaging and topography of the intersection area is that I see no indication that the rampart was material that flowed over or around the final crater rim. It appears that the rim thrust into a deposited ejecta blanket, which would have interesting implications for the timing of events in crater formation.

Conclusions: Most of the general observations are consistent with expectations from experimental work [1]. The asymmetries produced by nonvertical impact can be exploited to provide unique insights into the mechanics of cratering and the effects of different target surfaces. Because such craters are a small percentage of a planet's crater population, the new abundance of data at high resolution and on multiple bodies for the first time enables collecting enough data for systematic characterization.

References: [1] Gault D. E. and Wedekind J. A. (1978) *Proc. 9th LPSC*, 3843-3875. [2] Schultz P. H. (1992) *JGRP, 97,* 16,183-16,248. [3] Herrick R. R. and Forsberg-Taylor N. K. (2003) *MAPS, 38,* 1551-1578. [4] Herrick R. R. and Hessen K. K. (2006) *MAPS, 41,* 1483-1495. [5] Herrick R. R. (2007), *LPSC 38,* #1415. [6] Herrick R. R. (2012) *LPSC 43,* #2380.