A SYSTEMATIC SEARCH FOR LOW VELOCITY SECONDARY CRATERS OF SECONDARY CRATERS (AKA TERTIARY CRATERS) ON THE MOON. M. R. Huffman[1] and K. N. Singer[2], [1]The College of William & Mary, Williamsburg, VA, 23185 (mikaylarhuffman@gmail.com), [2]Southwest Research Institute.

Introduction: Extraterrestrial impact crater formation is important for geochronology, planetary formation, and placing empirical constraints on dynamic fragmentation theory. Counting primary impact crater populations is a useful way to determine the ages of planetary surfaces [e.g., 1,2,3,4]. However, each primary impact event throws out ejecta, which can in turn reimpact the surface, creating secondary impact craters [4]. Secondary impact craters throw out their own ejecta, which could create another generation of craters, known as tertiary craters.

There have been a few cases of potential tertiary craters reported in the literature [4], but, until relatively recently, high resolution planetary imaging has not been available to search for them. We are the first, to our knowledge, to make a concerted effort to search for tertiary craters. The Moon as seen through the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) is an excellent cratered surface with relatively low rates of crater degradation on which to search for tertiaries [5].

We present a potential set of possible tertiary impact craters from a small (~1.8 km in diameter), fresh primary crater to the SSW of Glushko crater on the Moon.

Image Processing and Analysis: We used the LROC Wide Angle Camera (WAC) global mosaic and Narrow Angle Camera (NAC) images (as viewed on the LROC Quickmap [5]) as the base map in our initial search for tertiary craters. We then processed selected images using the USGS ISIS program. We analyzed and mapped processed images in ArcGIS Pro using geodesic distances. The WAC images were used as context for the NACs. We mapped potential tertiary craters on the higher resolution NACs.

We examined, and will continue to search around, small, relatively fresh lunar craters. Older craters' secondary fields have been degraded over time. Thus far, we examined large and medium sized impact craters, including Petavius B, Tycho, Giordano Bruno, and Orientale. We expected that the larger primary size could translate to larger and more visible tertiary craters. However, even these impact events that are relatively young for their size are still fairly degraded. Thus, they were not as useful for the purpose of finding the small, shallow features like tertiaries.

The crater we focus on here is a 1.8km diameter primary crater to the SSW of Glushko. We informally refer to this crater as "Wallace" (Fig. 1).

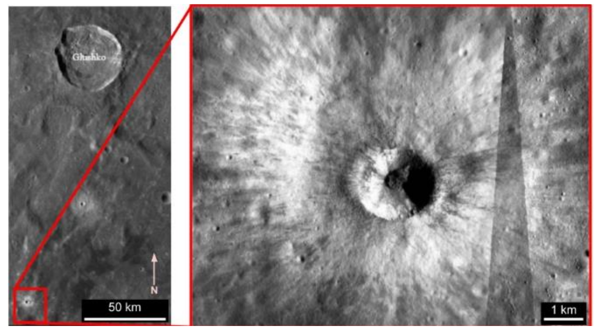

Fig 1: Young, fresh "Wallace" crater in context (1.8 km in diameter at 78.946°W, 3.100°N). Left image is from the WAC global mosaic, and right is an assemblage of NACs.

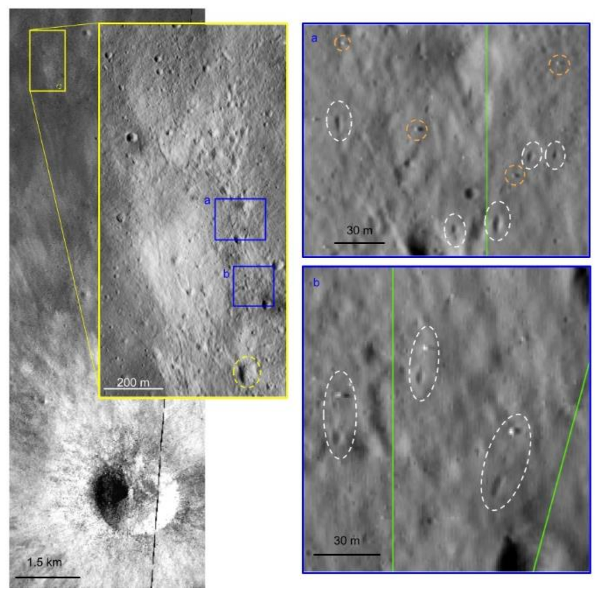

Fig 2: Gromit's (marked with a yellow ellipse) associated potential tertiary craters (which we refer to as "dents", marked with white ellipses). They are elliptical with their long axes pointing to Gromit [6,7]. Radial lines extending outward from Gromit are marked in green. Several potential tertiary craters have downrange boulders (orange). Some of these boulders have tracks that lead back to the tertiary in question, so they resemble other boulder bounce/roll tracks on the Moon. The dents downrange of Gromit are, on average, (7.4 ± 3.4)% the size of Gromit. The largest secondary craters tend to be 4-6% the size of their productive primary [6, 8, 9, 10, 11]. These values are a bit on the large size, but they overlap with the 4-6% rule of thumb [6,7].

Results: We have mapped 6,054 secondary craters around Wallace to date, working our way radially outward. We describe a potential tertiary-producing secondary crater 9.6 km to the NNW of Wallace, which is 62 m in diameter along the short axis. We refer to this secondary crater informally as "Gromit" (Fig 2).

We have mapped 40 potential tertiary craters around Gromit, several of which have associated downrange bolides. We calculated the ejection/impact velocities of the tertiary-forming bolide (Fig. 3) and the bounce velocity of the downrange boulders necessary to reach their present locations. We also produced size-range distributions for both the Wallace secondaries and the dents/tertiaries.

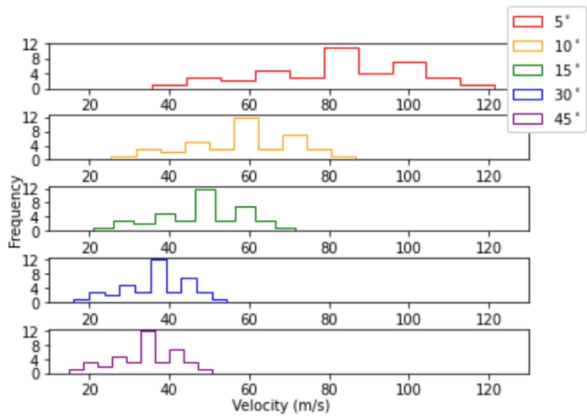

Fig 3: Histograms of Gromit ejecta fragment velocities necessary to form the dents, at a variety of ejection/re-impact angles. (See eqn. 5 from Singer et al 2020 [6]).

Discussion: For the suggested tertiary craters to actually be tertiaries, they must be secondaries of Gromit, which in turn must be a secondary crater of Wallace. Gromit exhibits several characteristics that align with secondary crater features [6,7]. It is apparently shallow (compared to other craters of its size in the region), with a poorly defined downrange rim, and is 3.3% the size of Wallace. This falls below the rule of thumb cutoff that the largest secondaries are 4-6% the size of the primary, and thus Gromit's size is not too large to be Wallace's secondary. Gromit is also similar in size to other obvious Wallace secondary craters in the area, albeit a bit larger.

It is unlikely that Gromit is a primary crater overlying Wallace's ejecta. Gromit is not morphologically similar to other overlying circular primary craters in the area and has radial features that are in the same direction as the ejecta from Wallace: Gromit is elliptical in the downrange direction from Wallace, and the elliptical dents and their associated boulders are also down-range of Gromit. If Gromit were a primary crater not associated with Wallace, it would be surprising but not impossible that all of the elliptical dents were downrange of both Gromit and Wallace.

For the final option, it cannot be ruled out that Gromit is an underlying primary that was scoured by Wallace's ejecta. Gromit is not as scoured as other underlying features in the area; however, the differences may lie in Gromit's larger size. Also, Gromit's rims are not as distinctive as some of the other secondaries in the area, but all secondaries might not form in the exact same sequence with the emplacement of other smaller ejecta fragments that form the disturbed soil/ray pattern but do not make distinct secondaries. In addition, the dents are not obviously scoured in appearance. This lends credence to Gromit not being a scoured primary.

Thus, we conclude that Gromit is most likely a secondary crater of Wallace but could also be a pre-existing crater scoured by Wallace's ejecta. Either way, the elongated dents and down range boulders are low-velocity ejecta with interesting properties.

Tertiary impact events would be much lower velocity and thus lower overall energy events than most primary impacts and even than many secondary impacts. We are probing the lower limit of velocity in terms of what will create a secondary/tertiary crater on the Moon and also finding interesting morphologies that may help us understand the fragment ejection mechanics and low-velocity crater creation.

Future Work: We will continue to map craters around Wallace and other fresh, young craters in the search for tertiaries, and to better determine the viability of Gromit as a secondary of Wallace. We plan to compare the velocity and fragment sizes of these potential tertiary craters to ejecta theory predictions.

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