CONTROLS ON THE FORMATION OF SECONDARY MARKINGS AROUND NEW IMPACTS ON MARS. C. M. Dundas¹, I. J. Daubar², A. S. McEwen³, V. J. Bray⁴, ¹U.S. Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001 (cdundas@usgs.gov), ²Brown University, ³University of Arizona.

Introduction: Secondary craters are an important part of the cratering record of planetary surfaces, with implications for surface age estimates and regolith evolution [1-4]. However, they are challenging to study because of the difficulty of identifying all secondary craters associated with a given primary crater, and differentiating secondary from small primary craters. Obvious secondary craters are concentrated in rays, but scattered inter-ray secondaries also exist, and primaries of similar size are scattered over most terrains.

One population of secondary impacts can be readily identified and associated with a particular primary impact event. Hundreds of new impact craters or clusters on Mars have been detected in the last two decades [5, 6]. These are distinctive because of dark blast zones which persist for only a few years [7], so even isolated new secondaries can be distinguished from the existing crater population. Many of these are surrounded by dark, radially oriented secondary markings, some of which have resolved craters at the head (Fig. 1), and which can be found many crater radii away from the primary cluster. We are analyzing these markings to understand controls on the formation and distribution of secondary craters.

Observations: We inspected 1,203 impact sites [6] in images from the High Resolution Imaging Science Experiment (HiRISE), nearly all at 25 cm/pix. A few were not suitable for analysis due to poor image quality or because the dark blast zone had faded by the time of imaging, which could make isolated markings without resolved craters unrecognizable. For the remaining 1,171 sites, we assessed whether secondary markings were present, regardless of whether there were resolved craters associated with the markings. Such markings (Fig. 1) can be distinguished from primary cluster members by their radial patterning from the primary. We also collected ancillary observations. These included a qualitative assessment of the rockiness of the surface based on rocks resolved by HiRISE, and whether there was any evidence for a strong layer at depth, such as flat-floored craters or excavated ice [8]. We updated some diameters from [6]. We also compared the results with regional surface property data including thermal inertia [9], albedo [10], and dust cover index [11] which are sensitive to surficial material properties at various depths.

These observations reveal a primary crater diameter dependence for resolved secondary markings (Fig. 2). Secondaries are rarely detected for impacts or clusters with an effective diameter <10 m but very common for diameter >40 m. The second major control on secondary formation is surface rocks. Rock-free sites were less likely to have secondaries than those with rocks for a given diameter. Apparent correlations with other properties such as the rays observed by [6] are likely due to size dependence of those other properties. We did not observe any correlation with albedo, dust cover index, or thermal inertia, or with evidence for stronger material at depth.

Discussion: There is clear size dependence for secondary marking formation. This is probably not primarily a resolution effect, as nearly all HiRISE images examined were at full resolution and markings are resolved around small craters in some cases. It is possible that some of the smaller craters have unresolved secondary markings, but we rarely encountered cases where we were uncertain about the existence of markings. Although simple extrapolation may be inaccurate, it is likely that most impacts with effective diameter >100 m produce fields of secondary impacts. Some markings occur with a well-defined ray structure, but inter-ray markings are also apparent.

The influence of surface rocks and the absence of an effect from strong subsurface material suggests that the secondary impactors are sourced from the surface layer, as expected for ejection by spallation [12]. At these size ranges, the projectiles may be the pre-existing rocks present at ground level in many cases.

Secondary markings usually have a point source, which in larger examples can be a resolved crater. This indicates that they form by impacts of discrete rocks or blocks of regolith. Unlike ejecta of new primary craters, the marking is strongly concentrated downrange from the impact point. This could indicate extremely shallow impact angles, but a more likely explanation is that some combination of the low impact speed and a wind or blast from the much higher-velocity primary directs all ejected material outwards. The markings qualitatively resemble some wind streaks, and it is possible that ejecta material saltates similar to aeolian transport. The markings appear distinct from dark blast zones, indicating that they are not simply a gradationally larger and less discrete form of the markings.

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Fig. 1. Example of a prominent field of secondary markings extending for several km around a 22.8 m-diameter primary impact (HiRISE image ESP_034285_1835, courtesy NASA/JPL/University of Arizona). The full-resolution cutout at right is located 1.75 km north-east of the source crater.

Fig. 2: Left: Fraction of impact sites with observable secondary markings as a function of effective diameter (combined for clusters). Right: Same observations, divided based on the presence of visible surface rocks.