DYNAMIC MOON REVEALED WITH HIGH RESOLUTION TEMPORAL IMAGING. E. J. Speyerer[1], M. S. Robinson[1], R. Z. Povilaitis[1], and R. V. Wagner[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ (espeyere@asu.edu).

Introduction: The Lunar Reconnaissance Orbiter Camera (LROC) began systematically mapping the Moon in the summer of 2009 with the goal of acquiring an image dataset to facilitate future exploration [1]. With the aid of the extended science mission, we have discovered hundreds of new impact craters, thousands of smaller probable secondaries, and evidence of recent crater modification using repeat observations with the high resolution Narrow Angle Camera (NAC) and a custom change detection program.

Temporal Dataset: As of 1 January 2015, LROC has acquired nearly a million NAC images of illuminated terrain. From this total, nearly 10,000 are images acquired of regions of the Moon where previous NAC observations with similar lighting and observational geometry exist (i.e. incidence angle difference <3°, incidence angle < 50°, and nadir pointing). These before and after image pairs, called *temporal pairs*, enable the search for a range of surface changes, including new impact craters, formed between the time the first and second image were acquired; individual temporal pairs currently span between 176 to 1241 Earth days.

Change Detection: Since a single NAC temporal pair can contain up to 10^9 pixels, manual scanning of thousands of temporal pairs is impractical. However, 131 images were manually scanned and 657 surface changes were identified [2] providing a baseline for the automated change detection algorithm.

We developed an automated change detection program that identifies and crops out suspected changes from each temporal pair. Thumbnails of these candidate areas are extracted and manually classified using a custom web interface. Of the 46,057 automatically identified surface changes recorded to date, manual inspection confirmed that over half (56%) are indeed changes to the surface. This semi-automated procedure reduces the human time required to inspect a temporal pair by over a factor of 200.

New Impact Craters and Secondaries: From the temporal pairs scanned to date (1 January 2015), we identified 225 new resolved impact craters (e.g. Fig. 1). These craters range in diameter from 1.5 m to 43 m and are distributed across the surface over a variety of terrain types (Fig. 2; red dots). In addition, targeted NAC observations imaged 18 and 34 m diameter craters where impact flashes were observed on 17 March 2013 and 11 September 2013 respectively (Fig. 2; blue dots).

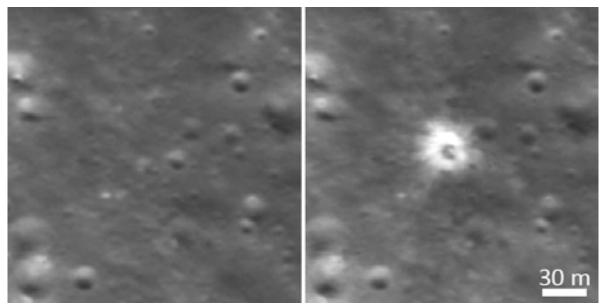

Fig. 1: Before (left) and after (right) images of a new 18 m impact crater discovered by automatically scanning NAC temporal pairs.

We also identified nearly 26,000 other surface changes that do not exhibit visible crater rims but only a change in surface reflectance. These include high reflectance changes (i.e. increase in surface reflectance), low reflectance changes, as well as mixed reflectance changes (Fig. 3). These changes are thought

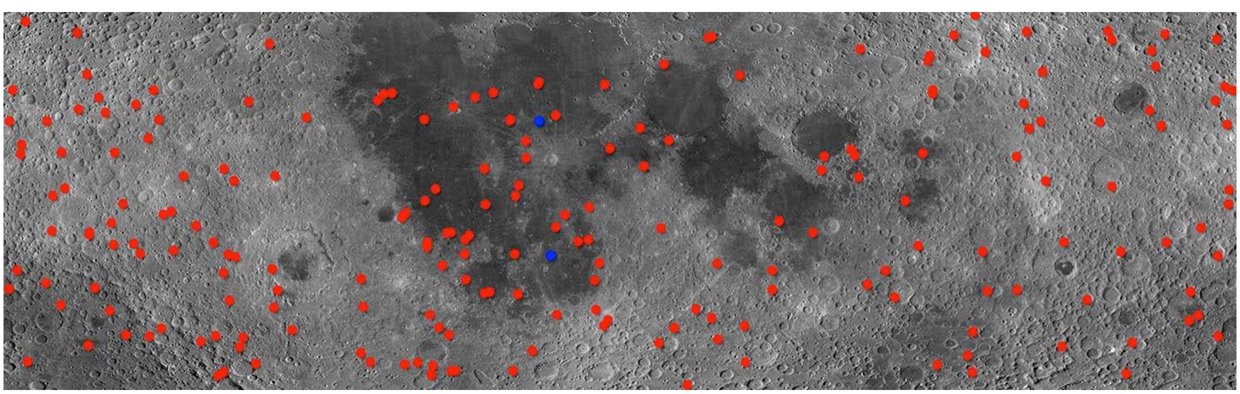

Fig. 2: Location of new impact craters overlaid on a LROC Wide Angle Camera basemap (Lat Range: 55°N to 55°S Lon Range -180 to 180°E). The red dots indicate the location of the 225 new impact craters discovered to date with NAC temporal pairs and the blue dots show the location of the two craters located with the help of Earth-based impact flash observations [3,4].

to be the result of small primary events in which the resulting impact crater is smaller than the resolution limit of the temporal pair or by a secondary disturbance caused by a nearby primary event. In several cases, these surface changes show clear directional indicators pointing back to a larger primary crater [3] confirming their origin as secondary craters.

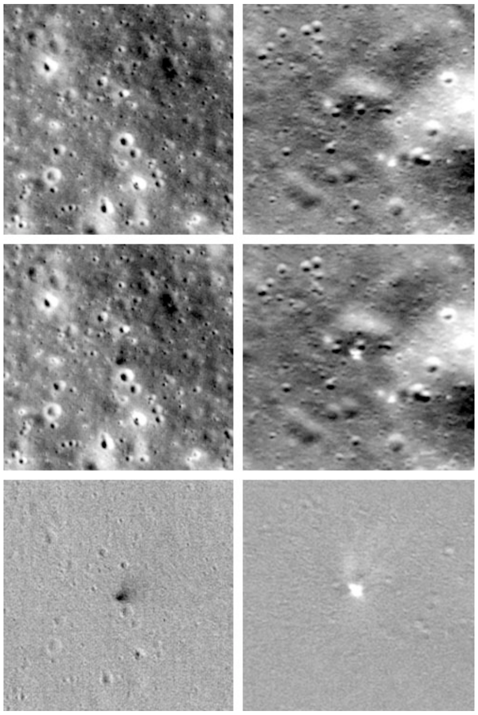

Fig. 3: Example of low (left column) and high (right column) reflectance changes identified with NAC temporal pairs. The top row consists of a pair of before images, the middle row is a pair of after images, and the bottom row is a ratio of the after/before observation. Each image is 250 m across.

Crater Modification: Temporal pairs also revealed seven new landslide events inside Copernican age impact craters (Fig. 4). Several of these landslides are the result of small impact events occurring on steep (slopes > 30°) crater walls. These landslides typically show boulder trails extending from the new impact crater and tracing a path toward the crater floor and occasionally growing in width as a result of the falling block dislodging material along the steep surface. One such event caused material to travel over 4 km to the floor of the larger parent crater. In addition, we discovered new landslides that lack any indicator of emanating from a new impact crater. These landslides exhibit a much broader surface change (>100 m wide flows instead of narrow boulder tracks witnessed with the previously described landslides). We speculate that these may be the result of a seismic event such as a Moonquake or a large distant meteor impact disrupting regolith poised near the angle of repose and causing the loosened regolith to cascade down to the crater floor.

Summary: As of 1 January 2015, we have scanned and classified changes in 8300 NAC temporal pairs using our automated change detection tool leading to the discovery of 225 impact craters ranging in size from 1.5 to 43 m. In addition, we also identified thousands of other surface changes, including:

- 23,458 low reflectance changes
- 1,911 high reflectance changes
- 468 mixed reflectance changes
- 1 Chinese lander/rover

Throughout the second extended science mission, the LROC team will continue to acquire and scan high resolution temporal pairs. From this new dataset, we plan on refining estimates on the flux of small (>0.5 m) bolides in the inner solar system as well as quantify secondary impact related hazards on the Moon which is not only an important scientific finding, but also a key engineering design concern for future long duration surface assets.

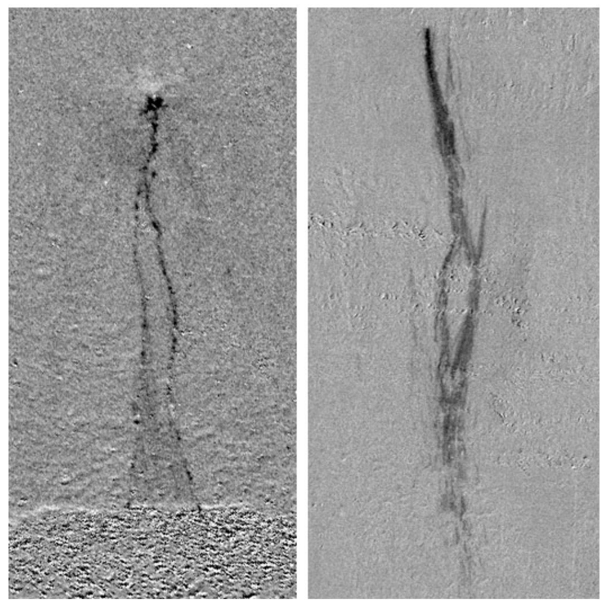

Fig. 4: Example of two temporal ratio images (after/before) showing recent landslide events. The image on the left is 250 m across and shows boulder trails extending down slope from a new impact crater. The image on the right is 600 m across and shows a larger landslide even with no indication that it is the result of an impact on the wall of the parent crater. In each example, the elevation decreases from the top to the bottom of the image.

References: [1] Robinson M.S. et al. (2010) *Space Sci. Rev.*, 150, 1-4, 81-124. [2] Thompson S.D. et al. (2014) *45^{th} LPSC*, Abstract #2769. [3] Robinson M.S. et al. (2014*) 45^{th} LPSC*, Abstract #2164. [4] http://lroc.sese.asu.edu/posts/810.