WASHBOARD AND FLUTED TERRAIN ON PLUTO: EVIDENCE FOR PAST EXPANDED GLACIATION. O. L. White[1], J. M. Moore[2], A. D. Howard[3], P. M. Schenk[4], O. M. Umurhan[1], S. A. Stern[5], H. A. Weaver[6], C. B. Olkin[5], K. Ennico[2,5], L. A. Young[5], A. F. Cheng[6], and the New Horizons Geology, Geophysics and Imaging Theme Team. [1]SETI Institute, 189 Bernardo Avenue, Suite 200, Mountain View, CA, 94043 (owhite@seti.org), [2]NASA Ames Research Center, Moffett Field, CA, 94035-1000, [3]Department of Environmental Sciences, University of Virginia, Charlottesville, VA, 22904, [4]Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX, 77058, [5]Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO, 80302, [6]The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD, 20723.

Introduction: The 2015 flyby of the Pluto system by NASA's New Horizons spacecraft [1] revealed that the landscape to the northwest and west of Sputnik Planitia (Fig. 1) has been eroded into a variety of dissected terrains, including what has been termed "washboard" and "fluted" terrain [2, 3], which consists of low, parallel to sub-parallel ridges that emboss portions of the uplands here. It has been suggested that the formation of these ridges may be related to sublimation, aeolian, or glacial processes [3]. In this study, we map and spatially analyze these ridges in order to constrain their origin.

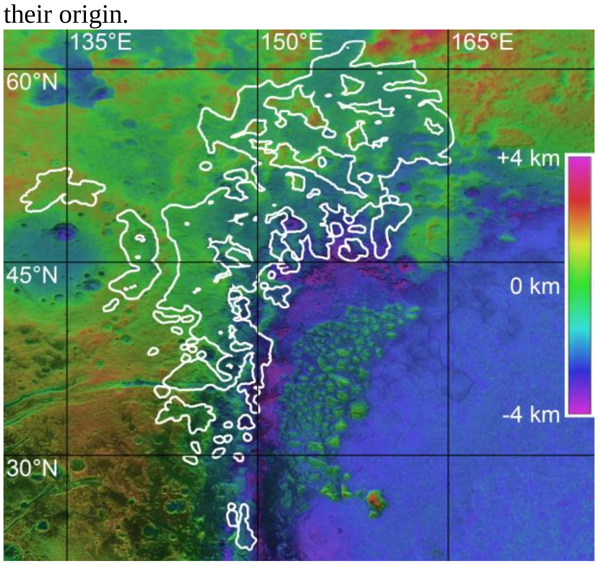
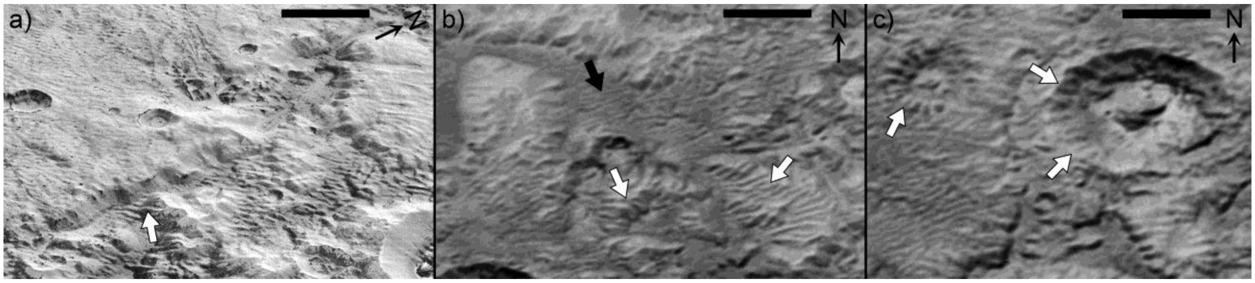


Figure 1. Occurrence of discernible washboard and fluted terrain, superposed on a colorized digital elevation model overlain on a visible mosaic of northwestern Sputnik Planitia.

Description: Washboard terrain consists of parallel to sub-parallel sets of mostly ENE-WSW-trending low ridges and troughs that are spaced ~1-2 km crest-to-crest (Fig. 2a). This terrain occurs in fairly level topographic settings within upland plateaus and valley floors to the northwest and west of Sputnik Planitia, as well as exterior to and within the outer rim of Burney crater. It occurs across an an elevation range of >4.5 km, from -2.9 km to +1.8 km. Fluted terrain (Fig. 2b) consists of similar ridge and trough sets, spaced ~2-3 km crest-to-crest [3], that are seen on high relief (>2 km), generally high albedo spurs and massifs that separate basins and valleys to the northwest of Sputnik Planitia. The ridges and troughs are oriented downgradient on hillslopes that reach up to 30°, with typical slope lengths of 2-5 km measured horizontally [3]. A notable type of fluted terrain is the "fluted craters" (Fig. 2c), the walls of which display a pattern of radially aligned, downslope-oriented ridges and troughs. Fluted terrain occurs across a narrower range of elevations than washboard terrain, from -2.7 to +1.1 km. Both types of terrain, however, concentrate at low elevations (mean of -0.4 km, $\sigma \pm 0.9$ km), and are never seen in topographic settings that are both high relief and high elevation. The albedo of washboard and fluted ridges matches that of nearby non-ridged terrain, and is higher in upland plateau and massif settings than in valley floor settings. The ridges generally parallel each other, and rarely branch.

Earlier studies have differentiated washboard and fluted terrain based on their distinct topographic settings [2, 3], although in some locations fluted terrain transitions to washboard terrain (e.g. white arrow in Fig. 2a). While fluted ridges are oriented downslope, they, like washboard ridges, typically maintain an ENE-WSW orientation, although this trend is not as strong as it is for washboard ridges. Fig. 3 presents our mapping of individual ridge crests for washboard and fluted terrain, defined as polylines in ArcGIS. The mean azimuth of all 3452 polyline segments is 71.8° ($\sigma \pm 16.8°$), while that for the 2780 washboard segments is 70.7° ($\sigma \pm 15.2°$), and that for the 672 fluted segments is 76.4° ($\sigma \pm 21.6°$). The corresponding mean slopes for each of these datasets (as determined using the digital elevation model in Fig. 1) are 7.9° ($\sigma \pm 3.5°$) for all ridges, 7.3° ($\sigma \pm 3.2°$) for washboard ridges, and 10.3° ($\sigma \pm 3.8°$) for fluted ridges.

Interpretation: Both washboard and fluted ridges predominantly trend ENE-WSW, and we interpret the broader range of azimuths displayed by fluted ridges to result from their occurrence within higher relief topographic settings with steeper slopes. We therefore interpret fluted and washboard terrain to ultimately represent different manifestations of the same landform-evolving process that produces these ridges. We hypothesize that both washboard and fluted terrain repre-



sent a deposit that has been emplaced, rather than an erosional texture, with deposition within high relief, steep-sloped settings tending to cause the ridges to diverge from their natural ENE-WSW orientation. We disfavor an aeolian hypothesis as the scale of the ridges is too large for them to be dunes formed by winds in Pluto's thin atmosphere, and because fluted ridges are seen to occur on convex, high-relief topography, which is not a plausible setting for dune formation.

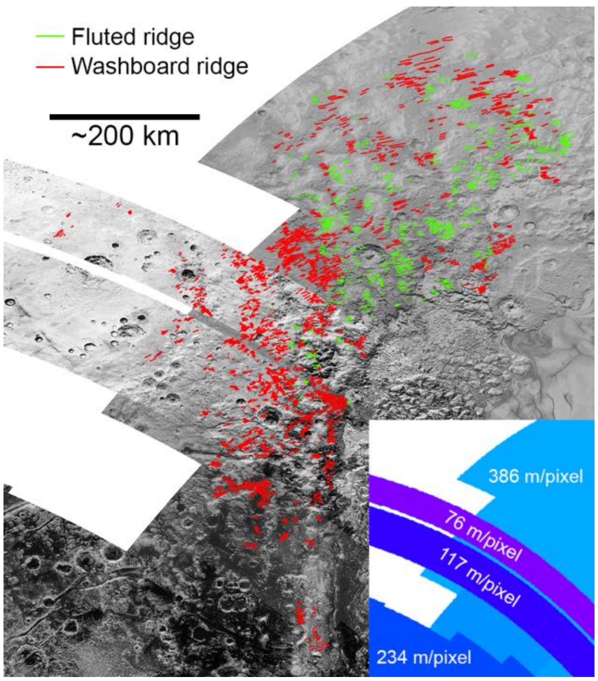


Figure 3. Mapping of individual washboard and fluted ridges, superposed on a visible mosaic ranging in pixel scale from 76 to 386 m/pixel (see map inset).

Instead, we consider the deposit to originate from past, expanded nitrogen ice glaciation. The ridges occur along a section of Sputnik Planitia's perimeter where elevations are lowest and slopes leading into the uplands are at their gentlest, a consequence of the laterally extensive, interconnected basins and sinuous valleys that extend inland from the margin of Sputnik Planitia, which display slopes of ~0.4° across lateral distances of >250 km, as compared to the 1° mean slope from the edge of Sputnik Planitia to the uplands around its whole perimeter across a similar lateral

Figure 2. High resolution images of washboard and fluted terrain. Scale bar measures 20 km in all images. (a) Washboard ridges occupying level terrain on high albedo plateaus and in low albedo valleys. White arrow indicates a ridge that extends from a valley floor up the slope of a neighboring massif. 76 m/pixel image centered at 43.7°N, 147.8°E. (b) White arrows indicate the ridge and trough morphologies of fluted massifs and spurs, which are separated by sinuous, lower albedo valleys that display occurrences of washboard texture on their floors (black arrow). 386 m/pixel image centered at 50.7°N, 155.2°E. (c) White arrows indicate the fluted walls of impact craters. 386 m/pixel image centered at 47.7°N, 151.5°E.

scale. This area is therefore especially disposed to accommodate glacial nitrogen ice should past climatic conditions have been favorable for expanded coverage of the nitrogen ice in Sputnik Planitia, and we interpret the ridges to be transverse moraines associated with retreat of a such formerly expanded glaciation. Although on a much larger scale, the Plutonian ridges may be akin to De Geer moraines on Earth [4], which consist of regularly spaced, parallel ridges of sediment that have been interpreted as marking former ice-margin positions where sediment is deposited or pushed up during brief stillstands or minor readvances. The Plutonian ridges may be formed of water and/or methane ice fragments that rested upon the higher density nitrogen ice, and they may owe their regular spacing to superseasonal retreat on the ~2.76 million year timescale of Pluto's obliquity oscillations [5]. The explanation for the remarkably regular ENE-WSW orientation of the ridges is as yet uncertain, but the apparent independence from regional-scale topography implies that it may be controlled at a global scale. Our continuing investigation will focus on how the response of nitrogen ice glaciation to climate change brought on by obliquity changes might produce these ridges.

References: [1] Stern, S. A. et al. (2015) *Science*, *350*, aad1815. [2] Moore, J. M. et al. (2016) *Science*, *351*, 1284-1293. [3] Howard, A. D. et al. (2017) *Icarus*, *287*, 287-300. [4] Todd, B. J. (2016) *Geological Society, London, Memoirs*, *46*, 259-260. [5] Binzel, R. P. et al. (2017) *Icarus*, *287*, 30-36.