WASHBOARD AND FLUTED TERRAINS ON PLUTO AS EVIDENCE FOR ANCIENT GLACIATION.

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Introduction: The 2015 flyby of the Pluto system by NASA's *New Horizons* spacecraft 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" terrains (WFT) [1,2]. These consist of low, parallel to sub-parallel ridges that emboss portions of the uplands here. Through mapping and spatial analysis of the ridges, we have argued that they represent crustal debris that were buoyant in pitted glacial nitrogen ice that formerly covered this area, and which were deposited after the nitrogen ice receded via sublimation early in Pluto's history [3]. This presentation reviews this and alternative hypotheses for their origin.

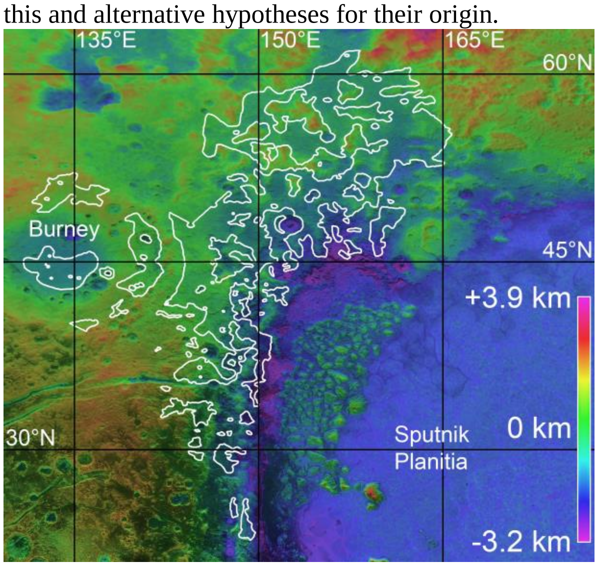

Figure 1. Occurrence of discernible WFT, superposed on a colorized digital elevation model overlain on a visible mosaic of northwestern Sputnik Planitia.

Observations: 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 level topographic settings within upland plateaus and valley floors to the northwest and west of Sputnik Planitia, as well as exterior to and within Burney crater. Fluted terrain (Fig. 2b) consists of similar ridge and trough sets, spaced ~2-3 km crest-to-crest [2], 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 20° [2]. 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. WFT ridges occur across an an elevation range of ~4.8 km, from -2.9 km to +1.9 km., concentrate at low elevations (mean of -0.5 km ± 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.

Early studies differentiated WFT based on their distinct topographic settings [1,2], although in some locations fluted terrain transitions to washboard terrain (e.g. white arrow in Fig. 2a). Fluted ridges are oriented downslope but they, like washboard ridges, typically maintain an ENE-WSW orientation, although this trend is not as strong as it is for washboard ridges. The mean azimuth of washboard ridges is 70.9° ± 17.0°, and that for fluted ridges is 76.5° ± 20.5° [3]. The corresponding mean slopes for each of these datasets (as determined using the digital elevation model in Fig. 1) are 2.3° ± 2.1° for washboard ridges and 4.5° ± 3.2° 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 regard fluted and washboard terrain as being different manifestations of the same landform-evolving process that produces these ridges. We consider WFT to represent a deposit that has been emplaced, with deposition within high relief, steep-sloped settings tending to cause the ridges to diverge from a 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-

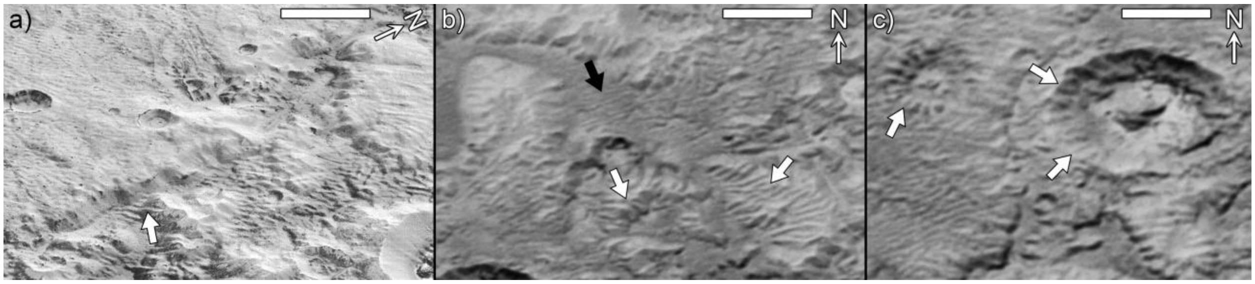

Figure 2. High resolution images of WFT. Scale bar measures 20 km in all images. (a) Washboard ridges occupying level terrain on high albedo plateaus and in low albedo valleys. White arrow indicates a ridge that extends from a valley floor up the slope of a neighboring massif. 76 m/pixel image centered at 44°N, 148°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 51°N, 155°E. (c) White arrows indicate the fluted walls of impact craters. 386 m/pixel image centered at 48°N, 152°E.

relief topography, which is not a plausible setting for dune formation. An origin as an exhumed compressional tectonic fabric is also disfavored as the WFT coverage should not be elevation- and relief-dependent if this were the case. In addition, the source of the NNW-SSE-aligned compressive stress is not apparent, especially as WFT occurs within the context of extensional tectonism consisting of large-scale normal faults and graben to the north and west.

Instead, we hypothesize that WFT originate from past, expanded nitrogen ice glaciation [3]. WFT mostly concentrates within a system of deep basins and sinuous valleys extending radially outwards from the northwest margin of Sputnik Planitia. This section of Sputnik Planitia's perimeter is where elevations are lowest and slopes leading into the uplands are gentlest (on a scale of hundreds of kilometers). These basins and valleys form part of a 3200-km-long, north–south-orientated tectonic system seen in global topography between the 145° E and 165° E meridians, which intersects the perimeter of Sputnik Planitia [4]. The coincidence of WFT with the large tectonic system can explain why the ridges are restricted to the uplands northwest of Sputnik Planitia and not seen in other areas bounding Sputnik Planitia that might have formerly hosted glaciation. The tectonism would have fragmented the water ice crust, allowing portions of it to be dislodged and ascend to the surface of the denser nitrogen ice, where they can be manipulated by glacial flow. After recession of the formerly extensive glaciation by sublimation, the buoyant debris would have been deposited to form the WFT ridges. Formation of the Sputnik Planitia basin early in Pluto's history would have instigated recession of nitrogen ice across Pluto, as the basin represented a powerful cold trap that the nitrogen ice migrated to [5,6]. Based on cratering rates estimated for Pluto [7], a crater size-frequency distribution derived for the WFT corresponds to an age of ~4 Gyr [3].

The consistent ENE-WSW azimuth of the ridges, regardless of latitude or location relative to Sputnik Planitia, suggests that they are not former margins of the nitrogen ice glaciation, which would be expected to conform more to local topography and Sputnik Planitia's boundaries. As such, they are not analogous to the morphologically similar De Geer glacial moraines on Earth [8], which have been interpreted as marking former ice-margin positions where sediment is deposited or pushed up during brief stillstands or minor readvances. Fields of elongated sublimation pits are seen at low latitudes in Sputnik Planitia [9], the patterning and scale of which resemble the WFT. We hypothesize that sublimation of nitrogen ice that formerly covered the WFT region produced a pitted texture comparable to what is seen in southern Sputnik Planitia today, and that during sublimation, the buoyant crustal debris covering the ice would move downslope and concentrate within these elongate pits, leaving the parallel ridges of debris as a record of the sublimation texture after recession of the nitrogen ice. The cause of the common alignment of the ridges is uncertain, but may be related to structural anisotropies in the nitrogen ice (i.e. stress fields associated with flow paths) that caused the pits to align and join together [9].

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References: [1] Moore, J. M. et al. (2016) *Science*, *351*, 1284-1293. [2] Howard, A. D. et al. (2017) *Icarus*, *287*, 287-300. [3] White O. L. et al. (2019) *Nature Astronom*y, *3*, 62-68. [4] Schenk P. M. et al. (2018) *Icarus*, *314*, 400-433. [5] Hamilton D. P. et al. (2016) *Nature*, *540*, 97-99. [6] Bertrand T. et al. (2018) *Icarus*, *309*, 277-296. [7] Greenstreet S. et al. (2015) *Icarus*, *258*, 267-288. [8] Todd, B. J. (2016) *Geological Society, London, Memoirs*, *46*, 259-260. [9] White O. L. et al. (2017) *Icarus*, *287*, 261-286.