LARGE-SCALE CRYOVOLCANIC RESURFACING IN THE WRIGHT MONS REGION OF PLUTO. K. N. Singer[1], O. L. White[2], Bernard Schmitt[3], Erika L. Rader[4], Silvia Protopapa[1], William M. Grundy[5], Dale P. Cruikshank[6], Tanguy Bertrand[7], Paul M. Schenk[8], William B. McKinnon[9], Kirby D. Runyon[10], Rajani D. Dhingra[11], S. Alan Stern[1], Jeffery M. Moore[12], Cristina Dalle Ore[2], Veronica J. Bray[13], James T. Keane[11], Ross A. Beyer[2], Francis Nimmo[14], Leslie A. Young[1], Catherine B. Olkin[1], Tod R. Lauer[15], Harold A. Weaver[10], Kimberly Ennico-Smith[12]. [1]Southwest Research Institute (ksinger@boulder.swri.edu), [2]SETI, [3]Université Grenoble Alpes, [4]University of Idaho, [5]Lowell Observatory, [6]University of Central Florida, [7]LESIA/Observatoire de Paris, [8]Lunar and Planetary Institute, [9]Washington University in St. Louis/McDonnell Center, [10]Johns Hopkins Applied Physics Laboratory, [11]JPL/Caltech, [12]NASA Ames, [13]University of Arizona, [14]UC Santa Cruz, [15]NSF NOIRLab.

Introduction: Data from the New Horizons spacecraft revealed that terrains on Pluto span a variety of ages, with a number of large areas exhibiting few-to-no craters, implying they are relatively young [e.g., 1,2,3,4]. Some of these young regions may be explained by sublimation and re-deposition of volatile ices (N_2, CH_4, and CO) over time, and some by convection of volatile ices [e.g., 5] and/or glacial flow. One vast, unique region does not appear to be made up of or explained by volatile ices. This young region (here called the Wright Mons region) is dominated by enormous rises with hummocky flanks (Fig. 1). Similar features do not exist anywhere else in the imaged solar system.

We analyze the geomorphology and composition of the features and conclude this region was resurfaced by cryovolcanic processes, of a type and scale so far unique to Pluto [6]. Creation of this terrain likely required multiple eruption sites and a large volume of material (>10^4 km^3) to form what we propose are multiple, several-km-high domes, some of which merge to form more complex planforms.

The existence of these massive features suggests Pluto's interior structure and evolution allows for either enhanced retention of heat or more heat overall than was anticipated before New Horizons, which permitted mobilization of water-ice-rich materials relatively late in Pluto's history.

Results: The region described here is a vast area beginning at the left side of bottom edge or tip of Sputnik Planitia (Fig. 1a). It continues as far south as we are able to see in the haze-lit region of Pluto's encounter hemisphere, thus the full extent is not known. The visible extent is ~400x650 km, with dome heights ranging from a few up to 8 km high. The

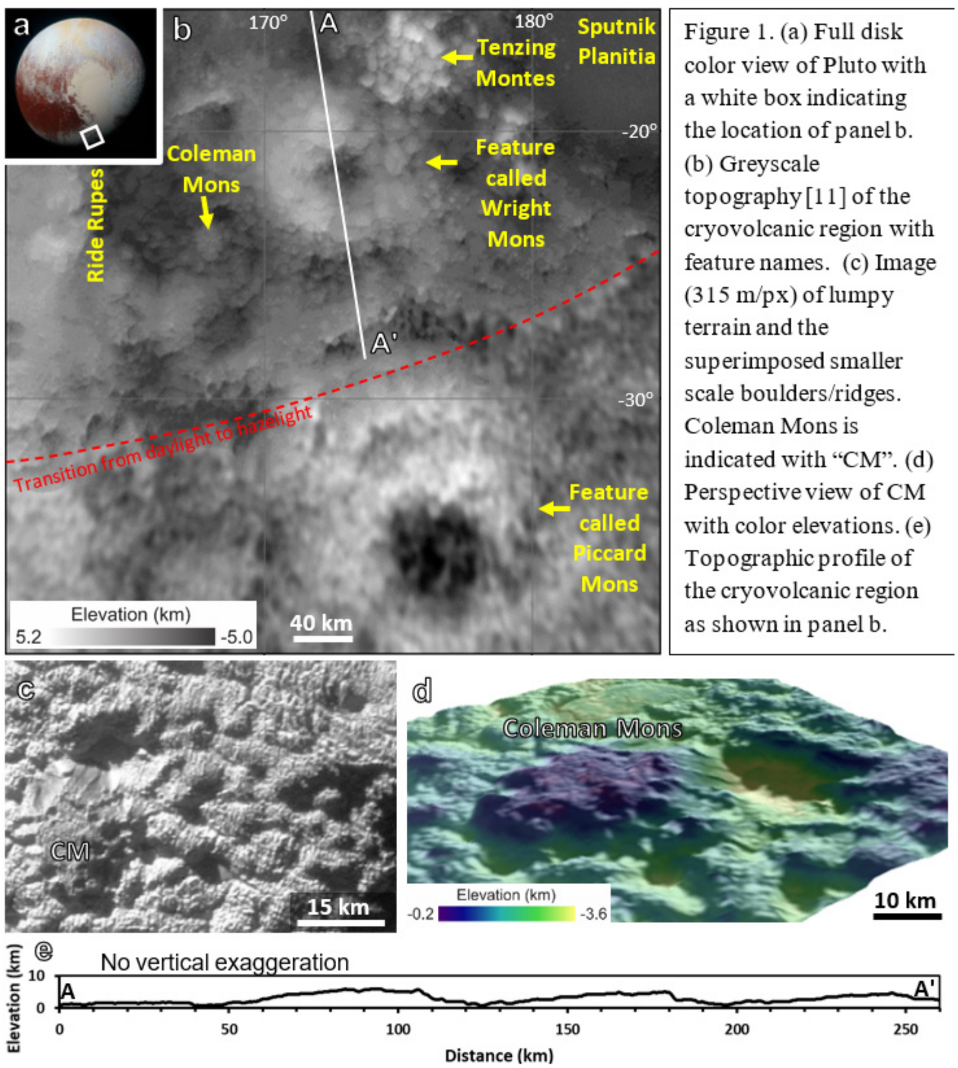

Figure 1. (a) Full disk color view of Pluto with a white box indicating the location of panel b. (b) Greyscale topography [11] of the cryovolcanic region with feature names. (c) Image (315 m/px) of lumpy terrain and the superimposed smaller scale boulders/ridges. Coleman Mons is indicated with "CM". (d) Perspective view of CM with color elevations. (e) Topographic profile of the cryovolcanic region as shown in panel b.

morphological and compositional constraints of the cryovolcanic region are described at length in [6]. Here we summarize the main findings.

Morphology and morphometry: There are three prominent scales of features in the region (Fig. 1b,c), as seen at 315 m px^{-1}: (1) large broad domes ~50+ km across, (2) a lumpy, somewhat ropey texture overprinting the domes with a somewhat consistent wavelength that is ~8-15 km across, and (3) 1-2 km wide boulders or ridges.

Composition: Volatile ices deposit on much of the surface of Pluto and are detected in all areas except for very low albedo/dark regions (that are somewhat warmer) [7,8,9]. This veneer of volatile ice often obscures any spectral information about the bulk of the material below it. In the Wright Mons region, water ice is detected wherever methane is not (in darker areas). Based on both compositional and morphological evidence, we suggest the features are most likely made primarily of water ice plus some other materials [6]; some additional components may help to lower the melting temperature, e.g., ammonia [10]. Although ammonia is not detected in this area, if it were present, it may also be obscured spectrally by other species.

Formation hypotheses:

- We find no strong evidence for the apparent central depressions of the features originally called Wright and Piccard Mons to be central vents. There are no collapse terraces, and the depression "floors" are at or below the level of the surrounding terrain. There are no distinct indicators of individual flows or flow directionality originating in the depressions. They do not resemble terrestrial or martian calderas.
- Instead, we suggest the many large rises in this area all had a similar formation mechanism (instead of some being quasi-annual and others not), where many eruption locations form domes above them, and some domes merge to form more complex planform rises.
- Many of the broad low areas/depressions that remain may be where no domes formed or merged, rather than being from collapse.
- We explored several possible mechanisms for the hummocky terrain, including (1) creation of individual small volcanic domes (first proposed in [11]), (2) viscous extrusion of rapidly cooled lavas analogous to pillow lavas, (3) compression of viscous material with a frozen skin analogous to pahoehoe, viscous pressure ridges, or funiscular terrain on Enceladus [12], and none were satisfactory for explaining this terrain [6].
- There are very few clear contacts or indicators of flow directionality. However, one smaller dome named Coleman Mons may be an example of an individual emplacement event (see details in [6]; Fig. 1c,d). If this feature formed by extrusion from an ~central vent below it, several models estimate a yield strength of ~6.4×10^4 Pa for this dome's aspect ratio [6].

Implications for Pluto's Internal Heat History: Given the low expected heat fluxes from Pluto's rocky interior (<5 mW m^{-2} throughout much of its history [13,14]), and Pluto's cold surface temperatures (average ~40 K [e.g., 15]), mobilizing material primarily made up of water ice is thermally challenging. However, the relative youth of the terrains implies that some heat must be available to emplace these features late in Pluto's history. Multiple, massive water-ice cryovolcanic constructs present new pieces of information towards understanding Pluto's thermal history, which complement other information from young areas on Pluto made up of volatile ices (e.g., Sputnik Planitia), and other small volume features that have been proposed as effusions of ammonia water [16,17]. Perhaps stratigraphic arrangement of the interior structure has stored internal heat generated from the rocky core that was later released (e.g., the clathrate layer proposed by [18]).

Acknowledgments: We thank NASA's New Horizons mission. KNS additionally thanks Dr. Michael Bland for helpful discussions. BS acknowledges the Centre National d'Etudes Spatiales.

References: [1] Stern S. A. et al. (2015) *Science, 350,* id.aad1815. [2] Moore J. M. et al. (2016) *Science, 351,* 1284-1293. [3] White O. L. et al. (2021) Chapter in *The Pluto System After New Horizons,* 55-87. [4] Singer K. N. et al. (2021) Chapter in *The Pluto System After New Horizons,* 121-145. [5] McKinnon W. B. et al. (2016) *Nature, 534,* 82-85. [6] Singer K. N. et al. (2022) *Nat. Comm.,* accepted. [7] Grundy W. M. et al. (2016) *Science, 351,* aad9189. [8] Schmitt B. et al. (2017) *Icarus, 287,* 229-260. [9] Protopapa S. et al. (2017) *Icarus, 287,* 218-228. [10] Dalle Ore C. M. et al. (2019) *Sci. Adv.*, 5, eaav5731. [11] Schenk P. M. et al. (2018) *Icarus, 314,* 400-433. [12] Bland M. T. et al. (2015) *Icarus, 260,* 232. [13] McKinnon W. B. et al. (1997) Chapter in *Pluto and Charon,* 295. [14] Robuchon G. and Nimmo F. (2011) *Icarus, 216,* 426-439. [15] Young L. A. et al. (2021) Chapter in *The Pluto System After New Horizons,* 321-361. [16] Cruikshank D. P. et al. (2019) *Icarus, 330,* 155-168. [17] Cruikshank D. P. et al. (2021) *Icarus, 356,* 113786. [18] Kamata S. et al. (2019) *Nat. Geo., 12,* 407.