PRESENT AND PAST GLACIATION ON PLUTO. A. D. Howard[1], J.M. Moore[2], O.L. White[2], O. Umurhan[2], P. Schenk[3], R. Beyer[2], W. McKinnon[4], K. Singer[5], J. Spencer[5], S.A. Stern[5], H. Weaver[6], L. Young[5], K.Ennico Smith[2], and C. Olkin[5], and the new Horizons Science Team. [1]Dept. Environmental Sciences, University of Virginia, Charlottesville, VA 22904, [2]NASA Ames Research Center, Moffett Field, CA 94035, [3]Lunar and Planetary Inst., 3600 Bay Area Blvd., Houston, TX 77058, [4]Dept. Earth and Planetary Sciences, Washington Univ. St. Louis, St. Louis, MO 63130, [5]Southwest Research Inst., 1050 Walnut St., Suite 300, Boulder, CO 80302.

Introduction: The New Horizons [NH] Mission has revealed many unexpected and dramatic features on Pluto [1], including active glacial flow of N_2 ices as well as erosional features we interpret to have formed through past N_2 glacial flow. The equatorial region is dominated by the flat plain of Sputnik Planum[1] [SP], an expanse of about 750 x 1400 km dominated by N_2 and CO ices which are involved in convective overturning of ~40 km diameter cells and a surface pockmarked by sublimation pitting.

Modern Glaciation: Rough-textured, pitted uplands with high albedo extend about 550 km eastward along 750 km of the eastern margin of SP, forming the eastern half of the half of the high-albedo feature Tombaugh Regio (which also includes SP). Nearly flat expanses of nitrogen-rich ices lie 2-3 km above the floor of SP and are connected through several trough-like valleys to the surface of SP (**Fig. 1**). Such connected flats extend up to 100 km beyond the eastern margin of SP. The N_2-rich flats are surrounded and generally enclosed by rough, pitted uplands. The 2-5 km wide troughs connecting the icy flats to SP are floored with N_2-rich ices and slope about 2 degrees. Stereo imaging shows that the upland flats systematically decrease in elevation where they border the troughs. High phase angle imaging by the MVIC scanning imager (320 m/pixel) reveals dark bands on the icy surfaces up to 1.5 km wide which start on the N_2 upland flats, converge within the throats of the connecting valleys, and expand onto SP (**Fig. 1**). Similar connections through narrow valleys between upland N_2-rich flats and SP occur along the 700 km boundary between SP and the high-albedo, pitted uplands to the east. The floor of SP within 100 to 200 km of its eastern edge has morphology distinct from the cellular pattern characteristic of central SP. Dark bands a few km wide extend toward the interior of SP from its eastern margin, including the banding spreading eastward from the valley. The dark bands enclose a 100-km wide region that encloses the dark bands radiating from the valley (red arrows in **Fig. 1**).

Interpretation: We conclude that the landform assemblage discussed above to result from geologically modern N_2 glaciation routing N_2-rich ices from the uplands onto the floor of SP. The upland N_2-rich surfaces slope in the inferred direction of flow and the steepest slopes occur where the flow would funnel through the trough-like valleys. The dark banding observed on the N_2 ices aligns with the topographic slope. We suggest these are analogous to medial moraines on terrestrial glaciers. These inferred flow lines diverge when emerging onto the SP lowlands. Subtle banding, pitting and, in some cases lines of knobs define the apparent limits of flows emerging onto SP. Fan-like forms occur at some locations where ice-filled troughs emerge onto SP. The low viscosity of N_2 ice implies appreciable flow rates would occur on the observed topographic slopes. The N_2 ices flowing onto SP are probably derived from nitrogen sublimating from SP and being redeposited on the uplands east of SP with return flow into SP, as suggested by the high albedo of this region. This implies an active N_2 glacial cycle.

Past Glaciation: The ancient uplands surrounding SP to the west, north, and northeast feature a variety of erosional morphologies, primarily expressed as linear depressions, broadly described here as valleys, but without genetic implication.

Fluted Terrain: Steeper slopes on much of the northwestern rim of SP are sculpted by ridge and trough sets, such that troughs are spaced at about 2-3 km intervals (**Fig. 2**). These are oriented downgradient on hillslopes that characteristically have gradients of about 20° and slope lengths of 2-5 km. Vertical relief can exceed 2 km. We informally name such ridge and trough sets “fluted terrain”. In places hills about 20 km across are entirely dissected by flutes radiating in all directions. Interior crater walls may also be fluted. The ridged and troughs extend nearly to divides and generally terminate at crater floors or at relatively flat-floored depressions.

Dendritic Valleys: Parts of the rolling, mantled terrain northeast of SP are dissected by interconnected valleys, which locally occur in a distinct dendritic pattern (**Fig. 3**). The valleys are organized much as terrestrial drainage networks, with headwater valleys being relatively steep and trunk valleys with gentle slopes, with a few networks clearly reaching 3rd order. Most of the networks terminate in broad depression several tens of kilometers. Relief between ridge tops and the deeper valleys is typically 1.5 to 2 km.

[1] All feature names on Pluto are informal.

Plateau Dissection: A dissected plateau extends above the crater at bottom of **Fig 4**. This dissection converges to wide, deep trunk valleys of nearly uniform width, possibly with a U-shaped cross sections (red arrows). The larges valley terminates in a fan-like splay (blue arrow). The tributary valleys enter trunk valleys at steep gradients, possibly "hanging" valleys.

Alpine Dissection: Southwest of SP an uplands region is characterized by dissected mountainous ridges surrounded by plains and broad valleys (**Fig. 5**). A ~90 km dissected ridge is capped by methane ice, providing a superficial resemblance to terrestrial ice-capped mountain chains. This mountain chain with its fluted terrain-like dissection is surrounded on its southern and western margins by 5-6 km wide, flat-floored valleys in a crude dendritic pattern (red arrows).

Interpretation: We have considered several processes that might produce the landforms shown in **Figs. 2-5**, including mass wasting, precipitation with runoff, and past N_2 glaciation [2]. The latter appears to be capable of explaining all of these morphologies, with spatial variation in morphology being a response to local topographic setting, substrate properties, latitudinal variations in insolation, and variation in depths and durations of ice accumulation.

Glaciers composed of N_2 have characteristics and behavior very different from water ice glaciation on Earth. N_2 ice will not expand upon freezing, so that the freeze-thaw processes which are thought to be the dominant process creating the headwall erosion producing cirques, and arêtes in terrestrial mountain glaciation will not occur on Pluto. Nitrogen ice is also denser than Pluto's water ice, so that any dislodged water ice could be floated and carried away, potentially robbing the basal N_2 flow of abrasive debris. If N_2 ice accumulated to a depth of 1-4 km (depending upon the geotherm) it might be subject to basal melting and sub-ice drainage. Liquid N_2 is less dense than N_2 ice and be subject to surface breakout flooding if flow rates were sufficient to prevent freezing.

Conclusions: The discovery of present and past glaciation on Pluto indicates that the outer reaches of the Solar System can be as geomorphically active as inner regions. The paleoglacial features suggest Pluto has experienced long-term loss of N_2 to space, but its detailed geologic history remains to be deciphered.

References: [1] Stern S.A. et al. (2015) *Science 350,* 292-300. [2] Moore, J. M. et al. (2016) *Science, in press.*

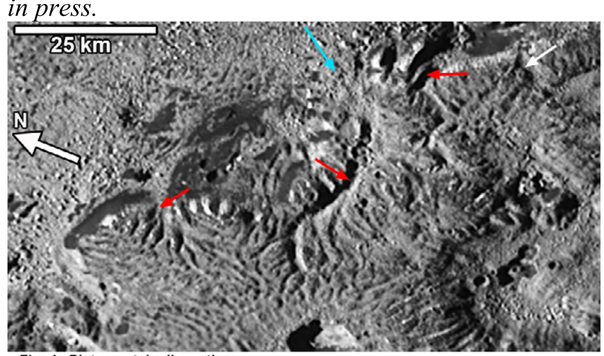

Fig. 4. Plateau-style dissection.

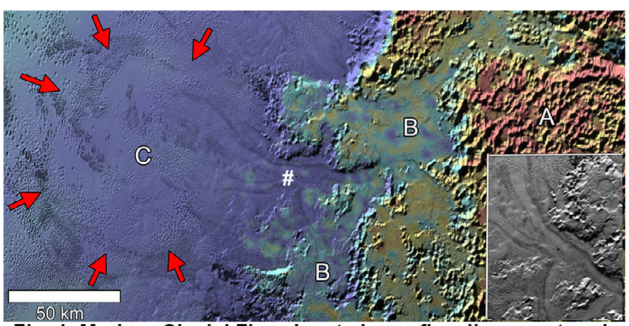

Fig. 1. Modern Glacial Flow. Inset shows flow lines centered and rotated at "#".

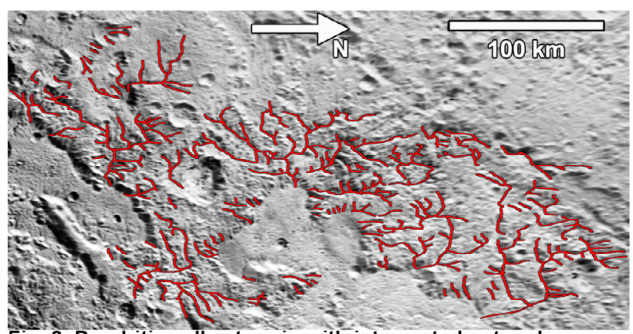

Fig. 3. Dendritic valley terrain with interpreted network structure.

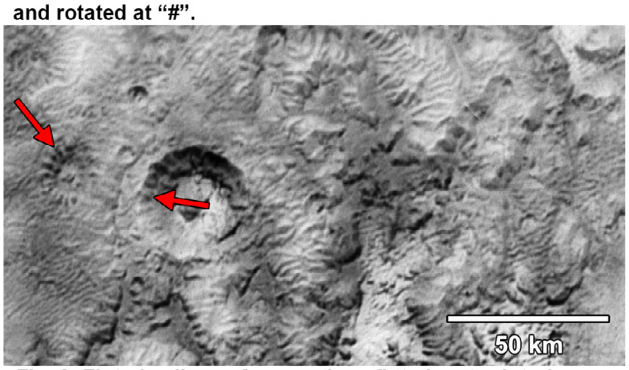

Fig. 2. Fluted valleys. Arrows show fluted crater interiors.

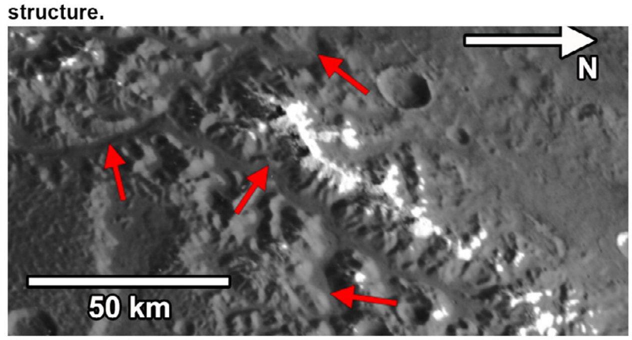

Fig. 5. Alpine style dissection. Arrows mark main valleys.