BOULDER-LAYER PAVEMENT ACROSS THE SOUTHERN HIGHLANDS AND COLD-BASED CONTINENTAL-SCALE GLACIATION. An Yin (yin@epss.ucla.edu) and Kobe Y. Wang, Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California 90095-156702, USA

Introduction: A first-order question in the studies of Mars is whether most or the entire southern hemisphere highlands were once occupied by a single ice sheet ([1], [2], [3]). A related question is whether the inferred glaciation occurred only in the Noachian ([1], [4]]) or extended into the Hesperian-early Amazonian ([5], [6]) and even the late Amazonian ([7]). Additionally, debate has also been centered on whether the proposed ice sheet was moving through wet-based ([8]) or cold-based ([9], [10], [11]) processes. The two end-member ice-transport models make specific predictions that are testable by photogeologic mapping. The wet-based transport model predicts (1) *water-assisted soft-sediment deformation*, and (2) *presence of eskers, kames, subglacial lacustrine deposits, and drumlins* ([16]). The cold-based transport model predicts (1) *the absence of the aforementioned features* [16], (2) *basal debris entrainment and pavement-like deposition* ([12], [13], [14], (3) *a lack of frontal and lateral moraine ridges* ([14], [15]), (4) *a bimodal sand-boulder size distribution* ([14], [16]), and (5) *partial preservation of pre-glaciation landforms* (e.g., [17]). The goal of this study is to test the two end-member ice-transport models. By doing so we address the fundamental question of whether the southern highlands were once occupied by a single ice sheet.

Data and Methods: MOLA topographic data are used for locating possible glacial flow paths (**Fig. 1**). HiRISE images are then used to examine the landforms and textures of layered deposits exposed on the steep walls of younger craters and cliffs of irregularly shaped cookie-cutter-like depressions. Similar analysis was also conducted along ridges bounding the hypothesized glacier flow paths.

Preliminary Results: *Observations* Our reconnaissance work reveals the widespread occurrence of a boulder-pavement unit across the southern highlands. This unit occurs preferentially in linear troughs and irregularly shaped basins outlined in **Fig. 1**. The boulder-bearing unit filled up older craters and is exposed on the steep walls of younger craters and irregularly shaped depressions (**Fig. 2A**). The surface of the boulder-bearing unit is mostly flat except near the headwater regions of the major outflow channels; the boulder-unit surface is traceable for 10s-100s km and displays much lower densities of craters than those on the surfaces of the bounding high-elevation regions. The boulder-unit surface is commonly associated with irregularly shaped "cookie-cutter-like" depressions (**Fig. 2A**) covered in most sites by a layer of fine-textured and light-toned mantling material; the mantling layer displays polygonal patterns in the south (**Figs. 2B and 2C**) but occurs as a dust layer obscuring bedrocks below in the north near the dichotomy boundary. The boulder-bearing unit is crudely layered and exhibits matrix-support texture (**Fig. 2D**). The clast size of the boulders is ca. 2-5 m, with the percentage and size decreasing northward. The grain size of the supporting matrix is smaller than the pixel size (25-35 cm) of the HiRISE images. The boulder unit locally occurs as piles with outward radiating ridges close to the heads of the major outflow channels; the piles have undulating surfaces and exhibit lobate debris flow/apron features (**Fig. 3**). The higher-elevation regions bounding the boulder-bearing troughs are generally absent of the boulder-bearing units; their surfaces exhibit ostensibly higher densities of craters. Our preliminary survey of the Thaumasia plateau does not reveal a regionally extensive boulder unit associated with irregular depression, filled craters, and lobate flow features.

Interpretations. The parallel layering at scales of > a few km to a few tens of km suggests that the boulder material was laid down through a blanketing process, either by deposition of impact ejecta or a high-energy-transported sediments. However, the generally absence of the boulder pavement unit along the trough-bounding ridges in the southern highlands suggests that the boulders were laid down preferentially in topographically low regions, which is not consistent with the impact-ejecta interpretation. In addition, the close association of boulder deposits with lobate-flow features and irregularly shaped cookie-cutter-like depressions also does not support the impact-deposition interpretation. Here, we suggest that the boulder-pavement unit has a glacial origin: lobate features are ice-bearing debris and irregularly shaped depressions were sites of ice blocks removed by sublimation. The absence of (1) lateral and frontal moraine ridges, (2) drumlins, and (3) water-assisted soft-sediment-deformation features rule out wet-based ice-transport processes. The lack of boulder pavement in the Thaumasia plateau suggests that the interpreted glaciation predates the latest Noachian and early Hesperian. Thus, our preliminary results favor the cold-based – ice-transport mechanism and the Noachian icy-highlands hypothesis [4]. The lack of boulder deposits along the ridges bounding the linear troughs and irregularly shaped basins in **Fig. 1** is also consistent with a cold-based ice-transport mechanism [14]. Rather than a single ice sheet as suggested in the earlier studies (e.g.,

[1], [4]), we envision that the southern highlands were occupied mostly by numerous valley glaciers (**Fig. 1**). Outbursts of supra-glacial lakes and breakthrough of large englacial reservoirs may have created episodic flooding along the outflow channels. The cold valley ice was mostly sublimated away *in situ* without creating large liquid-water lakes.

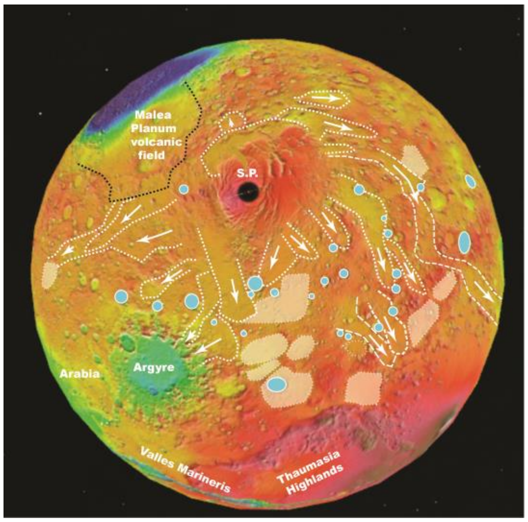

Figure 1. Hypothesized pathways of valley glaciers across southern highlands (white dashed lobes) and glaciated topographic depressions (gray regions).

References: [1] J.S. Kargel & R.G. Strom (1992) *Geol. 20*, 3-7 [2] R. Wordsworth et al. (2013) Ica*rus 222*, 1-19. [3] R.M. Ramirez and R.A. Craddock (2018) *NG. 11*, 230-237. [4] R. Wordsworth, *AREPS 44*, pp.381-408. [5] V.R. Baker et al. (1991) *Nature 352*, 589-594 [6] V.R. Baker (2001) *Nature 412*, 228-236. [7] Dickson et al. (2008) *Geol. 36*, 41-44. [8] J.S. Kargel et al. (1995) *JGR 100*, 5351-5368. [9] B.K. Lucchitta (1980) *LPSC 11*, 634-636. [10] J.L. Fastook & J.W. Head (2014), Planet. Space Sci. 91, 60-76. [11] J.P. Cassanelli and J.W. Head (2015) Icarus 253, 243-255. [12] G.S., Boulton (1970) *J. glacio. 9*, 213-229. [13] C.M. Clapperton (1975), *J. glaocio. 14*, 395-406. [14] C.B. Atkins (2013) *Geol. Soc. London Spe. Publ. 381*, 299-318. [15] M.A. Paul & N. Eyles (1990) *Quat. Sci. Rev 9*, 51-69. [16] M.J. Hambrey & N.F. Glasser (2012) *Sed. Geol. 251*, 1-33. [17] P.R. Bierman et al. (2015) Geol. 43, p. 1059-1062.

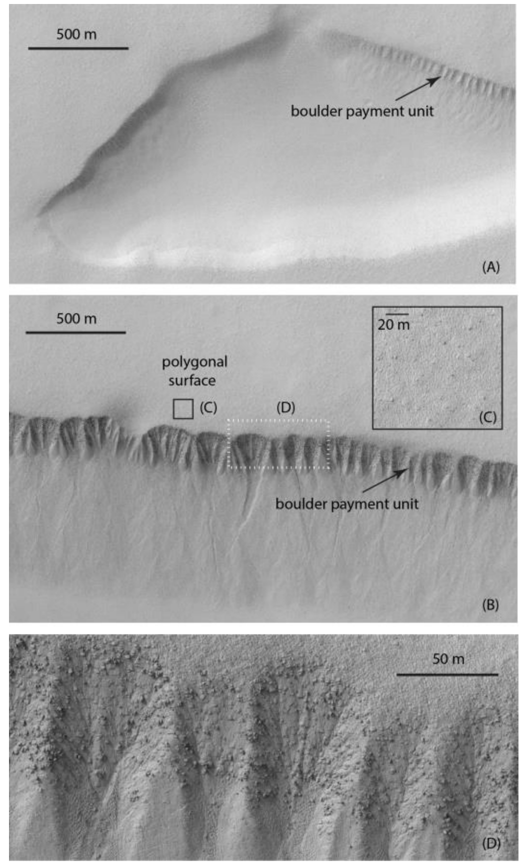

Figure 2. (A) “Cookie-cutter-like” depression. (B) and (C) Polygonal mantling surface. (D) Matrix-supported boulder unit. All from HiRISE image ESP_013651_1075.

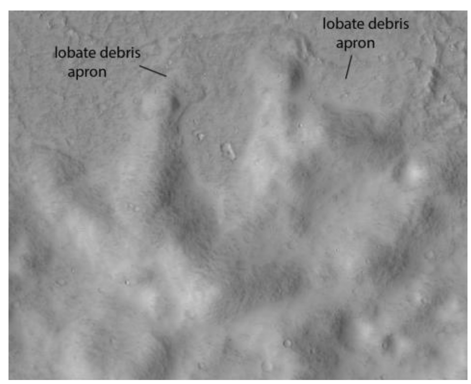

Figure 3. A boulder-bearing pile with lobate debris aprons and undulating surface (HiRISE image PSP_003279_1585).