NON-DIFFUSIVE REGOLITH TRANSPORT ON THE MOON.

M. Kreslavsky[1], *A. Zubarev*, *I. Nadezhdina*, *N. Bondarenko*[1], [1]Earth and Planetary Sciences, University of California – Santa Cruz, Santa Cruz, CA, 95064, USA, mkreslav@ucsc.edu

Introduction: Surface of the Moon is covered with regolith, a specific layer of loose unsorted material. A typical regolith surface looks smooth and subdued at scales of meters and tens of meters. It has long been understood that this smoothness is due to regolith gardening by micrometeoritic impacts. In [1] it has been rigorously shown that ejection of regolith particles at low velocities by micrometeoritic impacts cause regolith transport accurately described by the model of topographic diffusion. Such a process reasonably reproduces the degradation sequence of small craters [2]. Later it has been shown [3,4] that anomalous diffusion (with scale-dependent effective diffusivity) better fits observations of crater populations. Here we present observations that indicate that non-diffusive regolith transport plays a significant role in shaping the surface of the lunar surface

Diffusive transport: The key property of diffusive transport is its locality. By definition, topographic diffusion is a transport process, when at each point of the surface, material is transported downhill at a rate depending on the slope at the same point only, steeper slopes causing a higher downhill flux. Thus, diffusive transport at a given point is not affected by anything away from this point. If the flux is proportional to the slope tangent, the evolution of the surface is described by the linear diffusion equation. Any topographic diffusion (not only linear) erodes convex relief areas, fills concave relief areas, and smooths slope breaks. The effect of diffusion is smoothing; smaller and sharper features are smoothed more rapidly than larger features. Diffusion cannot produce any emergent patterns or "crisp" features and sharp slope breaks. In contrast to true diffusion, anomalous diffusion [e.g. 5] is essentially non-local, however, under reasonable assumptions it behave like diffusion smoothing everything and not producing emergent patterns.

Observations suggesting non-diffusive transport:

Sharp wall bases. This is the most reliable demonstration of non-diffusive, and therefore, non-local regolith transport. At mare / highland contacts there are usually sharp slope breaks between a generally horizontal mare surface (right half of Fig. 2) and highland slope (left half). **Fig. 1** shows an example of topographic profile across such a boundary in mare-filled crater Le Monnier, in the Lunokhod-2 site. The profile is extracted from a high-quality high-resolution stereo-derived digital terrain model (DTM) generated semiautomatically with a software complex PHOTOMOD 7.2 [8], which seemingly better deals with small-scale topographic features and produces less resolution-scale noise in comparison to SOCET SET traditionally used for DTM production. **Fig. 1a** illustrates how presently sharp slope break at the Le Monnier wall base (bold gray curve) would be smoothed by linear diffusion after 200 Ma, assuming diffusivity $K = 5.5\ \mathrm{m^2\ Ma^{-1}}$ [2]. To keep the slope break as sharp as it is now, some other non-diffusive process is needed to compensate diffusion, which inevitably occurs at some rate due to micrometeoritic impacts. **Fig. 2** shows a relatively fresh crater (D ~ 250 m) partly covered by highland wall material apparently advanced toward the right. Such morphology cannot be created by local diffusive transport. This example is far not unique. Both sites (Fig. 1,2) and many other sites with similar morphologies are far away from sites of recent tectonic deformation [7,8,14]. There are no signs of geologically recent landslides, avalanches, etc.; the slopes are gentler than the angle of repose (~22° on average in Fig. 1, from ~23° to ~15° in left half of Fig 2); regolith on the slopes is mostly optically mature.

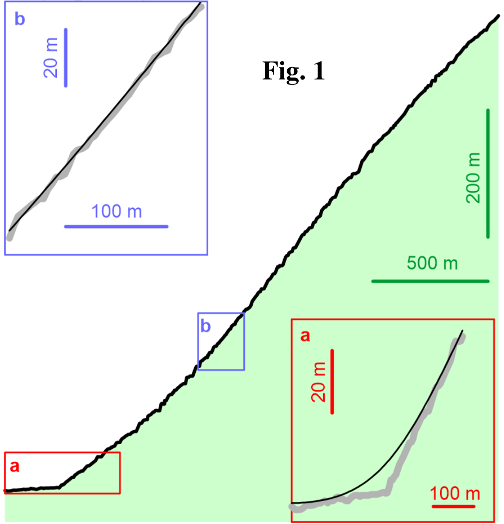


Fig. 1

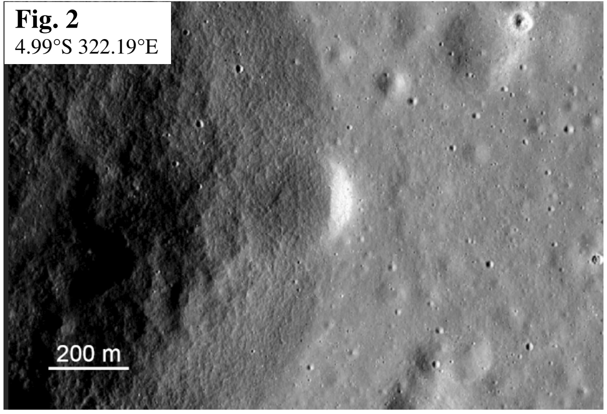


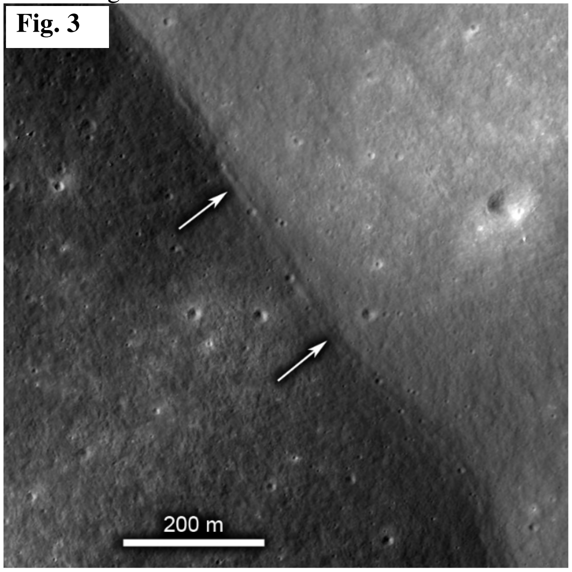
Fig. 2
4.99°S 322.19°E

"Elephant hide" texture (EHT). Specific subtle meters-to-decameters-scale texture (Fig. 2 left half, Fig. 3) dubbed "elephant hide" texture [9-11] or "leathery" [12] texture, or "creeps" [13] occurs on virtually all slopes steeper than ~5° – 8°, regardless of latitude and slope

orientation [10]. EHT appearance and apparent anisotropy change with the change of illumination direction. EHT has no characteristic spatial scale [11]. Profile of Le Monnier wall (**Fig.1a,b**) shows the largest steps and terraces of EHT well resolved in the high-quality DTM. Diffusion would smooth out these steps and terraces in ~10 Ma, assuming $K = 5.5\ \text{m}^2\ \text{Ma}^{-1}$ [2] (thin line in **Fig. 1b**). Formation mechanism of EHT is unknown, however, it should be essentially non-local.

Ridges on valley thalwegs. They are much less common in comparison to sharp wall bases and EHT. **Fig. 3** shows an example of a valley in dissected and terraced rim of Tsiolkovskiy impact basin. The valley walls are rather steep, however, they are gentler than the angle of repose and do not possess morphologies suggestive of recent landslides. The valley's thalweg is sharp (similarly to the sharp wall bases) and has a small ridge (arrows in Fig. 3) 6 - 10 m wide. If regolith transport occurred according to the diffusion creep mechanism, the ridge would never form, and the valley would get smooth floor geologically quickly. Diffusive process cannot produce such a ridge.

Fig. 3



Quick removal of craters on slopes. Small (D<~100m) craters on the Moon are in equilibrium, meaning that crater formation by new impacts is balanced with crater obliteration by topographic diffusion. It has been noted long ago that density of small craters on steep (~15°-25°) slopes (like in Fig. 2 left half, Fig. 3) is much lower than on horizontal surfaces. The natural explanation for this is that craters on slopes degrade and disappear more rapidly. However, linear topographic diffusion model predicts exactly the same degradation sequence for craters on a horizontal surface and on a tilted surface, and therefore, the same crater life span. It would be natural to invoke non-linear diffusion, which involve more intensive transport on steeper slopes. We ran a nonlinear diffusion model with a reasonable nonlinearity [15]. Initial rapid crater degradation went more rapidly on a slope, however, the later, longer stages of crater smoothing were very similar on a slope and on a horizontal surface, and the difference in life span was minor, which is a direct consequence of locality of diffusion. Rapid crater obliteration on slopes requires a nonlocal regolith transport process.

Discussion: Morphological evidence shown above indicates that non-diffusional regolith transport plays an important role on the Moon. The physical nature of this transport process remains unclear. The process does not produce familiar morphology of landslides or lobate flows. This means that it is not related to any kind of dynamic fluidization of regolith. The process operates on stable slopes much gentler than the angle of repose. This means that some mobilization mechanism is needed. Mobilization by micrometeoritic impacts leads to diffusive transport. A reasonable hypothesis is that limited mobilization is caused by seismic and/or acoustic waves. Low lunar gravity is favorable for such type of mobilization. However, details of the process remain poorly understood. In particular, it is not clear, if regolith moves massively in response to rare powerful events, for example, Copernicus-forming impact, or non-local regolith creep occurs as a series of frequent minor mobilization episodes triggered by weak seismicity, small impact, etc. These alternatives can potentially be distinguished by further analysis of lunar morphology.

Although diffusive regolith transport inevitably occurs due to micrometeoritic impacts, it is likely that the unknown non-diffusive transport process dominates degradation and obliteration of small impact craters and mimics anomalous diffusion. This may explain the unexpectedly steep dependence of the effective diffusivity on crater size ($K \propto D^{0.9}$) as deduced from analysis of crater populations [3].

References: [1] Soderblom (1970) JGR 75, 2655. [2] Fassett & Thompson (2014) JGR 119, 2255. [3] Fassett et al. (2018) LPSC 49, 1502. [4] Minton et al. (2019) Icarus 326, 63. [5] Foufoula-Georgiou (2010) JGR 115, F00A16. [6] https://en.racurs.ru/about/ [7] Banks et al. (2012) JGR 117, E00H11. [8]. Valantinas & Schultz (2020) Geology 48, 649. [9] Plescia & Robinson (2010) EPSC 2010, 731. [10] Kreslavsky et al. (2021), LPSC 52, 1826. [11] Bondarenko et al. (2022), LPSC 53, 2469. [12] Antonenko (2012) LPSC 43, 2581. [13] Xiao et al. (2013) EPSL 376, 1. [14] Nypaver & Thomson (2022) GRL 49, e2022GL098975. [15] Roering et al. (1999) Water Recourses Res. 35, 853.