

LUNAR THRUST FAULTS: IMPLICATIONS FOR THE THERMAL HISTORY OF THE MOON.

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Introduction: The largest scale tectonic landforms on the Moon, contractional wrinkle ridges and extensional rilles or graben, are directly associated with the mare basins [see 1, 2]. In contrast to these nearside, basin localized tectonic features are the relatively small-scale lobate scarps, easily resolved only in the highest resolution Apollo Panoramic Camera and Lunar Orbiter images [2, 3, 4]. Although lobate scarps are found in mare basalts, they most often occur in the lunar highlands and in highland craters, are the dominant tectonic landform on the farside [2], and are interpreted to be the surface expression of thrust faults [2, 3, 4]. Limited by the paucity of high resolution image coverage with optimum lighting geometry, lunar scarps are not yet well cataloged or characterized and their global spatial distribution is unknown. Newly obtained high resolution 0.5 to 2 m/pixel images from the Lunar Reconnaissance Orbiter Camera (LROC) have revealed previously undetected lobate scarps and remarkable new features related to some previously known scarps.

Lee-Lincoln and Newly Viewed Scarps: LROC Narrow Angle Camera (NAC) images show meter-scale tectonic landforms associated with previously known and newly discovered lunar scarps. The Lee-Lincoln scarp cuts roughly north-south across the mare basalt-filled Taurus-Littrow valley near the Apollo 17 landing site, trending between two highland massifs (Fig. 1A). Where the fault scarp extends into the highlands of North Massif it cuts up-slope for a short distance and abruptly changes trend to the northwest cutting along slope. An array of fractures and shallow extensional troughs or graben have been revealed in the back-scarp area. These graben are among the smallest-scale tectonic landforms yet observed on the Moon, with maximum widths of ~25 m and lengths of ~100-200 meters. Topography derived from NAC stereo images shows the fractures and graben are spatially correlated with a narrow, low-relief rise and the elevated back-scarp terrain (Fig. 1B). The graben and associated rise are interpreted to be the result of flexural bending of the valley floor basalts with bending stresses causing extension of the upper regolith.

A survey of NAC images obtained thus far has revealed seven previously unknown lobate scarps. One of these scarps is located in the floor material of

Slipher crater (~48.3°N, 160.5°E). This lobate scarp is among the smallest known scarps with a length of only ~3 km (Fig. 2). The east-west trending Slipher scarp terminates to the west in a series of small-scale splay faults expressed by multiple scarp segments. These splay faults form multiple, low-relief terraces that suggest imbricate thrust faulting, a characteristic shared by other lunar scarps.

Spatial Distribution of Lunar Scarps: Most of the previously known lobate scarps are located in the ~20% of the lunar equatorial zone imaged by the Apollo Panoramic Cameras [2, 4] (Fig. 3). Six of the newly detected lobate scarps occur at latitudes greater than ±60° with two of these located very near the lunar north and south poles. The discovery of lobate scarps at high lunar latitudes along with known and newly viewed mid- and low-latitude scarps, suggests that lunar scarps are globally distributed (Fig. 3).

Crosscutting Relations and Relative Age: The lack of superposed, relatively large-diameter (>500 m), impact craters and their generally crisp morphology led workers to interpret the lunar scarps to be among the youngest tectonic landforms on the Moon [2-5]. Crosscutting relations with small impact craters revealed in NAC images of known and newly detected scarps show craters with diameters as small as ~5-10 m are cut by the lobate scarps. Crosscutting of meter-scale craters indicates a very young age for the lunar scarps.

Implications for Lunar Thermal History: The initial temperature and thermal evolution is strongly constrained by estimates of lunar radial contraction [6, 7]. The clear absence of large-scale lobate scarp thrust faults like those found on Mercury, which are attributed to significant radial contraction [8, 9], argues against secular cooling of a nearly or completely molten early Moon [6, 7]. Globally distributed, very young, small-scale lunar thrust faults are evidence of late-stage radial contraction. The estimated areal contractional strain expressed by the previously known lobate scarps is ~0.008% [2]. Extrapolated to the entire lunar surface, this strain is equivalent to a radius change of ~70 m and corresponds to isotropic compressional stresses of <10 MPa [2]. This small amount of contraction supports thermal history models that predict low-level, late-stage compressional stresses and a relatively small

change in lunar radius. The strain and radial contraction will be more accurately determined when the total population of lunar scarps is known from a global survey of LROC NAC images obtained over the life of the LRO mission.

References: [1] Wilhelms, D.E. (1987) U.S. Government Printing Office, Washington, DC. [2] Watters T.R. and Johnson C.L. (2009) in *Planetary Tectonics*, Cambridge Univ. Press, 121-182. [3] Binder A.B. (1982) *Earth, Moon, and Planets*, 26, 117-133. [4] Binder A.B. and Gunga, H.-C. (1985) *Icarus*, 63, 421-441. [5] Schultz P.H. (1976) University of Texas Press, Austin, TX. [6] Solomon S.C. and Chaiken J. (1976) *Proc. Lunar Sci. Conf.* 7, 3229-3243. [7] Solomon S.C. (1986) in *Origin of the Moon*, Lunar and Planetary Institute, 311-329 [8] Solomon S.C. et al. (2008) *Science*, 321, 59-62. [9] Watters T.R. et al. (2009) *Earth Planet. Sci. Lett.*, 285, 309-319.

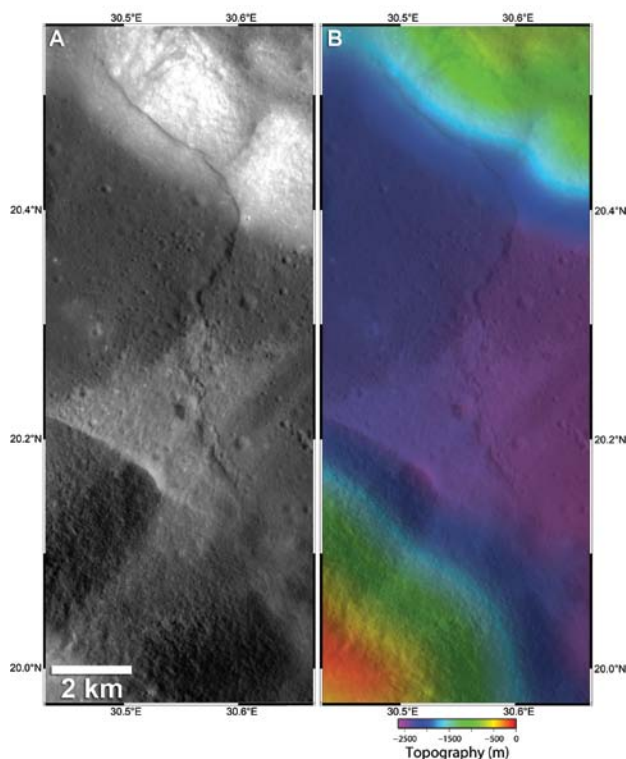


Figure 1. NAC image and stereo derived topography of the Lee-Lincoln scarp. (A) The lobate scarp extends from South Massif (bottom) across mare basalt-filled Taurus-Littrow valley to North Massif (top). (B) The DEM indicates a low-relief, narrow rise associated with the scarp and elevated back-scarp terrain. The DEM has a spatial resolution of ~15 m/pixel. LROC NAC frame M104318871LE.

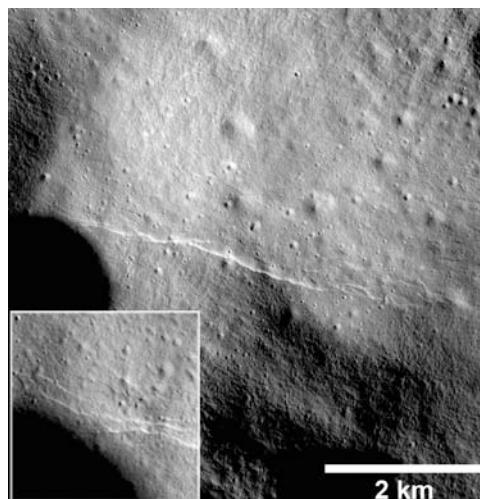


Figure 2. Newly discovered lobate scarp located in Slipper crater floor material. Splay faults mark the western terminus of the scarp (inset). LROC NAC mosaic includes frames M103466592LE and M103466592RE.

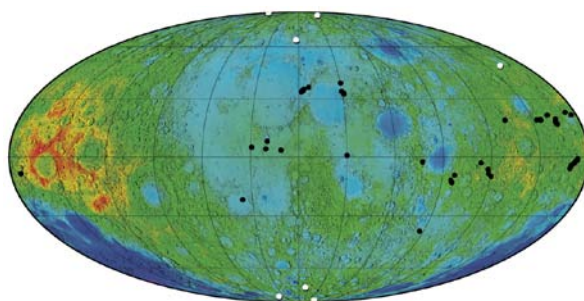


Figure 3. Distribution of previously known (black dots) and newly discovered (white dots) lobate scarps. Six of the newly detected lunar scarps occur at latitudes $>60^\circ$.

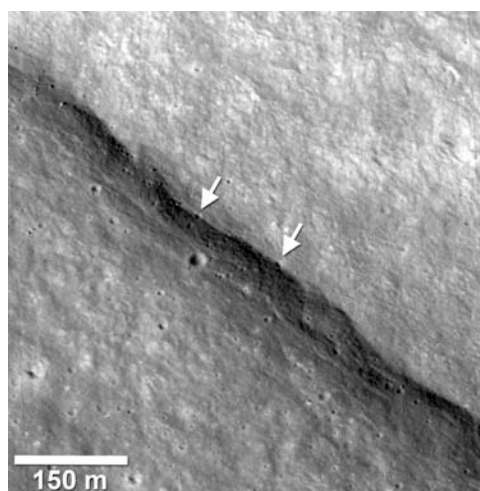


Figure 4. The segment of Lee-Lincoln scarp in North Massif crosscuts ~10-m-in-diameter impact craters (large white arrows). Boulders have collected along the scarp face. LROC NAC frame M104318871LE.