EVIDENCE OF YOUNG EXTENSIONAL FAULTING ON THE MOON. **Thomas R. Watters**[1], **Mark S. Robinson**[2], **Maria E. Banks**[1], **Thanh Tran**[2], **and the LROC Team**, [1]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560 (watterst@si.edu); [2]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85251.

Introduction: Broad-scale extensional tectonics in the form of linear or sinuous rilles or graben are associated with the nearside mare basins, Mare Procellarum and Mare Orientale [see 1, 2]. Basin-radial and basin-concentric graben are typically found near the basin margins and in the adjacent highlands [see 2, plate 6]. Other evidence of lunar extension is confined to floor fractured craters where graben often form roughly polygonal patterns [1, 2, 3]. Apollo era images showed no evidence of extension in the highlands beyond the influence of mare basalt filled basins and floor fractured craters. The absence of extensional tectonic landforms on the farside outside of Mare Orientale is striking [4]. Newly obtained high resolution 0.5 to 2 m/pixel images from the Lunar Reconnaissance Orbiter Camera (LROC) have revealed previously undetected small-scale graben that deform both highland material and mare basalts.

Graben Associated with Lobate Scarps: Thus far, LROC Narrow Angle Camera (NAC) images show meter-scale graben associated with four lobate scarps (contractional landforms) [5]. These graben are located in the back-scarp terrain, typically <3 km from the lobate scarps with maximum widths of <50 m and maximum lengths of 500 m or less. Orientations of these graben vary from subparallel to nearly perpendicular to the trend of nearby scarps.

Small-Scale Graben in Mare Basalts: LROC NAC images reveal a series of graben in a small patch of mare basalts south of Mare Humorum, flanking a wrinkle ridge (~33.1°S, 323°E) (Fig. 1). The E-W to NE-SW oriented Vitellio graben extend over a distance of ~3.5 km and exhibit clear en echelon steps, indicating that faults grew by segment linkage. The longest of the Vitellio graben is ~600 m with a maximum width of ~15 m. Unlike the graben associated with lobate scarps, these graben occur over a larger area and many are regularly spaced, with a spacing between ~100-200 m. Lunar Orbiter Laser Altimeter (LOLA) data show that the graben are associated with a topographic rise with a maximum relief of ~15 m (Fig. 1).

Farside Highland Graben: The largest newly detected graben are found in the farside highlands (~17.8°N, 180.8°E). We informally named this feature Virtanen graben. They are NW-SE orientated and extend over 11 km with maximum widths of up to ~450 m (Fig. 2). The graben are closely spaced and overlapping, displaying complex fault linkages that resemble those seen in larger-scale rifting [see 6]. Stereo derived topography show that the graben occur on the slopes, and along the crest, of a rise with several hundred meters of relief (Fig. 3). The depths of the measured graben vary from 2 to 17 m. The graben and rise are located on the floor of a heavily degraded, pre-Nectarian basin ~580 km in diameter. A lobate scarp, one of a cluster of scarps with orientations subparallel to the graben, occurs ~8 km south of the Virtanen graben. However, the distinct difference in the distance from the scarp, scale, complexity, and topographic setting of the graben from those associated with scarps described above suggests that these graben are not linked to a contractional tectonic landform. The similar orientations of the graben and scarps may be evidence of control by a preexisting fabric of fractures in the degraded basin.

Crosscutting Relations and Relative Age: The ages of the newly detected, small-scale graben appear to be very young based on their overall crisp morphology and a lack of superposed, relatively large-diameter impact craters (>400 m). Crosscutting relations with impact craters show the Virtanen graben cut the flank of a heavily degraded ~2.5 km diameter crater. The largest diameter crater superimposed on the Virtanen graben is ~100 m in diameter. The Vitellio graben crosscut craters with diameters as small as ~7 m (Fig. 1). Estimates of relative ages of lunar craters with various diameters and degrees of degradation indicate that 50-100 m diameter craters or smaller and fresh craters up to 400 m in diameter are Copernican in age [7]. The absolute age of the base of the Copernican is estimated to be ~800±15 million years (if defined by the age of Copernicus crater) [8]. In addition to their pristine appearance, graben formed in regolith with as little as 2 m relief or less will not survive on the Moon for billions of years. Thus, the small-scale graben are <1 billion years old and join the lobate scarps [5] as the youngest tectonic landforms on the Moon.

Implications for Lunar Geologic History: Based on crater density ages of the mare basalts cut by graben associated with nearside mare basins, extension associated with the basins ceased at ~3.6 Ga ago [9-12]. The cessation of basin related extension may be due to the superposition of compressional stresses from global contraction on flexural extensional stress due to loading by mare basalts, marking a stage in the Moon's thermal history where interior cooling resulted in a shift from net expansion to net contraction, with compressional stresses of ~100 MPa or less since the end of the period of late heavy bombardment [13-15]. The presence of young, small-scale graben indicates areas of localized extension in the dominantly contractional stress regime. Graben located in the back-limb areas of lobate scarps are likely the result of extensional stresses due to flexural bending [see 5]. The farside Virtanen graben and the nearside Vitellio graben do not appear to be related to flexural bending associated with contractional deformation. The topographic rises associated with the Virtanen and Vitellio graben suggest that extension resulted from localized uplift. A possible mechanism for the uplift and extension is the emplacement of shallow volcanic intrusives. Rising magma injected into preexisting shallow fractures induced mechanical uplift accompanied by extension. The young age of the Virtanen and Vitellio graben suggests recent intrusive

volcanic activity on the Moon. Lunar seismicity [see 2] and evidence of recent surface outgassing [16] may be related to residual intrusive volcanic activity. The young graben also support observations and thermal models that indicate a relatively low level of global compressional stress.

References: [1] Wilhelms D.E. (1987) U.S. Government Printing Office, Washington, DC. [2] Watters T.R. and Johnson C.L. (2010) in *Planetary Tectonics*, Cambridge Univ. Press, 121-182. [3] Schultz P.H. (1976) University of Texas Press, Austin, TX. [4] Scott D. H. et al. (1977) *Proc. Lunar Sci. Conf. 8*, 1119-1130. [5] Watters T.R. et al. (2010) *Science*, 329, 936-940 [6] Schultz R.A. et al. (2010) *J. Struct. Geo.* 32, 855-875. [7] Trask, N.J. (1971) *U.S. Geol. Survey Prof. Paper 750-D*, D138. [8] Stöffler D. and Ryder, G. (2001) *Space Sci. Rev.* 96, 9. [9] Lucchitta, B.K. and Watkins, J.A. (1978) *Proc. Lunar Planet. Sci. Conf. 9*, 3459-3472. [10] Boyce, J. M. (1976) *Proc. Lunar Planet. Sci. Conf. 7*, 2717-2728. [11] Hiesinger, H. et al. (2000) *J. Geophys. Res.*, 105, 29239-29276. [12] Hiesinger H. et al. (2003) *J. Geophys. Res.*, 108, 5065. [13] Solomon, S.C. and Head, J.W. (1979) *J. Geophys. Res.*, 84, 1667-1682. [14] Solomon, S.C. and Head, J.W. (1980) *Rev. Geophys. Space Phys.*, 18, 107-141. [15] Solomon S.C. and Chaiken J. (1976) *Proc. Lunar Sci. Conf. 7*, 3229-3243. [16] Lawson S.L. et al. (2005) *J. Geophys. Res.*, 110, E09009.

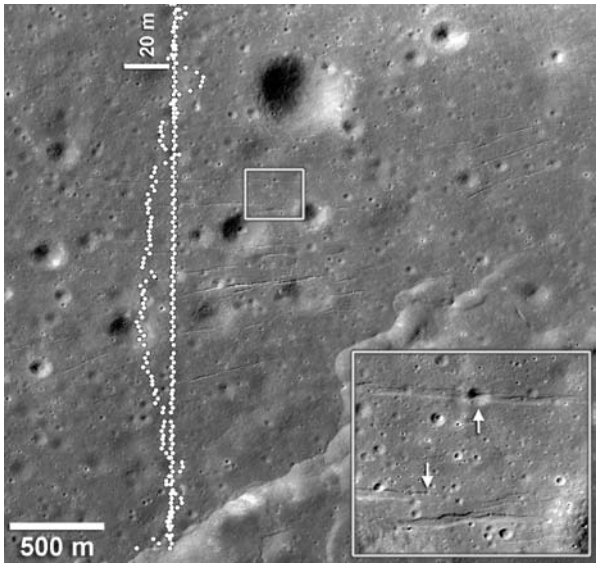

Figure 1. Small-scale, regularly spaced Vitellio graben in mare basalts south of Mare Humorum. LOLA profile indicates that graben are associated with a low relief rise (white dots show the location of the LOLA track with elevations plotted relative to the track). The narrow graben crosscut a ~28 m diameter crater (inset, upper arrow) and a ~7 m diameter crater (inset, lower arrow). LROC NAC frame M10475646RE.

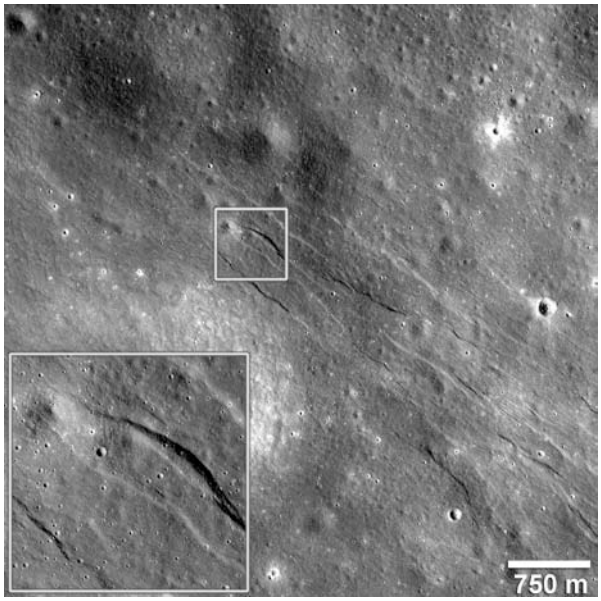

Figure 2. The farside Virtanen graben occur in highlands material within a ~580 km diameter heavily degraded impact basin. Graben are closely space and overlap (inset), displaying complex fault linkages. NAC frames M118668817LE, M118668817RE, M134001093LE.

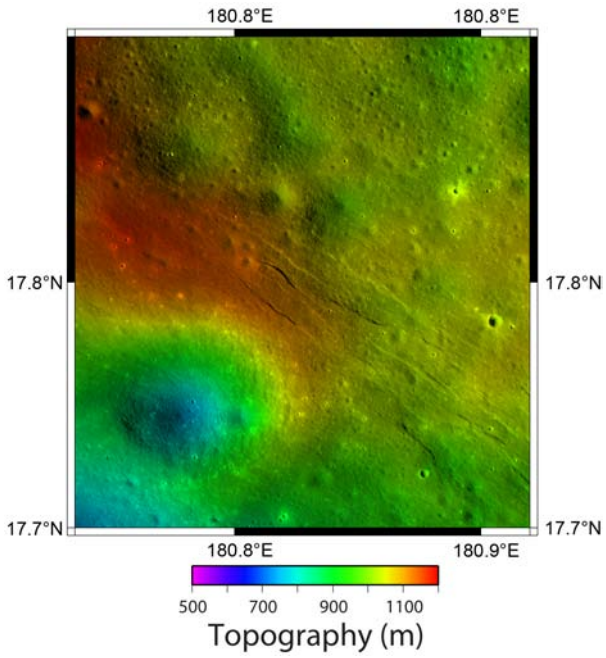

Figure 3. NAC stereo derived topography of the Virtanen graben. The digital elevation model (DEM) indicates that the graben are associated with a several hundred meter topographic rise. The DEM has a spatial resolution of 2 m/pixel. Elevations are referenced to a sphere of 1,737,400 m.