IGNEOUS DIKES ON THE MOON: EVIDENCE FROM LUNAR ORBITER LASER ALTIMETER TOPOGRAPHY. Christian Klimczak, Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA

Introduction: The Lunar Orbiter Laser Altimeter (LOLA) [1] aboard the Lunar Reconnaicance Orbiter (LRO) returned topographic information of the Moon's surface in unprecedented detail. Such fine-scale detail allows to better characterize the deformation associated with the many tectonic landforms on the Moon [2]. For example, LOLA topography across some of the many small-scale lobate scarps (thrust faults) [3, 4] can be utilized to infer the amount of displacement along the fault [5, 6] for further insight into the tectonic history and resultant interpretations for the thermal evolution of the Moon [2, 6].

The mare-dominated lunar near-side is host to many troughs [e.g. 2] (Fig. 1) that are interpreted to be graben, each consisting of a pair of antithetic normal faults dipping toward each other. However, some of these troughs, especially those surrounding large mare-filled impact basins, show topographic signatures that are atypical for normal faulting alone. Instead, LOLA tracks across graben suggest that they are the surface manifestations of igneous dike intrusions at depth [7-12]. This is motivation to further characterize the topography across these graben and to match the topography with models for surface displacements of igneous dikes.

Topography across graben: Fault-related graben topography is typically characterized by concave upward flanks of the graben in a cross-strike profile with

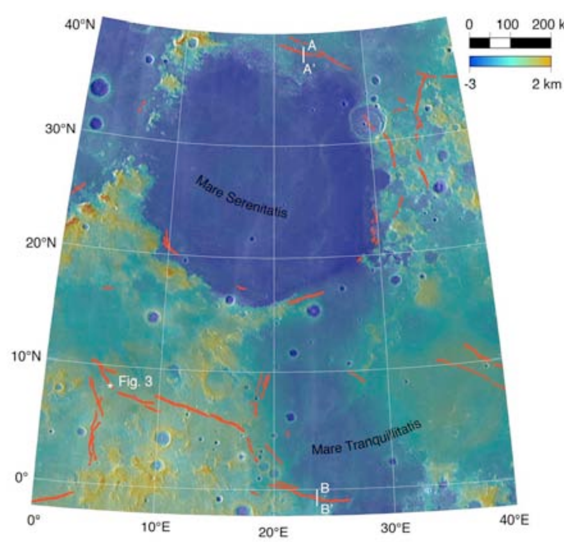

Figure 1. Area of studied graben (red) on the lunar near-side. Note that Mare Serenitatis and Tranquillitatis are outlined by graben. Topographic profiles A−A' and B−B' (Fig. 2) shown in white.

topographic maxima directly at the graben rim. Profiles across graben perpendicular to LOLA tracks surrounding Mare Tranquillitatis and Mare Serenitatis (Fig. 1) show a rather concave downward profile without pronounced topographic highs at the graben rim (Fig. 2). The studied graben occur central to a ~30 km wide rise (Fig. 2) with elevation differences of up to 100 m. Graben incise the rise by 60 to up to 200 m and are 2 to 3 km wide. Other graben in the area are located on such topographic rises as well, however, they have typical normal fault-related topographic signatures, as well. These observations are consistent with the topography of near-surface igneous dike intrusions [7, 8] on which the normal fault-related signature is superimposed [9-11].

Modeling: Suface deformation over igneous dike intrusions can be simulated using the elastic dislocation program COULOMB [13, 14]. Utilizing the stress functions for an elastic half-space [15] and specifying dike dimension, depth of intrusion, and opening displacement yields solutions for stresses and material displacements. Modeled material displacements from dike intrusions at depth can then be compared to those observed around the graben, as the associated material displacements on airless planetary bodies with minimal erosion, such as the Moon, are available from measurements of the surface topography. Prior to comparison of model results to LOLA topography, individual LOLA tracks across graben (Fig. 2) require minor adjustments to remove regional slopes.

Results: Opening displacements, depths of intrusion, and dike dimensions are varied in the model in order to match the simulated material displacements with the observed topography across the graben. Preliminary results indicate that good fits between observations and simulations can indeed be achieved (Fig. 2). This confirms that igneous dike intrusions outline the mare-filled basins in the study area (Fig. 1). More detailed topographic analyses of the graben surrounding these basins and evaluation of graben around other large mare-filled basins will provide insight to the geographic extent of dike intrusions on the Moon and their relation to mascon tectonics.

Moreover, geometric properties of the dike intrusions provide contribute toward understanding the structure of the lunar crust and also yield insight into the depths of source regions for the magmas. Modeled material displacements match observations best for dikes of heights of ~10 km and with opening dis-

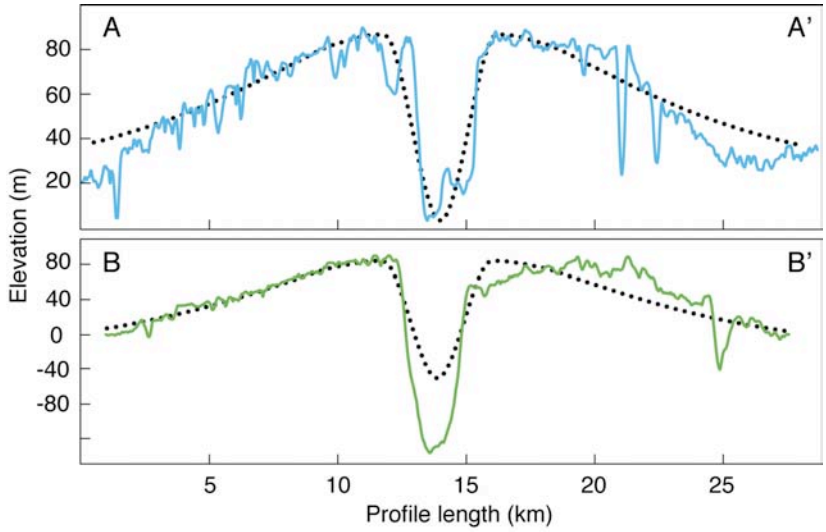

Figure 2. LOLA tracks showing topographic profiles across graben with best-fit simulated surface displacements of dikes at depth (black dotted lines). Profile A−A' shows a broad topographic rise of 60 m in elevation and ~25 km in length. Profile B−B' shows a ~30km wide and ~100 m high rise. Topographic signatures of profiles A and B are best matched with shallow (400 and 700 m deep) dikes of 10 km dike height and 300 and 400 m, respectively.

placements of ~300 to 400 m. The simulations also indicate that dikes have propagated up to relatively shallow crustal levels of only 400−700 m below surface. This finding is supported by the many linearly aligned volcanic pits in the floors of some of the graben in this area (Fig. 3).

Conclusions: Topographic data obtained from LOLA tracks across graben that outline the mare-filled basins Tranquillitatis and Serenitatis (Fig. 1) are consistent with the surface material displacements of shallow igneous dikes. This confirms previous studies suggesting the presence of near-surface dikes on the Moon [16-17] and allows to detect them on a much finer scale than the giant dikes inferred from GRAIL gravity signatures [18]. Higher-resolution gravity data from GRAIL's extended mission might reveal dikes of scales comparable to the findings here. Further characterization of LOLA and stereo-derived topography across the lunar graben and investigations in their geographic distribution will contribute toward the understanding of the tectonic and magmatic history of the moon.

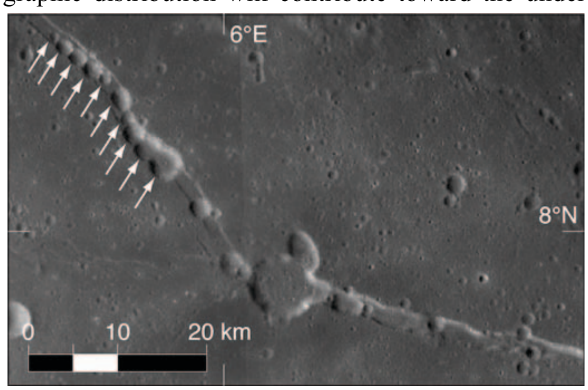

Figure 3. Series of pits co-aligned with a graben. The graben is the surface expression of a shallow dike, where pits formed due to interaction of ascending magma with geological units at the surface.

References: [1] Smith D. et al. (2010) *GRL, 37,* L18204. [2] Watters T. R. and Johnson C. L. (2010) in *Planetary Tectonics*, Cambridge Univ. Press, 121−182. [3] Watters et al. (2010), *Science, 329,* 936−934. [4] Banks M. E. et al. (2012) *JGR, 117,* E00H11. [5] Williams N. R. et al. (2011) *AGU Fall Mtg.,* abstract P43D−1707. [6] Banks M. E. et al. (2012) *AGU Fall Mtg.,* abstract P53A−2040. [7] Pollard D. D. et al. (1983) *Tectonophysics, 94,* 541−584. [8] Mastin L. G. and Pollard D. D. (1988) *JGR, 93,* 13,221−13,235. [9] Rubin A. M. and Pollard D. D. (1988) *Geology, 16,* 413− 417. [10] Rubin A. M. (1992) *JGR, 97,* 1839−1858. [11] Schultz R. A. et al. (2004) *Geology, 31,* 889-892. [12] Schultz R. A. et al. (2010) in *Planetary Tectonics*, Cambridge Univ. Press, 457−510. [13] Lin J. and Stein R. S. (2004) *JGR, 109,* B02303. [14] Toda S. et al. (2005) JGR, 110, B05S16. [15] Okada, Y. (1992) *BSSA, 82,* 1018−1040. [16] Head J. W. and Wilson L. (1993) *PSS, 41,* 719−727.[17] Wilson L. and Head J. W. (2003) *GRL, 30,* 1605. [18] Andrews-Hanna J. C. et al. (2012) *Science Express,* doi:10.1126/science.1231753