MORPHOMETRIC ANALYSIS OF SMALL-SCALE LOBATE SCARPS ON THE MOON USING DATA FROM THE LUNAR RECONNAISSANCE ORBITER. M. E. Banks[1], T. R. Watters[1], M. S. Robinson[2], L. L. Tornabene[1], T. Tran[2], L. Ojha[3], N. R. Williams[2], and the LROC team. [1]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560, USA (banksme@si.edu), [2]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85251, USA, [3]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.

Introduction: Lobate scarps on the Moon are relatively small-scale tectonic landforms observed in mare basalts and more commonly, highland material [1-4]. These scarps are the surface expression of thrust faults, and are the most common tectonic landform on the lunar farside [1-4]. Prior to Lunar Reconnaissance Orbiter (LRO) observations, lobate scarps were only detected in equatorial regions because of limited Apollo Panoramic Camera and high resolution Lunar Orbiter coverage with optimum lighting geometry [1-3]. Thus, our previous understanding of lobate scarp morphology and scale was based on measurements of a limited number of low-latitude scarps.

Lunar Reconnaissance Orbiter Camera (LROC) images and Lunar Orbiter Laser Altimeter (LOLA) ranging enable detection and detailed morphological analysis of lobate scarps at all latitudes. To date, previously undetected scarps have been identified in LROC images and mosaics in more than 75 different locations, and are globally distributed [5-6]. LROC stereo-derived digital terrain models (DTMs) and LOLA altimetry are used to measure the relief and characterize the morphology of 26 lobate scarps ranging in latitude from ~86°S to 88°N and occurring on both the nearside and farside. Lunar examples are compared to lobate scarps on Mars, Mercury, and the asteroid 433 Eros.

Data and Methods: LROC consists of a Wide Angle Camera (WAC) and two Narrow Angle Cameras (NACs) which provide images at a scale of up to 0.5 m/pixel [7]. Five DTMs derived from LROC NAC stereo pairs, with vertical precision errors ranging from ~2 to 5 m [8], were analyzed to obtain measurements of maximum relief for 5 lobate scarps (Fig. 1).

LOLA profiles were used to measure the relief of 21 scarp segments where the profiles traverse the scarps at near orthogonal angles (Fig. 2). Because of LRO's polar orbit, only principally E-W trending scarps with sufficient LOLA and NAC coverage were examined with LOLA topography. All available LOLA tracks along the length of each scarp were examined and the relief of the scarp was measured in each profile. For the scarps characterized with LOLA altimetry, we report only the greatest relief found for each scarp along its length. However it should be noted that this is not necessarily the maximum relief as the LOLA tracks do not provide continuous coverage along the entire length of each scarp.

Lengths were measured on 79 scarp segments. Where possible, scarp lengths were measured using NAC mosaics. In cases where the full extent of the scarp has not yet been covered by NAC imagery, a WAC 100 m global mosaic was used in combination with NAC imagery to estimate scarp lengths. Slopes were determined along the steepest section of the scarp face in profiles showing the greatest relief.

Results: The lobate scarps typically exhibit asymmetric profiles with relatively steeply sloping scarp faces and more gently sloping back scarps [1, 5, 10] (Fig. 1-2). They share similar basic morphological elements with lobate scarps observed on Mars, Mercury, and Eros. Maximum scarp-face slopes for the munar examples range from ~5°-29° (mean=13°; median=12°; n=26) [5] and are comparable to slopes reported for planetary lobate scarps (≤17°) [10-11] and Hinks Dorsum (~20°) on Eros [12].

Lengths of lobate scarp segments range from ~0.6-21.6 km (mean=6.0 km; median = 4.4 km; n=79) (Fig. 3) [5]. The longest scarp segments (>10 km, n = 11), with the exception of one, occur within 33° of the equator. The significance of this observation is not yet clear. Relief of the 26 lobate scarps analyzed with NAC DTMs and LOLA profiles ranges from ~5-150 m (mean=35 m; median=20 m) (Fig. 4) [5]. All but five of the scarps measured so far have a relief of <41 m. While the scarps with the largest relief (≥64 m; n = 5) are located near the equator (within 20°) and at very high latitudes (polewards of 84°), scarps with a relief up to ~20-30 m are observed at nearly all latitudes. Current data indicate that the lobate scarps as a whole typically exhibit tens of meters of relief and are tens of kilometers or less in length [5], consistent with previous estimates [1, 3]. Lunar lobate scarps are typically smaller than examples found on Mercury and Mars, some of which have reliefs >1 km and are up to 100s of kilometers in length [13-17], but are comparable to Hinks Dorsum on Eros with scarp segments ranging in relief from 25-60 m, and up to 18 km in length [12].

Using the relief (h) and a range of 20°-40° for the fault plane dip (θ), we estimate a range for the lower limit of horizontal shortening (S) expressed by the lobate scarp thrust faults by assuming it is a funtion of the relief of the scarp and the dip of the surface-breaking fault-plane ($S = h/\tan\,\theta$) [i.e. 10, 18-19]. Estimated lower limits for S range from ~10 to 410 m [5]. The horizontal shortening of individual lobate scarps is an expression of either the regional or global contractional strain. The range in S estimated for the lunar examples is thus consistent with a small amount of global contractional strain. Lunar lobate scarps are comparable in scale and *S* to Hinks Dorsum (~0.072-0.165 km) [12]. The origin of compressional stresses with sufficient magnitude to form thrust faults on Eros is still not well understood, but likely includes impact-induced compression [12, 20]. The lunar results are roughly an order of magnitude lower than estimates of *S* for planetary thrust faults (up to ~3-4 km), consistent with larger amounts of regional and global contractional strain associated with the scarps on Mars and Mercury respectively [10-11, 16-17, 19].

The frictional strength of the upper crust and megaregolith determines the stress necessary to initiate thrust faulting on the Moon. The minimum horizontal stress necessary to initiate faulting can be given by:

$$\Delta\sigma_{xx} = \frac{2f_s(\rho g z - p_w)}{(1 + f_s^2)^{1/2} - f_s}$$

where z is the depth of the fault, g is the acceleration due to gravity, ρ is the density of the crustal material, f_s is the coefficient of static friction, and p_w is the pore pressure which for the Moon, is set to zero [21]. Because of the comparable scale and horizontal shortening expressed by Hinks Dorsum, we use the modeled depth of these faults (~240 m) [12], to conservatively estimate a maximum depth of 1 km for the lunar scarps. Laboratory measurements on the maximum shear stress needed to initiate movement as a function of normal stress are best fit by a maximum coefficient of friction of 0.85 for thrust faults [21]. Assuming failure in the upper lunar crust is controlled by the frictional strength [21], we use lunar gravity of 1.63 m/s^2, an estimated megaregolith average density of 2700 kg/m^3, f_s = 0.85, and z =1 km to estimate an upper limit for the near-surface shear strength of the Moon of ~16 MPa. Assuming there is no significant unexpressed contractional strain, compressional stresses on the order of ~16 MPa would be needed to initiate thrust faulting on the Moon [5-6].

The relatively low relief and small amount of horizontal shortening estimated for the measured scarps is consistent with a small amount of global radial contraction. A low level of isotropic compressional stress due to a small amount of radial contraction is consistent with the low levels of compressional stress needed to initiate shallow-rooted thrust faults on the Moon.

References: [1] Watters T. R. and Johnson C. L. (2010) in *Planetary Tectonics*, Cambridge Univ. Press, 121, [2] Binder A. B. (1982) *Earth, Moon, and Planets*, 26, 117, [3] Binder A. B. and Gunga, H.-C. (1985) *Icarus*, 63, 421, [4] Schultz P.H. (1976) *Moon Morphology: Interpretations based on Lunar Orbiter Photography,* University of Texas Press, [5] Banks M. E. et al. (2011) *JGR* in press, [6] Watters T. R. et al. (2010) *Science*, 329, 936, [7] Robinson, M. S. et al. (2010) *Space Sci. Rev.*,150, 81, [8] Tran, T. et al. (2010) *ASPRS/CaGIS*, [9] Smith, D. E. et al. (2010) *Space Sci. Rev.*, 150, 209, [10] Watters T. R. and Robinson M. S. (1999) *JGR*, *104*, 18, 981, [11] Watters et al. (1998) *Geology*, 2, 991, [12] Watters et al. (2011) *Geophys. Res. Lett.*, 38, L02202, [13] Strom R. G. et al. (1975) *JGR*, 80, 2478, [14] Watters T. R. et al. (2009) *Earth Planet. Sci. Lett*., 285, 283, [15] Solomon S. C. et al. (2008) *Science*, 321, 59, [16] Watters T. R. and Nimmo F. (2010) in *Planetary Tectonics*, Cambridge Univ. Press, 15, [17] Watters T. R. (2003) *JGR*, 108, 5054, [18] Wojtal, S. F. (1996) *J. Struct. Geol*., 18, 265, [19] Watters et al. (2000) *Geophys. Res. Lett.*, 27, 22, 3659, [20] Richardson et al. (2004) *Science*, 306, 1526, [21] Turcotte, D. L. and G. Schubert (2002), *Geodynamics*, Cambridge University Press, 456.

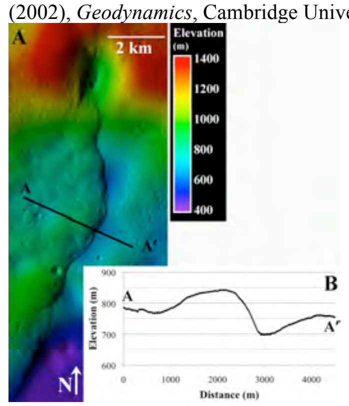

Figure 1: A) DTM from NAC stereo images of lobate scarp Racah X-1, the scarp with the largest relief measured to date. The black line marks the location of the profile. B) Profile across Racah X-1 derived from the NAC DTM.

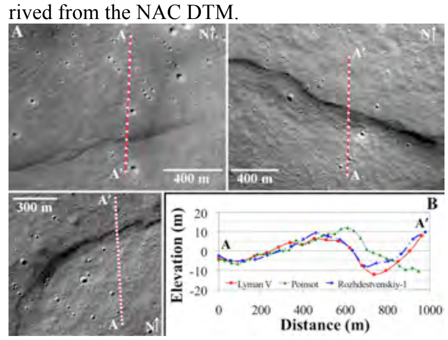

Figure 2: LOLA profiles of three high latitude lobate scarps newly identified in LROC imagery. A: The location of the LOLA track is indicated by a red line where it traverses each lobate scarp. White dots indicate individual data points. B: Detrended LOLA profiles.

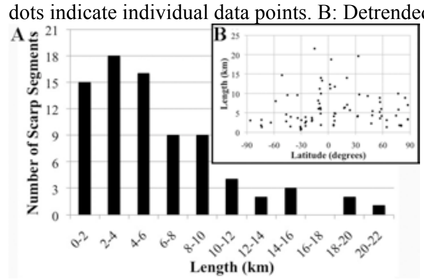

Figure 3: A) Histogram showing the distribution of lobate scarp length. B) Distribution of lobate scarp length by latitude.

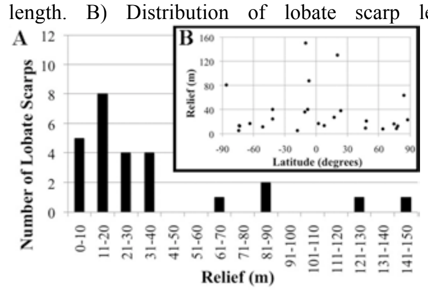

Figure 4: A) Histogram showing the distribution of measured lobate scarp relief. B) Distribution of lobate scarp relief by latitude.