SEISMIC ENERGY RELEASE FROM MOONQUAKES ON SMALL LUNAR LOBATE SCARPS. Amanda L. Nahm[1] and Aaron A. Velasco[1], [1]Department of Geological Sciences, University of Texas at El Paso, El Paso, TX 79968, alnahm@utep.edu and aavelasco@utep.edu.

Introduction: Lunar lobate scarps are small–scale surface–cutting thrust faults found primarily in the highlands. Recent work [1–3] using high–resolution Lunar Reconnaissance Orbiter (LRO) imagery has increased the number and distribution of known lobate scarps. Lobate scarps appear to be among the youngest endogenic features on the Moon [4–6]. Current age estimates of the lobate scarps range from 1 Ga [5] to less than 100 Ma [7].

The presence of these young, globally distributed lobate scarps suggests late–stage thermal cooling and contraction of the Moon [1, 2]. Their presence also implies recent seismic activity, but the possible sizes of the moonquakes responsible for the lobate scarp growth have not previously been determined. A catalog of locations and lengths of lobate scarps has recently been published [2]. Using these lobate scarps, we calculate the seismic moment and moment magnitude for each.

Data: Seventy–nine previously mapped lobate scarps were used in this study. The lengths, names, and locations of these scarps can be found in [2]. These scarps were identified and measured using LRO Wide Angle Camera (WAC) mosaics (resolution 100 m/px) and Narrow Angle Camera (NAC) images where available [2]. Lengths of these structures range from 0.6 to 21.6 km, with an average of 6.0 km [2].

Depth of faulting: The maximum depth of faulting calculated by [5] for the arcuate lobate scarps ranged from 0.7 to 3.5 km (N = 25), with an average value of 1.6 km. Estimates of the maximum depth of faulting of have been conservatively placed at 1 km for the lunar lobate scarps [2]. Thus, we adopt a range of values for the depth of faulting T of 0.5 to 4 km for all 79 lobate scarps used in this study.

Fault dip angle: Fault dip angles were determined by [5] by indirectly measuring the half angles of the arcuate scarps (N = 25), resulting in an average dip angle of 21.4 ± 0.5º. Based on their values, experimental results [8], and elastic dislocation models of thrust faults on terrestrial bodies, we assume a conservative range in thrust fault dip angle of 20º–40º.

Displacement: As the displacement along the thrust faults underlying the lobate scarps cannot be directly measured from images, displacement–length scaling is used in this study to calculate the possible amount of displacement for each of the 79 lobate scarps. The maximum displacement D has been shown to scale with the planimetric fault length L [*e.g.*, 9, 10]. The relationship between displacement and length is given by $D = \gamma L$, where γ is the displacement–length ratio. Recent work by [3] gives the value of γ as 2.6×10^{-2} to 1.7×10^{-2}, close to our chosen value of $\gamma = 10^{-2}$. We investigate a range in γ values between 10^{-1} and 10^{-3} to account for uncertainty associated with measuring the lengths and maximum relief of the small–scale lunar lobate scarps.

Seismic moment: One measure of the size of an earth– or moonquake is its seismic moment, M_0. It is calculated by multiplying the shear modulus of the ruptured rock G by the area of the ruptured portion of the fault A and the average displacement D produced during the quake [11, 12]. The shear modulus for anorthosite is 35 GPa [13]. Integrating D–L scaling with fault dimensions, the seismic moment M_0 is calculated by

$$M_0 = GAD = G(LH)(\gamma L)$$

where the down dip fault height, H, is $T/\sin\delta$. The seismic moment for a fault can also be described as the amount of deformation attributed to a fault given by the quasi–static fault moment, which is calculated using the same parameters [14]. The quasi–static fault moment, and by extension the seismic moment, represents the total energy consumed in producing fault displacements [14].

Energy: Although seismic moment has units of energy (erg ≡ $g \cdot cm^2/s^2$, 1 erg = 10^{-7} J), it is better thought of as the stress change over the portion of the fault that ruptured during the quake [12]. The amount of energy released during a quake is related to the seismic moment. The energy released in a quake E_0 of given seismic moment M_0 is instead $E_0 = M_0 / 2\times10^4$ [12].

Moment magnitude: Moment magnitude M_w is related to the seismic moment M_0 by [11]:

$$M_w = \frac{\log M_0}{1.5} - 10.73$$

The seismic moment and moment magnitude for maximum theoretical moonquakes for each lobate scarp were calculated assuming the entire present–day fault surface ruptured. Realistically, small portions of faults rupture at a time as opposed to the entire fault plane. Thus, the results of these calculations should be taken as maximum possible values.

Results: Selected results of the seismic moment, moment magnitude, and seismic energy release calculations are shown in Tables 1, 2, and 3, respectively. Results were chosen to display the range in values for each of the three γ values. Largest displacements are associated with the largest displacement–length ratio ($\gamma = 10^{-1}$) and thus, result in the highest values of M_0, M_w, and E_0.

In each case, minimum values are obtained for the combination of $\delta = 40°$ and $T = 0.5$ km and maximum values for $\delta = 20°$ and $T = 4$ km [Tables 1, 2, and 3]. Seismic moment, moment magnitude, and released energy increase with increasing depth of faulting (T), decrease for decreasing γ, and decrease with increasing fault dip angle, δ. Average M_0 ranges from 1.51×10^{24} to 2.27×10^{28} ergs, M_w ranges from 5.1 to 7.9, and E_0 ranges from 7.56×10^{13} to 1.14×10^{17} J [Tables 1, 2, and 3].

Table 1. Maximum, minimum, and average values of seismic moment in ergs for the given displacement–length ratios, fault dip angle, and depth of faulting for the 79 faults used in this study.

			Seismic moment M_0 (ergs)		
γ	**δ (º)**	**T (km)**	**min**	**max**	**average**
10^{-1}	40	0.5	1.12 x 10^{25}	1.27×10^{28}	1.51×10^{27}
	20	4	1.68×10^{26}	1.91×10^{29}	2.27×10^{28}
10^{-2}	40	0.5	1.1×10^{23}	1.27×10^{26}	1.51×10^{25}
	20	4	1.68×10^{24}	1.91×10^{27}	2.27×10^{26}
10^{-3}	40	0.5	1.12×10^{22}	1.27×10^{25}	1.51×10^{24}
	20	4	1.68×10^{23}	1.91×10^{26}	2.27×10^{25}

Table 2. Maximum, minimum, and average values of moment magnitude for the given displacement–length ratios, fault dip angle, and depth of faulting for the 79 faults used in this study.

			Moment magnitude M_w		
γ	**δ (º)**	**T (km)**	**min**	**max**	**average**
10^{-1}	40	0.5	6.0	8.0	7.1
	20	4	6.8	8.8	7.9
10^{-2}	40	0.5	4.6	6.7	5.8
	20	4	5.4	7.5	6.5
10^{-3}	40	0.5	4.0	6.0	5.1
	20	4	4.8	6.8	5.9

Table 3. Maximum, minimum, and average values of energy released in joules for the given displacement–length ratios, fault dip angle, and depth of faulting for the 79 faults used in this study.

			Energy released E_0 (J)		
γ	**δ (º)**	**T (km)**	**min**	**max**	**average**
10^{-1}	40	0.5	5.58×10^{13}	6.35×10^{16}	7.56×10^{15}
	20	4	8.38×10^{14}	9.55×10^{17}	1.14×10^{17}
10^{-2}	40	0.5	5.58×10^{12}	6.35×10^{15}	7.56×10^{14}
	20	4	8.38×10^{13}	9.55×10^{16}	1.14×10^{16}
10^{-3}	40	0.5	5.58×10^{11}	6.35×10^{14}	7.56×10^{13}
	20	4	8.38×10^{12}	9.55×10^{15}	1.14×10^{15}

Discussion and conclusions: For comparison, the Earth's two largest earthquakes since 1900, which occurred near Temuco, Chile in 1960 and Prince William Sound, Alaska in 1964, had seismic moments M_0 of 2×10^{30} and 8.2×10^{29} ergs, respectively [11]. The seismic moment for the devastating 1906 San Francisco earthquake was estimated to be 1×10^{28} ergs [11]. Moment magnitudes for these earthquakes have been calculated at 9.5 (Chile), 9.2 (Alaska), and 7.9 (San Francisco) [11].

Moonquakes detected by the Apollo seismometers can be divided into two groups: deep and shallow moonquakes [15–17]. The total seismic moment for deep moonquakes per year based on Apollo seismic data was calculated to be 1.6×10^{18} ergs and for shallow moonquakes to be 4×10^{21} ergs [18]. Assuming all the energy from these moonquakes each year was relieved in one moonquake, the equivalent moment magnitudes would be 3.7 for shallow moonquakes and 1.4 for deep moonquakes.

The largest theoretical maximum lobate scarp moonquake calculated here is on the order of the 1906 San Francisco earthquake, indicating that these relatively small structures could theoretically release a large amount of stored energy over the entire lunar globe. This suggests that potentially a high amount of accumulated stress was released through these quakes. This has implications for the seismic and thermal histories of the Moon as will be addressed by future work.

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