WHAT CAUSED THE LANDSLIDES IN VALLES MARINERIS, MARS? C. Akers[1], A. D. Schedl[1], L. Mundy[1] *(1) Physics Dept., West Virginia State University, Institute, WV 25112-1000 USA, schedlad@wvstateu.edu*

Introduction: In the 1970s images from Viking showed that Valles Marineris (Mars) contained many large landslides 100-6,000 km^2. Earthquakes, human activity and processes involving the long-term presence of liquid water (liquid precipitation, rivers undercutting of slopes, rapid sedimentation in oceans, etc.) initiate landslides on Earth [1]. Valles Marineris formed 3.5 billion years ago (Ga) and hence processes involving the long-term presence of liquid water can be ruled out. For earthquakes the release of seismic energy initiates landslides. As the seismic waves pass along the ground surface, the surface accelerates. This acceleration initiates landslides. Meteorite impacts also produce seismic waves and the critical ground acceleration for landslides. Tectonic activity initiates Earthquakes. Mars is considerably less tectonically active than Earth, so it is appealing to look at processes other than Mars-quakes to initiate landslides. In this study we investigate whether meteorite impacts initiated most of the landslides in Valles Marineris.

Methods: Valles Marineris provides a unique opportunity to investigate whether there is a relationship between meteorite impacts and landslides on Mars. Quantin et al. [2] dated landslides in Valles Marineris using isochron diagrams [3]. Bigot-Cormier and Montgomery [4] examined gradients of stable slopes and landslides to show that rocks in Valles Marineris could withstand ground accelerations up to 0.2 g_{Mars}. Using this latter maximum strength one can develop equations relating crater diameter to the radius of a region inside of which there is >50% probability of landslides or a radius of a region outside of which there is <5% probability of landslide. If a landslide and impact are likely to be linked they must have the same age and landslide must fall in the > 50% region. If the landslide and meteorite impact are different ages or the landslide falls in the <5% region a causal link is ruled out.

Using the program JMars® crater dimensions were measured and used to calculated binned average-areal-crater densities. These densities were then plotted on an isochron diagram [3] and a rough age of the large impact was determined. An age was also determined through regression using the program CratterStats [5]. A third dating method used a polynomial expression of Neukum [6] relating age to the area-normalized number of included craters ≥ 1 kilometer.

Equations Relating Impact Size to the Region Where Landslides Occur: Landslides on earth are a seismic hazard so considerable effort has been put into evaluating hazards in earthquake prone regions such as Los Angeles. Wilson and Keefer [7] developed equations for predicting the areal limits and probabilities of earthquake induced landslides for a particular size earthquake. These equations were modified to predict meteorite-impact-induced landslides. There equations involved earthquake magnitude, M, and the Arias intensity, which is defined as the integration over time of the acceleration squared. The following equation is the empirical relationship between Arias Intensity and critical ground acceleration, $\frac{\log(A_c) + 1.095}{0.79} = \log(I_A)$ where A_c = critical ground acceleration; I_A = Arias Intensity. Bigot-Cormier and Montgomery [4] examined gradients of stable slopes and landslides to show that rocks in Valles Marineris could withstand ground accelerations up to 0.2 g_{Mars}. Using this value of critical ground acceleration the Arias Intensity is $0.50 = \log(I_A)$. Plugging this value into the magnitude-distance-relationship: $\log(I_A) = -4.1 + M - 2\cdot\log(r) + 0.44\cdot P$ and setting $P = 0$ [7], where M = Moment Magnitude; r = Distance to landslide in kilometers; P = Probability in standard deviation from the mean, $P = 0$ is 50% probability of landslide and $R = 10^3 r$ is distance in meters.

$$0.50 = -4.1 + M - 2\cdot\log(R) + 2\cdot\log(10^3) + 0.44\cdot 0$$

$$M = -1.4 + 2\cdot\log(R)$$

Through the Gutenberg-Richter Equation the seismic energy of a particular magnitude earthquake, M, can be calculated.

$\log(W_s) = 4.8 + 1.5\cdot M$, where W_s = Seismic Energy; Now substitute for M and simplify

$$\log(W_s) = 4.8 + 1.5\cdot(-1.4 + 2\cdot\log(R))$$

$$\log(W_s) = 2.7 + 3\log(R)$$

$$W_s = s\cdot W_{im}$$

s = Seismic Efficiency; W_{im} = Meteorite Impact Energy Release. Seismic efficiency is the seismic energy released divided by the total energy for a given process (volcanic eruptions, meteorite impacts, earthquakes, etc.). The seismic efficiency for impacts ranges from 10^{-3} to 10^{-5} [8]

$$\log(s\cdot W_{im}) = 2.7 + 3\log(R)$$

$$\left(\frac{s\cdot W_{im}}{10^{2.7}}\right)^{1/3} = R$$

The above relation is applicable to the Earth, but we are interested in a relation that is applicable to Mars. The equation must be scaled with respect to the gravity of Mars relative to the Earth giving:

$$\frac{g_{Earth}}{g_{Mars}}\left(\frac{s\cdot W_{im}}{10^{2.7}}\right)^{1/3} = R$$

Relations giving the energy released during impact (W_{im}) are formulated using the transient crater diameter, D_{tc}, whereas what is observed in satellite images are the final crater diameters, D_c. Thus we need to recast energy equations using final crater diameter, i. e. the final crater diameter is specified and calculations start from there. McKinnon and Schenk's [9] equation gives values intermediate between other relations in the literature, so we will use their relationship. $D_c = \frac{1.17 D_{tc}^{1.13}}{D_{tr}^{0.13}}$, where D_{tr} is the transition diameter between simple and complex craters. On Mars the transition diameter is 6 kilometers [10,11]; so solving for D_{tc}: $D_{tc} = 1.08 D_c^{1/1.13}$

Using the energy relations for a vertical impact (Equation 7.8.4, [8]) and solving for R:

$$R = \frac{g_{Earth}}{g_{Mars}}\left[\frac{s}{10^{2.7}}\left(\rho_m^{-0.11}\rho_t^{1/3} g_{Mars}^{0.22} L^{-0.13} D_{tc} / 1.8\right)^{1/0.22}\right]^{1/3}$$

ρ_m = density of meteorite; ρ_t = density of target, Mars; g_{Mars} = gravitational acceleration of Mars; L = meteorite diameter; D_{tc} = transient crater diameter and R is the radius of the region that has a ≥50% probability of landslides.

Results & Conclusions: Most craters are older or the same age as Valles Marineris (3.5 Ga) and hence older than the landslides. This shows that the late heavy bombardment contributed most of the craters seen in visible light images. Only 3 craters met the distance and age requirements for possible producing landslides, crater 8, crater 14 and Oudemans. These impacts explain six landslides, 19, 29, 30, 41, 42 and 46 (Numbering system for landslides is from Quantin et al. [2]), of the 56 landslides in Valles Marineris, ≈10% (Figure 1). This suggests that Mars-quakes produced most of the landslides. The observation that faults cut across some landslides supports this interpretation.

References: [1] Wieczorek, G., (1996) *Spec. Report 247*, (A. K Turner and R. L. Schuster eds.) Nat. Acad. Press, 76-90. [2] Quantin, C. et al. (2004) *Icarus*, 172, 555–572. [3] Hartmann, W. K. and Neukum G. (2001) *Space Sci. Rev.*, 96, 65-194. [4] Bigot-Cormier, F. and Montgomery, D. R. (2007) *EPSL*, 260, 179-186. [5] Michael, G. G. and Neukum, G. (2010) *EPSL*, 294, 223-229. [6] Neukum G. (1983) Ph. D. Dissertation, Univ. of Munich, 186. [7] Wilson, R. C. and Keefer, D. K. (1985) *U. S. Geol. Surv. Prof. Paper*, 1360, 317-345. [8] Melosh H. J. (1989) *Impact Cratering: A Geologic Process.* Oxford University Press, 245. [9] McKinnon W. B. and Schenk P. M. (1985) *LPS XVI*. p. 544–545. [10] Pike, R. J. (1988) In: *Mercury* (F. Vilas, C. Chapman and M. Matthews, eds.), University of Arizona Press, 165-273. [11] Garvin, J. B, et al. (2000) *Icarus*, 144, 329-352.

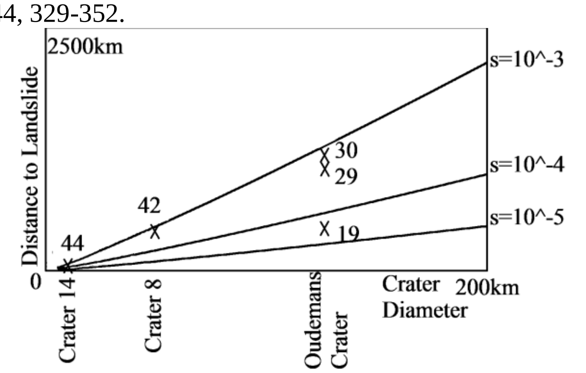

Figure 1: Shows craters and landslides that have similar isochron ages, and that have a >50% probability that the landslides are the result of the seismic energy released during impact. We examined more than just the name craters such as Oudemans. The crater numbers are based on the order in which we obtained isochron ages. The numbers by the X's on the graph are the landslide number following Quantin et al. [2] and they lie above the associated crater. The left vertical axis is the distance from the landslide to the center of the crater in kilometers and the horizontal axis is the crater diameter in kilometers. On the right axis are given the seismic efficiencies, s, (^ indicates exponent) for the associated lines indicating a 50% probability of landsides for a given impact diameter and distance from impact.