RHEOLOGICAL CONSTRAINTS ON MARTIAN LANDSLIDES. K. H. Harrison[1] and R. E. Grimm[1,2], [1]Laboratory for Atmospheric and Space Physics, University of Colorado, Campus Box 392, Boulder, Colorado 80309, keith.harrison@colorado.edu, [2]Blackhawk Geoservices, Inc., 301 B Commercial Rd., Golden, Colorado 80401, grimm@blackhawkgeo.com.

Introduction: Landslide features on Mars bear an unambiguous resemblance to terrestrial landslides and have been described in detail [2]. They occur mainly in the equatorial Valles Marineris (VM) canyon system, fall through heights of up to 8 km, and cover horizontal distances (runouts) as great as 80 km. The failed section of canyon wall is typically tens of kilometers wide and cuts several kilometers into the plateau behind it. Features resembling landslides also occur on the lower flanks of Olympus Mons, forming the Aureole deposits which are at least an order of magnitude larger than the VM slides, with runouts of hundreds of kilometers.

The largest VM landslides have features that are difficult to explain, such as longitudinal grooves, rather than transverse ridges like those observed on terrestrial slides. They also have unusually long runouts that imply lower internal friction angles than expected. Processes thought to produce long runouts generally require water [4, 5], air [6, 7], or the degassing of CO_2 [8]. Other processes, however, do not require a lubricating fluid, and include dispersive grain flow [9] in which the weight of the sliding material is supported by impacts between its constituent rock particles; and acoustic fluidization [10] in which an acoustic field is sufficient to support briefly the static overburden pressure of the material. Arguments have been given in support of both the presence [11] and absence [12] of fluid in the VM slides.

The rheology of landslide material is an important influence on its final configuration. Given a particular runout path and initial mass configuration, it is largely the rheology that determines key features such as runout length and final deposit thickness and slope. We present numerical models of long runout martian landslides with the aim of measuring the suitability of a range of rheologies.

Model: We use a dynamic analysis model (DAN) [13] which, given the runout path and initial mass profile, calculates the time-varying shape and velocity of the slide material. A Lagrangian approach is used which tracks individual mass blocks as they move together down the runout path. DAN represents the slide as a sequence of blocks (20 in our models) connected in the downslope direction. The width of the runout path is prespecified and where possible is matched to the observed scar configuration. The model is also made more accurate by the loss of material from the deposit along the final, level part of the runout slope. Quantities that vary normal to the runout path are represented by their average values. The gravitational force on each block works against a basal resistance force and a pressure force (which simulates the internal normal stresses at work in the slide). The basal resistance force at each point along the runout path is determined by the chosen rheology. Inputs common to all rheologies include unit weight (20 $kN.m^{-3}$ in all cases), volume yield rate (allows deposition or entrainment of material), and three pressure coefficients which determine the relative strength of tensional and compressive stresses in the material. Additional inputs depend on the rheology and include yield strength, pore pressure, viscosity, and friction angle (20° in all cases).

We consider four rheologies: frictional, Bingham, acoustic fluidization, and general fluidization. The latter two consist of an initial frictional stage, followed by a power law stage, while the others apply without interruption to the entire runout path. Acoustic fluidization assumes zero pore pressure and thus represents a more conservative approach to martian landsliding. When acoustic energy in the material reaches a critical value, the flow is fluidized. This energy is converted from potential energy during the initial (usually steepest) part of the runout path. For simplicity, we model this transition as a fixed point along the runout path, hence the designation of uphill points as frictional and downhill points as power law [14, 15]. The position of the transition was chosen to coincide with flow characteristics (such as maximum velocity) or structural features (such as abrupt changes in final profile slope). DAN models reveal an approximately linear relationship between the position of the threshold and the final runout. We note that our acoustic fluidization rheology has no explicit reference to acoustic properties and could feasibly cover other processes with similar behavior. Similarly, general fluidization also models processes with a frictional/power law transition, but allows non-zero pore pressure.

We apply the rheologies to DAN models of specific martian and terrestrial landslides, choosing parameters which result in a final configuration closest to that observed (we model one terrestrial slide, 6 VM slides, an Aureole deposit, and a lunar slide). Profiles of martian landslides are obtained from vertical cross-sections of MGS MOLA topographic data. Slide volume is measured (with the same data) relative to an assumed base level and together with landslide scar geometry is used to infer the initial mass profile. In some cases, runout paths can be approximated by cross-sections taken near the landslide. If not, they are based on the slope of the scarp embayment.

Results: The results for the eastmost Ophir Chasma landslide (Figure 1) demonstrate the different final profiles produced by the four rheologies. In this case, as in 7 of the 9 slides modeled, general fluidization produces a very good fit (Table 1). The Bingham and acoustic fluidization rheologies produced comparably good results for 1 and 2 of the 9 slides respectively. Although some slides generate favorable frictional profiles, required pore pressures are unreasonably high. No rheology produces satisfactory results for the Olympus Mons aureole, suggesting an alternate mode of emplacement such as gravity spreading [16].

A principal inference from the success of general fluidization in VM slides is the requirement of non-zero pore pressure. Given a reasonable contemporary geothermal gradient (15 K.km^{-1} or higher), water would be liquid below 2.5 km or less, putting the failure zone of many of the VM slides in the liquid phase (it is unlikely that friction during failure could melt sufficient volumes of ice to produce required liquid pore pressure). Alternatively, if the VM were filled with lakes [3,17] whose waters were released catastrophically via outflow channels, the water-saturated walls would be left exposed and depressurized leading to pore pressure-assisted failure. A third scenario invokes CO_2 as an alternative pressure agent. Degassing after the initial failure may be sufficient to break up the landslide material further and expedite its descent [8].

References: [1] Lucchitta B. K. (1977) *Icarus*, *30*, 80-90. [2] Lucchitta B. K. (1979) *JGR*, *84*, 8097-8113. [3] Lucchitta B. K. *et al.* (1994) *JGR*, *99*, 3783-3798. [4] Habib P. (1975) *Rock Mech.*, *7*, 193-197. [5] Goguel J. (1978) *Rockslides and Avalanches*, 693-705. [6] Kent P. E. (1966) *J. Geol.*, *74*, 79-83. [7] Shreve R. L. (1966) *Science*, *154*, 1639-1643. [8] Hoffman N. (2000) *Icarus*, *146*, 326-342. [9] Bagnold R. A. (1954) *Proc. Royal Soc. Lon.*, A, *225*, 49-63. [10] Melosh H. J. (1979) *JGR*, *84*, 7513-7520. [11] Lucchitta B. K. (1987) *Icarus*, *72*, 411-429. [12] McEwen A. S. (1989) *Geology*, *17*, 1111-1114. [13] Hungr O. (1995) *Can. Geotech.*, *32*, 610-623. [14] Melosh H. J. (1987) *Rev. Eng. Geol.*, *7*, 41-49. [15] Goetz P. and Melosh H. J. (1980) *Trans. AGU.*, *61*, 373. [16] Tanaka K. L. (1985) *Icarus*, *62*, 191-206. [17] Carr M. H. (1996) *Water on Mars*.

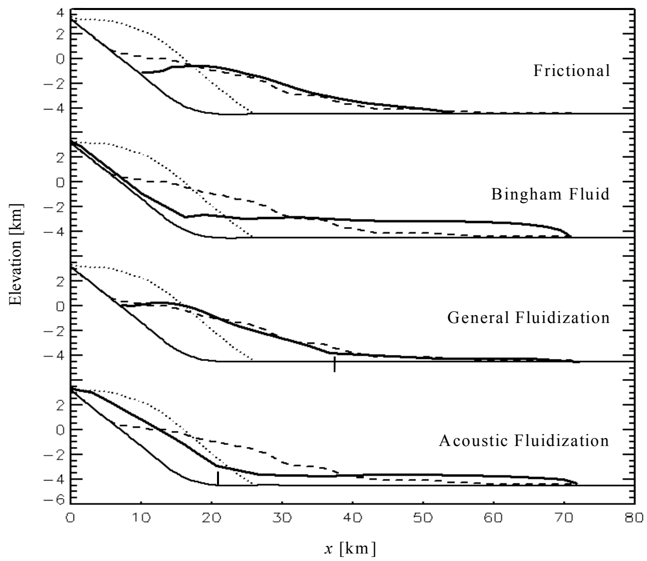

Figure 1 Final landslide configuration for the east most of the three Ophir Chasma landslides. Dashed line = actual final profile, dotted line = initial profile, light solid line = runout path, and heavy solid line = DAN's computed final profile. The short vertical lines indicate the transition from frictional to power law behavior.

Slide	Frictional	Bingham		General Fluidization			Acoustic Fluidization	
	r_u	τ_0 [kPa]	μ [kPa.s]	τ_0 [kPa]	μ [kPa.s]	r_u	τ_0 [kPa]	μ [kPa.s]
1. Blackhawk, California	0.65	24.5	10	13.5	5.0	0.31	-	-
2. Ophir Chasma	0.56	870	200	135	20	0.49	245	20
3. Ophir Chasma	0.47	790	50	49.5	10	0.35	157	20
4. Gangis Chasma	0.58	265	40	79.0	50	0.29	-	-
5. Gangis Chasma	0.58	75.0	20	21.8	5.0	0.00 (ϕ = 22.8°)	21.8*	5.0*
6. Coprates Chasma	0.71	170	40	65.5	10	0.48	-	-
7. Melas Chasma	0.58	525	200	145	50	0.41	146	50
8. Aureole	0.94	50.0	20	49.2	5.0	0.98	-	-
9. Apollo 17	0.41	0.50	0.30	1.8	0.50	0.00	1.8*	0.50*

Table 1 Summary of DAN results. r_u = ratio of fluid pressure to total normal stress, τ_0 = yield strength, and μ = viscosity. Rheologies other than general fluidization produced unequivocal best-fits for slides indicated by asterisks. The frictional phases of all slides had ϕ = 20°, except where indicated, and for acoustic fluidization r_u = 0 in all cases. Where no data for acoustic fluidization are given, this rheology did not cause the initial mass to fail.