Experimental Simulations of Dark Slope Streaks on Mars

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EXPERIMENTAL SIMULATIONS OF DARK SLOPE STREAKS ON MARS
EXPERIMENTAL SIMULATIONS OF DARK SLOPE STREAKS ON MARS

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Space and Planetary Sciences

By

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ABSTRACT

Martian slope streaks were first observed in Viking images but their formation still remains ambiguous. Martian slope streaks are currently occurring geological phenomenon on Mars, which requires any formation theory to be in agreement with Mar’s current temperature and pressure conditions. Planar morphology of martian slope streaks suggest a potential fluvial formation, but current conditions on Mars are not conducive to water remaining liquid long enough to erode the surface. Debris flows, fluid stains and dry dust avalanches have all been previously cited as a potential formation mechanism for martian slope streaks. Recent experimental simulations indicate that a fluvial source for martian slope streaks should again be evaluated as a potential formation mechanism. Using solutions of varying viscosities, martian slope streak characters were successfully replicated. Viscous fluids simulated would be analogous to liquid brines, which are likely to be found on Mars. Liquid brines may be stable long enough to erode the planet’s surface. Although numerical and theoretical simulations have been done, these are the first experimental simulations on martian slope streaks.
This thesis is approved for recommendation to the Graduate Council

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Chapter 1

Introduction

**Objectives**
Recent geological features on Mars have been likened to terrestrial features formed by liquid water (Malin and Edgett, 2000; Heldmann *et al.*, 2005, Mangold *et al.*, 2003, Coleman *et al.*, 2009). Potential fluvial features on Mars are a source of controversy as current conditions are not conducive to water remaining in the liquid state long enough to erode the surface. Adding salts to water increases the stability of the fluid, potentially long enough for the liquid to carve fluvial features on Mars (Fairen *et al.*, 2009; Chevrier *et al.*, 2009). The addition of salt, or sediment, to a fluid increases its viscosity. Viscosity can be used as an identifying characteristic in determining the type of fluid creating a hillslope failure, in both wet and dry flows (Pierson and Costa, 1987). The viscosity of various liquids is known and by identifying the viscosity of the fluid creating features on Mars, it may be possible to identify the nature of the fluids carving various martian fluvial features, such as martian gullies and slope streaks.

The objective of this study was to place constraints on the viscosity of a potential fluid creating martian slope streaks. It is possible that slope streaks and martian gullies are related so it was also an objective of this research to investigate potential links between the two of features. These objectives were accomplished by experimental simulations in a flume and analysis of images taken by satellites orbiting Mars.
Recent Mars orbiters

In 1976, the first Viking lander landed on the martian surface. The Viking orbiters had two slow-scan vidicon cameras on scanning platforms to take high resolution images of the martian surface (Carr, et al., 2004). For six years, the orbiters took images of the martian surface, totaling over 50,000 images, with much of their surface coverage at an 8x8m resolution (Carr, 1996). With each successive mission to Mars, the image resolution improves. Mars Global Surveyor (MGS) began its orbit around Mars in 1997. Onboard MGS are five scientific instruments, including the Mars Orbiter Laser Altimeter (MOLA) and the Mars Orbiter Camera (MOC).

The Mars Orbiter Camera (MOC) is a linear array push broom scanner. It consisted of three cameras, two wide angle cameras for low spatial resolution and one narrow angle camera. The narrow angle camera operates in the 500-900nm (Cantor, 2002); this camera was designed to image geological formations (Malin et al., 1991). The wide angle cameras were designed for global weather research (Malin et al., 1991); it operated in the red (580-620nm) and blue (400-440nm) wavelengths (Cantor, 2002).

In 2006, the Mars Reconnaissance Orbiter (MRO) was inserted into Mars orbit. It has six scientific instruments, including the High Resolution Imaging Science Experiment (HiRISE) camera. HiRISE camera operates in the near-infrared (800-1000nm), visible blue-green (400-600nm) and red (550-850nm) wave lengths (Delamere et al., 2003) HiRISE can take images with ground resolution up to 0.3m, the highest resolution of Mars’ surface to date (Li et al., 2011).
**Slope streaks**

Martian slope streaks were first observed in Viking images but their origin is still controversial. Although they form over a variety of geology and geography, all martian slope streaks share similar morphologies (Figure 1). Their morphology and some characteristics of slope streaks indicate a potential aqueous formation process (Schorghofer *et al.*, 2002; Kreslavsky and Head, 2009).

![Figure 1: Typical characteristics of martian slope streaks found on a knobby hill; slope streaks can also be found in other geographical locations and have the same characteristics. Although both dark and bright streaks are found on Mars, the dark slope streaks are far more common (HiRISE image PSP_002396_1900).](image-url)
Figure 2: This pair of images was taken only six years apart; the left image by MOC in 2001 and the right image by HiRISE in 2007. Multiple new streaks have formed in the intervening time, showing that martian slope streaks are currently active on Mars, which makes them some of the youngest geological features on the planet. This is an important factor in developing any model of formation for these features (HiRISE, 2010).

Slope streak formation is classified as an active geological process on the martian surface as new slope streaks were imaged on successive flybys where previously there were no slope streaks (Figure 2). By studying images containing slope streaks from across the surface of Mars, formation rates have been estimated at 0.03 (Schorghofer et al., 2007) and 0.07 (Aharonson et al., 2003) new slope streak formation per existing slope streak per martian year. Slope streaks imaged by Viking are still visible in MOC and HiRISE images, indicating that the fading rate of slopes streaks is significantly lower than their formation rate (Aharonson et al., 2003). Others
argue that it is not possible to determine the fading rate of slope streaks since the atmosphere opacity for the Viking images used is unknown (Baratoux et al., 2006); which leaves open the possibility that if a high opacity of the atmosphere existed during the imaging, not all slopes streaks present on the surface were imaged, leading to a biased fading rate. The formation of new martian slope streaks in the current Mars environment is an important constraint on martian slope streak formation theories.

### Characteristics

In general, slopes streaks are narrow, dark fan shaped features that emerge from a point source, slowly widen and then narrow to a lobate or digitate termination point. These features have little to no discernable topography associated with their formation and tend to preserve the macro textural patterns of the terrain they transverse. Compared to the adjacent terrain, slope streaks most often appear dark; although far less common than dark slope streaks, bright slope streaks do exist (Baratoux et al., 2006). Slope streaks lighten and fade over time, under the assumption that atmospheric dust is covering the features, allowing them to blend into the terrain once more (Sullivan et al., 2001). This assumption is based on images of darker streaks superposing lighter streaks (Figure 3).

While slope streaks share a general over all shape, there are some microscale features that differ between individual slope streaks and between groups of slope streaks (Miyamoto et al., 2004). The slight variations may be due to differences in the involved fluids, local geology and geography or formation processes. It is beyond the scope of this research to classify the
differences in slope streak morphology. Reported below are the similarities shared between the majority of martian slopes streaks.

Figure 3: When together, dark slope streaks superimpose bright slope streaks, indicating they are younger. Bright streaks are not found everywhere dark streaks are and there is no indication that dark streaks turn into bright streaks even though the dark streaks do lighten over time (HiRISE image ESP_012383_1905).
Geometry

Slope streaks have a distinctive linear shape and very sharp edges contrasting with their surroundings that allow them to be easily identified (Sullivan et al., 2001). Streaks tend to emerge from a point source, gradually widen downslope before narrowing again. Some slope streaks divide and form multiple lobate fronts while others are single lobate fronts.

Typical slope streak lengths range from 300m to 500m, though streaks as long as 2km have been noted as well as slope streaks as short as the camera’s resolution (Kreslavsky and Head, 2009). Slope streaks widths are typically less than 200m (Baratoux et al., 2006) and maximum widths are often achieved before the half length of the slope streak (Miyamoto et al., 2004).

Upslope section

Slope streaks initiate at relatively isolated areas with sites of local steepening, topographic highs or areas that are rough or knobby (Sullivan et al., 2001). No obvious connection to possible sources for the material contributing to slopes streaks, such as a dark eroded rock, can be resolved in images (Sullivan et al., 2001). In some images, slope streaks seem to emerge at contacts between rock layers but at other sites, there is no indication of a link between bedrock layers and slope streaks (Miyamoto et al., 2004). It has been difficult to determine quantitatively the terrain slope on which slope streaks form due to lack of data from MOLA profiles (Sullivan et al., 2001).

Data from Digital Elevation Models (DEMs) created from HiRISE stereo images has been used in other geomorphic processes on Mars but these models cover very little martian terrain and are
not easily created (Li et al., 2011). The complexity of the HiRISE images is such that no software is available to utilize the images without extensive processing (Li et al., 2011). The USGS developed ISIS, which can process HiRISE raw image in order to remove geometric distortions and imperfections (Li et al., 2011). The University of Arizona uses ISIS to create DEMs from stereo pair images. Scientists at the University of Arizona are working to create more DEMs from stereo images but the process is time consuming. Other groups (Li, et al. 2008; Kim and Muller, 2004) have reported on image processing procedures to create usable imagery from HiRISE stereo pair images. The description of these processes is beyond the scope of this paper.

**Midslope section**

Some streaks maintain a fairly constant width after emerging form the point of origin and others change with the changing terrain texture or slope (Miyamoto et al., 2004). Most slope streaks widen and then narrow, with the maximum width of the slope streak being achieved before the half way length (Miyamoto et al., 2004). If slope streaks encounter topographic irregularities, they often bifurcate and/or have anastomosing patterns, suggesting the balance between kinetic energy and friction is more complicated than the balance of a simple sliding plane (Miyamoto et al., 2004).

**Downslope section**

Most slope streaks end in a digitate termination point, with some having multiple digits. Other slope streaks widen and never narrow, such that their maximum width is found at their termination point and in these cases, the termination end is fan shaped (Miyamoto et al., 2004).
Unlike terrestrial mass movements, at the end of these features, there is no evidence of depositional debris (Sullivan et al., 2001).

**Texture**

Subtle textures have been observed inside the streaks that closely resemble those on the adjacent terrain (Figure 4), which gives martian slope streaks a slight variation in their morphologies as they flow over and around objects in their path. The branching and digitations of the slope streaks as well as the preservation of underlying textures indicate slope streaks are formed by a ground-hugging material with low kinetic energy that can easily be diverted around obstacles, follows depressions in the surface and effected by the local topography (Miyamoto et al., 2004). Interaction between slope streak and small scale features (meter to decameters) in the terrain is minimal (i.e. the slope streaks flow through them) while larger topographic obstacles (hectometers) divert the streaks (Kreslavsky and Head, 2009). The larger scale obstacles often represent changes in topographic gradient (Kreslavsky and Head, 2009). Slope streaks are highly sensitive to the local terrain. They flow around obstacles, indicating they are moving with insufficient momentum to carry them over objects (Figure 4).

**Topography**

Slope streaks are traditionally thought to exhibit no depositional or erosional features (Sullivan et al., 2001). HiRISE images analyzed show a few slope streaks to have a slight topographic relief of up to 1 m if viewed at a low sun angle and high resolution (Chuang et al., 2007). Although both authors note slope streaks in the images that appear to have topographic relief, not many
images did and not all slope streaks with in those images analyzed showed relief; these images were the exception to the rule.

Figure 4: An important characteristic of martian slope streaks is their lack of disturbance of the terrain they form on and their ability to form around objects. Although though all martian slope streaks have the basic same morphology, their lack of interfering with the terrain gives them a variety of textures and micro morphologies that can vary. In this image, there are multiple streaks that flow around obstacles and curved in their path. The inserts show a slope streak that has a boulder in the middle of the flow where the slope streak formed around the boulder, leaving an area on the lee side of the boulder unaffected by the fluid forming the slope streak (HiRISE image ESP_014394_2045).
Albedo

The identifying features of slope streaks are their sharp contrast in albedo from the regolith. Dark slope streaks have about 10% difference in albedo compared to the surrounding surface whereas the bright slope streaks have about 3% difference (Kreslavsky and Head, 2009). In images of slope streaks, the difference often appears to be greater but that is an artifact of the imaging process (Baratoux et al., 2006). Albedo within a specific feature rarely varies or reverses but both bright and dark slope streaks can be found in the same area (Figure 3). Bright slope streaks only form where dark streaks are but do not occur everywhere there are dark streaks (Sullivan et al., 2001). Bright streaks are not nearly as common as dark streaks but they do share similar characteristics to the dark streaks and are found in association with dark streaks. Although it is thought that dark streaks fade over time, there is no indication that dark streaks age to bright streaks or that bright streaks form as recently as dark streaks (Schorghofer et al., 2007).

Variability

Although slope streaks share a similar overall morphology, there does exist some variation in their morphology. The variations can often be linked back to the terrain the slope streaks form on. Many slope streaks with patterned features in the streak are preserving the pattern they flow over, giving them a feathery appearance. Some slope streaks have a high degree of bend in them, rather than traveling a straight path, due to the slope of the terrain or a large obstacle in their path. Slope streaks exhibit single and braided channels, most likely due to the presence or absence of obstacles. The maximum of slope streaks generally occurs before their halfway point (Sullivan et al., 2001) but the variation in the location of the maximum width may be due to the slope of the terrain or may be linked to fluids of different viscosities forming the slope streaks.
**Geology and geography**

Slope streaks are most often associated with knobby hills, caldera walls, and trough walls but can also be found on carter walls, pit craters, and isolated hill tops. They are not associated with a particular geological unit and can be seen to form from multiple layers with in the same image (Figure 5). It is generally accepted that slope streaks form on gentle slopes, often less steep than the angle of repose for sand sized particles (Sullivan et al., 2001), but it is difficult to determine quantitatively the terrain slope on which slope streaks form due to lack of data from the Mars Orbiter Laser Altimeter (MOLA) on board the Mars Global Surveyor (MGS); exact slope is calculated when a MOLA track passes over a study site (Schorghofer et al., 2007). A few profiles have been constructed and estimated slopes to be 10°-20° (Sullivan et al, 2001) and even up to 30° (Miyamoto et al., 2004).

Schorghofer et al. (2002) noted that out of 761 MOC images that contained slope streaks, the features tended to group in three low-latitude areas of low thermal inertia. No slope streaks were found in areas of high thermal inertia Schorghofer et al. (2002). Thermal inertia of a geological unit is a function of grain size and dust size particles have low thermal inertia (Christensen, 1986). Dark slope streaks form in areas associated with high albedo and low thermal inertia (Ferguson and Lucchitta (1984). Some areas of low thermal inertia in the Schorghofer et al. (2002) study do not have slope streaks but further analysis revealed these areas of low thermal inertia were also absent in rougher terrain and did not fall in the 275K temperature contour.
Figure 5: Martian slope streaks are not associated with a specific bedrock layer, but they do tend to initiate at rough surfaces that can be exposed bedrock layers. As shown here, many slope streaks initiate at the same layer but they are not restricted to those layers (HiRISE image PSP_004116_1935).

Others have confirmed that slope streaks occur in regions of low thermal inertia; typically 80-130 Jm\(^{-2}\)K\(^{-1}\)s\(^{-1/2}\) (Schorghofer \textit{et al.}, 2002). Thermal inertia of the terrain is dependant on thermal conductivity of the material and, on Mars, it is often associated with dust covered terrain (Christensen, 1986). This observation implies that slope streaks form in fine grained regolith (Sullivan \textit{et al.}, 2001). The low thermal inertia alters the stability of seasonal ground ice, allowing the ground ice to be present (rather than sublimate away) and to, therefore, seasonally flow when the ground temperature increases (Schorghofer \textit{et al.}, 2002).
It is interesting to note that the Gamma Ray and Neutron Spectrometers on Mars Odyssey have detected elevated hydrogen levels in the low thermal inertia areas where slope streaks are found (Miyamoto et al., 2004). Slope streaks are latitude confined and possibly follow surface temperature contours, specifically the 275K contour, indicating a potential involvement with a liquid source (Schorghofer et al., 2002). THEMIS images show slope streaks brighter, or thermally warmer, than the adjacent terrain (Schorghofer et al., 2007).

**Formation theories**

Although first identified in Viking images, there is not yet any agreement on the formation of martian slope streaks. Some support dry formation while others argue for a liquid component in the flow. The leading dry formation theory involves dust avalanches triggered by disturbance of the top layer of dust (Sullivan et al., 2001). Wet formation theories include: debris flows (Morris, 1982; Ferguson and Lucchitta, 1984), dark stains from upslope (Williams, 1991), spring discharge (Ferris et al., 2002) and run away percolation (Kreslavsky and Head, 2009).

**Dust avalanche**

Dust storms are continuously depositing material onto the martian surface in layers of varying thickness. In the dust avalanche theory (Sullivan et al., 2001), the terrain is composed of very fine grained material that accumulated on the slope surfaces made of coarser material. At some point the dusty slope fails and begins to flow. Dry granular material cannot initiate flow until the angle of repose for the material has been reached. The angle of repose for martian grains is unknown and it is likely variable with location due to the dependence on grain size, shape and roughness (Baratoux et al., 2006). Due to the low internal friction and fine grain size, Sullivan et
al. (2001) suggest the dust avalanche can trigger itself on slope angles less than that of the angle of repose for sand sized particles. Other triggering mechanisms include rock falls, mars quakes, the weight of the material and high winds. Wind patterns and slope streak orientation are high correlated, as are slope streak activity and dust deposition rates, suggesting that dust avalanches are controlled by local dust accumulation rates (Baratoux et al., 2006).

The upslope walls are often steeper than downslope and therefore offer more favorable triggering opportunities, which is consistent with the observation that slope streaks initiate on locally steeper terrain. When the dust accumulates on a steep slope surface, the dust layer may become unstable and collapse into a dust avalanche. Once started, the dust avalanche travels downslope on shear planes under its own weight, entraining dust from the surface (Sullivan et al., 2001). If the removed layer of dust is lighter in color or finer grained then the underlying layer, it may leave behind a dark streak on the surface, creating a dark slope streak (Williams, 1991 and Sullivan et al., 2001). Also, as it removes dust form the surface, it removes a source of material for future slope streaks, creating a situation that allows for parallel but not intersecting features.

Run away percolation

The run away percolation theory (Kreslvasky and Head, 2009) allows for a “wet” formation without a large quantity of liquid, which is consistent with present day Mars conditions. This theory assumes that the surface and subsurface soil contains solid brine in the pore spaces. As the seasonal temperatures change and the ground ice warms, the temperature will pass the eutectic temperature of brine ice and liquid brine will form. The liquid brine will begin to fill the pore spaces in the regolith. As the pore spaces fill with more brine droplets, the droplets will begin to
move down slope, infiltrating through the pore spaces. As the brine infiltrates, it encounters lower temperatures and refreezes in the pore spaces, creating an impermeable layer. This process repeats and the impermeable layer grows closer to the surface. Once it reaches a depth where the droplets do not refreeze on its surface, the droplets coalesce and grow. When the droplets have enough mass, they start to flow downslope and engulf other droplets, which continues their growth and downslope movement. This movement disturbs the overlying dust slowly and slope streaks are formed slowly. The dark albedo of the streak may be from the brine wicking to the surface, evaporating and leaving salts behind or from the dust layer being disturbed and leaving behind a coarser grained material (Kreslavsky and Head, 2009).

**Viscous fluid**

A viscous fluid would allow for a “wet” formation of martian slope streaks but would not require a high concentration of liquid water, like the run away percolation theory. Salts are present on the surface of Mars and can be incorporated into a liquid brine that is stable in a liquid form long enough to flow (Kreslavsky and Head, 2009, Chevrier and Altheide, 2008). The extent to which the salts are incorporated into liquid brine will have an effect on the brine concentration and therefore the viscosity of the liquid flowing (Chevrier et al., 2009). The present study examines the simulated formation of slope streaks using flows of different viscosities under standard temperature and pressures to investigate the potential role of viscosity on slope streak morphology.
In order to examine the morphologies of flow features created by fluids of varying viscosities, a set of simulations were undertaken in a geomorphology flume at standard temperatures and pressures at different slope angles. Fluids of different viscosities were created, using a thickening agent and water. The fluids were hand poured down a sand slope, creating flow features. The interactions between the fluid and the substrate were observed and the resulting features were systematically measured. In order to compare simulated slope streaks to martian slope streaks, HiRISE images were downloaded. ENVI software was used to analyze some of the images in order to make measurements for comparison to simulated slope streaks.

**Flume design**

Experimental simulations were run in a 3.0 m x 0.5 m x 0.25 m wooden flume (Figure 6). The frame of the flume was built using 2 in x 4 in boards; the bottom was constructed out of plywood and supported by 1 in x 3 in beams. A hinge connected the top $\frac{2}{3}$ of the flume to the bottom $\frac{1}{3}$ of the flume. An epoxy floor sealant was applied to the plywood flooring in order to prevent water damage to the wood.
Figure 6: The flume used to test hillslope failure processes was 3.0mx0.5mx0.25m. The top section is attached to a hinge (A) and can be propped up by the wooden boxes (B) in order for the flume to adjust to various angels. The PVC pipe (C) drains any fluid collected into a bucket below.

The flume was split into two sections; the top 2m are joined to the bottom 1m by a hinge. The hinge has two purposes: 1) to allow for easier adjustment of the flume angle to the ground and 2) if desired flows onto flat surfaces (i.e. crater floors) could be simulated. The hinge left a gap between the top and bottom sections and so the hinge area was covered in heavy plastic that was glued and then screwed onto the frame over the hinge. The plastic kept the substrate and liquid from escaping through the cracks and also protected the metal hinge from water damage.
Figure 7: The fluid delivery device is braced to a support that allows the exit tube to rest on the surface. The delivery device consists of: a funnel tapped to a support or stabilized by hand; the tubing attached to the funnel; a weight, or hand, is used to stabilize the end of tubing on substrate. Arrow indicates down slope direction.

In order for fluid to drain from the flume, a drain was inlaid in the bottom section of the flume (Figure 6). The drain, a 4cm diameter PVC pipe, was placed about 0.6m from the bottom of the flume so that it was flush with the surface of the plywood. A sheet of plywood was installed on either side of the drain and an angle towards the drain, facilitating any liquid to flow towards the drain. In order for the fluid to go into the PVC pipe, 0.25cm holes were drilled into the top section of the drain. The drain was 0.2m longer than the width of the flume, so that it stuck out through a hole drilled in the side of the flume frame. The end of the drain sticking out had a PVC
elbow attached to the end for the fluid to drain into a bucket on the floor. In order to easily increase the slope angle by $10^\circ$ increments, box frames, 0.35m high, were constructed out of 2inx4in timber (Figure 6). At more than $20^\circ$, the structure became unstable so L-braces were recommended for any angle greater than that.

The fluid delivery system (Figure 7) was attached to the top section of the flume with tape so that it could be easily removed between simulations for cleaning and data collection. It consisted of a flexible plastic tube with an inner diameter of 16cm attached to a funnel with an inner diameter of 125cm. It was positioned such that the tubing rested gently on the surface of the sand without leaving an imprint. The tubing was hand stabilized during the simulation.

**Natrosol preparation**

In order to produce fluids of various viscosities, a commercial thickening agent, Natrosol 250HHR, was used. It is a non-ionic water-soluble polymer available in a variety of forms. When mixed with water, it can produce solutions of varying viscosities and does not significantly alter the other properties of water, such as density (Hercules Incorporated, 1999). A 1L beaker was used to weigh out 247.5 g of de-ionized water. The beaker was placed on a magnetic stir plate and a 3cm magnetic stirring bar was added. The stirrer was set on the maximum setting that would not disrupt the stirring process (Figure 8).
The desired amount of Natrosol was measured out in a thin plastic weighing dish on a scale. The weighing dish was flexible so it could be folded for accurate pouring into the beaker of water. The powder was slowly added to one of the sides of the spinning vortex of water. As the powder dissolved, the solution began to thicken and the stir bar setting could be periodically increased to achieve maximum stirring in the minimal amount of time. In order to completely dissolve, the solution was covered with parafilm and left to stir for 4-8 hours, depending on the amount of Natrosol added. Once the solution was clear and free of particles, it was ready for use in the simulations.

Figure 8: To mix the Natrosol mixture, a magnetic stir plate and rod were used. Once the vortex of water was established, the powdered Natrosol was slowly poured on the side of the vortex. As the mixture thickened, the vortex top would retreat from the base of the beaker. When this happened, the stir speed would be increased. If the speed was too great, the vortex tip would hit the bottom of the beaker and the stirring was interrupted.
Simulations

The flume was filled with medium grain sized sand at a consistent thickness from top to bottom. Before each simulation, the sand was smoothed with a flat piece of lumber so there were minimum surface irregularities. The simulation and subsequent removal of the resulting slope streak feature left a mold which was re-filled with clean sand and then re-smoothed.

For each experiment, 100 mL of Natrosol solution was poured into a small beaker. The length of the flume limited the amount of fluid used in the experiments, as larger volumes of fluid would hit the flat portion of the flume. Three or four drops of food coloring were added in order to easily distinguish the fluid from the surface. The food coloring was stirred into the fluid using a magnetic stir bar just prior to the simulation.

A delivery device was secured to the top end of the flume and the tubing held in place with a wooden block or by hand to prevent movement (Figure 7). The Natrosol solution was poured into the funnel at a rate of approximately 3.85-4.55 ml/s. After the simulation was complete, the feature was photographed and then left to dry before measurement. For greater accuracy, the feature was allowed to dry before quantitative morphometric data was taken. After drying, the feature was removed, in pieces, from the flume for measurement using calipers.

Since the feature was commonly linear, measurements were taken at regular intervals (Figure 9). Every 5cm a width and depth measurement was taken and any additional features (i.e. levees,
large grain clusters) were recorded. Since the features were U-shaped to rectangular in cross section (Figure 9), the deepest part (nearly always in the middle) was measured as the section’s depth. If the feature was too crumbly to be removed, the calipers were driven into the dried feature and the depth measured in place after the width measurement was taken on the undisturbed surface. The levee form measurements were also recorded in this manner (Figure 9). Sometimes the levees were not exactly uniform on both sides or from top to bottom of the 5cm section. In these cases, it was noted which side the levee was more developed and an average of the widths and heights were taken.

Figure 9: The substrate was marked in 5cm sections so that measurements of the features could be taken as regular intervals. Insert: The 5cm sections of the feature can be taken out of the flume (insert), especially for difficult measurements such as depth and levees. Arrow indicates down slope direction.
For low viscosity simulations, the form features measured also included length, width and depth of the alcove, channel and apron. Length measurements of each section were taken as well as the total length of the feature (Figure 10). The widths of the top and bottom of each section were measured as well as the maximum widths. Depth measurements were also taken at the top and bottom of each of the three sections; the area of maximum depth was estimated and its measurement also recorded.

Figure 10: In the low viscosity simulations, in addition to measurements at regular intervals, the length, width and depth of produced features were also recorded. The alcove and channel sections required measurements of depths where as the apron required height measurements. Arrow indicates down slope direction.
At the higher viscosities, the solution moved at slow enough rates to calculate an average fluid velocity. Experimental simulations had an expected approximate total length. Slightly less than half that estimated distance down the slope, markers were placed about 8cm apart. The time it took the front of the feature to pass between the markers was recorded. The exact distance between the markers was also recorded. The velocity of the frontal lobe about half way down the slope could then be calculated. This was recorded for comparison between simulations.

**Determining viscosity**

Since the solution decreases in viscosity over time, viscosity determination occurred immediately after the simulation was completed to avoid discrepancies between the viscosity recorded and that of the fluid during the simulation. A Gilmont falling ball viscometer was used to measure the viscosity of each solution used during the simulations. Approximately 10 mL of solution, and then the drop ball, was added to a Gilmont viscometer tube and then the tube was sealed off with the capping attachment. The appropriate size and ball type were determined by the relative estimated viscosities and the viscosity range provided by the company. The glass tube has a red line marker at the top and bottom and the time the ball takes to fall between the two lines was recorded (Figure 11).

The fall time of the ball was recorded at least 7 times for all solutions in order to achieve consistent results. The greater the variance between recorded times, the more often it was
repeated. The Gilmont viscometer allowed for the calculation of viscosity in centipoises (cP) based on the tube size used and the type of ball dropped (glass or steel) ball fall time (equation 2.1). The larger tube and the denser object were used for the most viscous solutions.

Figure 11: The Gilmont ball drop viscometer used to test the viscosity of the fluid that created the simulated slope streaks (Roger Gilmont Instruments, Inc).
\[ \mu = k(D_B - D_S) t \]  
\( \mu \) = viscosity in cP  
\( t \) = time in seconds  
\( k \) = constant provided by the Gilmont company; there is a different constant for each tube size (Roger Gilmont Instruments, Inc).  
\( k_2 = 3.3 \)  
\( k_3 = 35 \)  

\( D_B \) = density of the ball  
\( D_S \) = density of the solution = 1 g/ml  
Density of glass ball = 2.53 g/ml  
Density of steel ball = 8.02 g/ml  

Viscosity values are more commonly reported on using Pa s, so values from equation 2.1 are converted to Pa s by dividing by 1000.

**Environment for Visualizing Images (ENVI)**

In order to compare parameters from simulated slope streaks to martian slope streaks, image analysis software Environment for Visualizing Image (ENVI) was used. From the HiRISE
website, images that contain slope streaks were obtained. Using the measurement tool in ENVI, the total length and maximum width of a variety of slope streaks in the images were measured. The total length measurement began at the point of origin for the slope streak. Measurements went through the middle of the slope streak, from tip to end, curving the measurement as the slope streak curved, as not all slope streaks followed a straight path. The maximum width of the slope streak was measured at the slope streak’s widest point, which sometimes was at the end of the slope streak. In each image, many slope streaks exist and 10-20 slope streaks of various scale and morphology were measured in order to get a representative sample of the image. The total length to maximum width (L:W) ratio was calculated in order to compare to the simulated slope streaks that were produced at a different scale. The L:W ratios were also compared to those found in the literature.
Chapter 3

Results

Low viscosity fluids produced features distinctly different from the medium and high viscosity fluids. The low viscosity fluids created forms which resembled martian gullies with distinct alcoves, channels and aprons (i.e. erosional and depositional features) while the medium and high viscosity fluids produced more linear features that had minimal to no erosion or deposition, resembling martian slope streaks. Results for each of the three viscosity ranges are presented in the following sections; each section reports on morphology and effects of slope on form. Using the T-test, differences between simulations run at low (10°) and high (20°) slopes using the same viscosity were not statistically significant. Differences between the viscosity ranges, on the other hand, were statistically significant between each viscosity type.

**Low viscosity (0.001-0.004 Pa s)**

Slope streaks produced by fluids of viscosities ranging from 0.001-0.004 Pa s displayed distinctive erosive and depositional features. These viscosities produced flow features with discernible alcove, channel and apron. The top of alcove was measured where the substrate began to be removed from the surface. It had distinct sides and bottom edge that were marked by steep slopes. The alcove ended where it emptied into the channel. The channel began where there was a distinct change in shape of the depression in the substrate as well as the depth of the erosion; compared to the alcove, the channel had gentler sides, was shallower and had a more linear shape. The end of the channel was often difficult to determine but the channel ended
where the apron began. The inflection point between channel and apron was where there was immeasurable depth (erosion from the channel) or height (deposition onto the apron). The apron was defined as the area where there was deposition that could be measured. It had a distinct termination point as well as sides. Sometimes the channel or apron split and formed multiple channels and digitate apron. For these simulations, the average of the main branch was used for determining the average value reported on. Average values at 10° and 20° for low viscosity simulations are listed in Table 1.

Low slope-10°
The overall form of the low viscosity features formed at low slope was long and narrow with straight sides and a digitate termination (Figure 12). The average total length of the features was 29.65cm. Alcoves were tear-dropped shaped. The average alcove width was 3.54cm with an average depth of 0.57cm and an average length of 4.08cm. The channels had average widths of 2.83cm, average depths of 0.06cm, and average lengths of 6.77cm. Although levees were present on an average of 35% of the channel length, they were too weakly developed and incohesive to measure the width and heights accurately; on average, the levees were 2-3 sand grains wide and high. The aprons were digitate shaped and averaged 3.49cm in width, 0.23cm in depth, and 22.03cm long. Data obtained for each experimental run is presented in Appendix A.

High slope-20°
Overall, the higher slope simulations at low viscosities produced longer streaks than their counterparts at low slopes, as would be expected (Figure 13). The average total length of these simulated streaks was 82.81cm. Alcoves were elongated, tear dropped shaped with their widest
point at their distal ends where they emptied into the top of the channel. The average alcove width was 1.12cm; the average alcove depth was 0.17; and the average length was 5.07cm. The channels had an average width of 1.85cm, an average depth of 0.13cm, and an average length of

Table 1: Average values for measured parameter of simulated slope streaks using low viscosity fluid.

<table>
<thead>
<tr>
<th></th>
<th>10°</th>
<th>20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average total length, cm</td>
<td>29.65</td>
<td>82.81</td>
</tr>
<tr>
<td>Average alcove length, cm</td>
<td>4.08</td>
<td>5.07</td>
</tr>
<tr>
<td>Average alcove width, cm</td>
<td>3.54</td>
<td>1.12</td>
</tr>
<tr>
<td>Average alcove depth, cm</td>
<td>0.57</td>
<td>0.17</td>
</tr>
<tr>
<td>Average channel length, cm</td>
<td>6.77</td>
<td>37.13</td>
</tr>
<tr>
<td>Average channel width, cm</td>
<td>2.83</td>
<td>1.85</td>
</tr>
<tr>
<td>Average channel depth, cm</td>
<td>0.06</td>
<td>0.13</td>
</tr>
<tr>
<td>Average apron length, cm</td>
<td>22.03</td>
<td>40.57</td>
</tr>
<tr>
<td>Average apron width, cm</td>
<td>3.49</td>
<td>1.64</td>
</tr>
<tr>
<td>Average apron height, cm</td>
<td>0.23</td>
<td>0.17</td>
</tr>
<tr>
<td>Average levee width, cm</td>
<td>0</td>
<td>0.29</td>
</tr>
<tr>
<td>Average levee height, cm</td>
<td>0</td>
<td>0.15</td>
</tr>
<tr>
<td>Number of simulations</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>
Figure 12: A representative image of simulated flow features produced at low viscosity and low slope. The erosive section, the alcove, is wider at the bottom than top. Where the alcove empties into the channel is also the widest part of the erosive channel. The apron, the depositional section, is split into two digits and the right most has multiple layers of digits. Arrow indicates down slope direction.

Figure 13: A representative image of simulated flow features produced at low viscosity and high slope. All three sections are more elongated than the lower slope features and the apron has morphology more resembling the medium and high viscosity termination ends. Arrow indicates down slope direction.
37.13cm. Two of the channels developed a single shallow curve while two channels developed two shallow curves. Levees formed on three of the channels but were present on about 20% of each of those channels. On average, the levees were 0.15cm high and 0.29cm wide. Aprons were long and thin with a tongue shaped end. The average apron length was 40.57cm, average width was 1.64cm and average height was 0.17cm. Measurement data for each experimental run is presented in Appendix A.

**Medium viscosity (0.005-0.075 Pa s)**

Slope streaks produced by fluids with viscosities ranging from 0.005-0.075 Pa s showed little evidence of erosion occurring. Medium viscosity fluids traveled down slope with a tear drop shaped frontal lobe (Figure 14) followed by a long and narrow tail. Planar shapes of simulated features produced by fluids of medium viscosities were fairly linear and flat, with a wider upper section that narrowed down slope. The medium viscosity simulations did produce sand grain sized depositions, “levees,” that were generally wider than high. Average values at 10° and 20° are listed in Table 2.

**Low slope- 10°**

Although some sand entrainment was associated with medium viscosity fluids traveling down a low sloped terrain, the planar shape of the simulated slope streak and the erosional/deposition features greatly differed from the low viscosity simulations (Figure 15). The average total length of medium viscosity, low slope simulations was 126.16cm. The average width of the simulated
Figure 14: The cross section view of the frontal lobe of a medium viscosity fluid traveling down a low sloped terrain. Sand grains can be seen on the edges of the flow but not in the frontal lobe. Although the fluid has height to it, the resulting feature does not. After the frontal lobe passes, the fluid that has stopped moving infiltrated down into the substrate. Arrow indicates down slope direction.

Table 2: Average values for measured parameters of simulated slope streaks using medium viscosity fluid.

<table>
<thead>
<tr>
<th>Medium viscosity simulations</th>
<th>10°</th>
<th>20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average total length, cm</td>
<td>126.16</td>
<td>139.02</td>
</tr>
<tr>
<td>Average width, cm</td>
<td>3.03</td>
<td>3.09</td>
</tr>
<tr>
<td>Average maximum width, cm</td>
<td>4.11</td>
<td>4.36</td>
</tr>
<tr>
<td>Average depth, cm</td>
<td>0.89</td>
<td>0.91</td>
</tr>
<tr>
<td>Average &quot;levee&quot; width, cm</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Average &quot;levee&quot; height, cm</td>
<td>0.09</td>
<td>0.89</td>
</tr>
<tr>
<td>Number of simulations</td>
<td>10</td>
<td>6</td>
</tr>
</tbody>
</table>
streaks was 3.03cm. The average maximum width of the simulated streak was 4.11cm. The maximum width was reached 5-10cm below the point of origin. The average depth of the simulated streaks was 0.89cm. Measurable topography on the edges resembled levees and averaged 0.18cm wide and 0.09cm in height. Levees formed on all 10 simulations but did not form along the entire length of the simulations. On average, levees formed on 69.03% of the simulated streak length. Measurement data obtained for experimental runs is presented in Appendix B.

**High slope-20°**

At higher slopes, the features associated with medium viscosities were similar to those at the low slope but, predictably, were longer (Figure 16). The average total length of medium viscosity, high slope simulations was 139.02cm. The average width of the simulated streaks was 3.09cm. The average maximum width of the simulated streaks was 4.36cm. The maximum width of the simulations was reached 5-10cm below the point of origin. The average depth was 0.91cm. Measurable topography included levees that averaged 0.18cm in width and 0.89cm in height. Levees formed on 5 out of 6 simulations. Again, the levees that formed did not extend the entire length of any of the simulations. On average, levees formed on 54.74% of the simulated streak length. Measurement data obtained for each experimental run is presented in Appendix B.

**High viscosity (0.075-1.2 Pa s)**

Fluids ranging from 0.075-1.2 Pa s moved with the same shaped frontal lobe as the medium viscosity fluids (Figure 14). Simulated streaks produced at these viscosities also resembled the
Figure 15: A representative image of simulated slope streaks produced at medium viscosity and low slope. The flow feature is very different than that of the low viscosity simulations. It has only one section that is very linear. Arrow indicates down slope direction.

Figure 16: A representative image of simulated slope streaks produced at medium viscosity and high slope. Except length, these features are very similar to the same viscosity at low slope. Arrow indicates down slope direction.
planar shape of those produced by medium viscosity fluids. Even though sand particles were removed from the interface between the fluid and substrate, no measurable levees on the simulated streaks were produced; instead a mini depression/ridge was observed at the edges produced from the sand grains at the interface between the fluid and sand being picked up (depression) and then deposited (ridge) just on the fluid side of interface boundary (Figure 17). The fluid moved slowly enough at high viscosities for the average fluid velocity to be measured. Average values for $10^\circ$ and $20^\circ$ are listed in Table 3.

Table 3: Average values for measured parameters of simulated slope streaks using high viscosity fluid.

<table>
<thead>
<tr>
<th>High viscosity simulations</th>
<th>10$^\circ$</th>
<th>20$^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average total length, cm</td>
<td>89.19</td>
<td>99.03</td>
</tr>
<tr>
<td>Average width, cm</td>
<td>4.88</td>
<td>3.65</td>
</tr>
<tr>
<td>Average maximum width, cm</td>
<td>8.18</td>
<td>6.85</td>
</tr>
<tr>
<td>Average depth, cm</td>
<td>0.71</td>
<td>0.78</td>
</tr>
<tr>
<td>Number of simulations</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

*Low slope-10$^\circ$*

Simulated streaks produced by high viscosity at low slope shared very similar shape to that of the medium viscosity (Figure 18). The average total length of high viscosity, low slope simulations was 89.19cm. The average width of was 4.88cm and the average maximum width was 8.18cm.
Figure 17: Cross section sketch of the difference between the levee system (top) and the “depression and ridge” system (bottom). The levee system excavates material as the fluid flows down slope and deposits the material as the flow loses energy. In the “depression and ridge” system, the fluid “grabs” a sand grain from the interface between the fluid and the sand, transports it slightly inward to the other side of the interface and deposits it along the edge as a single grain high ridge.

The maximum width was reached 0-5cm below the point of origin. The average depth was 0.71cm. Although there were depressions and ridges on all simulated streaks, they were not large enough to measure; only 1-2 grains in depth, width and height. During the simulation, the fluid moved slowly enough to be measured at an average rate of 0.13cm/s. Measurement data obtained for experimental runs is presented in Appendix C.
Figure 18: A representative image of simulated slope streaks produced at high viscosity and low slope. The upper most section of these streaks are the most noticeably different than the medium viscosity simulations, but generally share the same morphology as the medium viscosity simulated slope streaks. Arrow indicates down slope direction.

Figure 19: A representative image of simulated slope streaks produced at high viscosity and high slope. Arrow indicates down slope direction.
High slope-20°

Simulated streaks developed at 20° slope using high viscosity fluids were very similar to those that developed at lower slopes (Figure 19). The average total length of the streaks was 99.03cm and the average width was 3.65cm. The average maximum width of the simulated streaks was 6.85cm. The maximum width of the simulated streaks was reached 0-5cm down slope of the point of origin. The average depth measured was 0.78cm. The depression/ridge system, again, was present but not measurable. During the simulation, the fluid moved at an average rate of 0.39cm/s. Measurement data obtained for each experimental run is presented in Appendix C.

Length to Width (L:W) ratio

Simulated slope streaks measured on the meter scale whereas martian slope streaks on km scale. By calculating the total length to maximum width (L:W) ratio, the sets of data at different scales could be compared. Since simulated and martian slope streaks have similar linear morphology, the L:W ratio gives an estimate of the difference in the shape since a direct comparison is not appropriate. L:W ratio values are listed in Table 4.
Table 4: Average L:W ratios of simulated and martian slope streaks

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sullivan et al., 2001</td>
<td>5-30</td>
<td>NA</td>
</tr>
<tr>
<td>HiRISE, this study</td>
<td>7.45-35.33</td>
<td>15.92</td>
</tr>
<tr>
<td>Low viscosity/10° slope</td>
<td>36.14-49.88</td>
<td>44.98</td>
</tr>
<tr>
<td>Low viscosity/20° slope</td>
<td>7.21-8.59</td>
<td>7.91</td>
</tr>
<tr>
<td>Medium viscosity/10° slope</td>
<td>11.91-66.41</td>
<td>38.83</td>
</tr>
<tr>
<td>Medium viscosity/20° slope</td>
<td>11.89-56.17</td>
<td>35.86</td>
</tr>
<tr>
<td>High viscosity/10° slope</td>
<td>5.87-30.23</td>
<td>13.38</td>
</tr>
<tr>
<td>High viscosity/20° slope</td>
<td>8.73-18.09</td>
<td>14.94</td>
</tr>
</tbody>
</table>
Given the same experimental conditions, the simulated slope streaks exhibited very consistent morphologies. If viscosity or substrate were slightly different, the morphology and measurements were less consistent, as would be expected. Martian slope streaks are also very similar to one another in morphology. There are differences in textures (caused by the terrain), lengths, width, where maximum width is reached and termination lobes. It logically follows that either the terrain or the fluids viscosities vary in those situations. The slope streaks that form in one location (i.e. the terrain is similar) have streaks that closely resemble each other with only minor differences. In this case, it is likely that the viscosity of the fluid forming them is slightly different. Differences in viscosity can be caused by temperatures (i.e. different times of the year), salt/sediment concentration or amount of fluid. When comparing different locations, the slope streak morphology varies slightly more, which can be a function of the terrain or the fluid viscosities. There are some slope streaks that are more triangular in shape or have their widest points at the termination lobe. These slope streaks may more closely resemble a dry flow instead of a wet, viscous flow (Gerstell et al., 2004; Hugenholtz, 2008). Like other martian features as well as terrestrial features, there exists a spectrum of sources for the formation of a broad category of flow features.
Figure 20: Low viscosity simulations result in features that resemble martian gullies (left). Simulations at lower slopes resulted in termination aprons of a multiple aprons (right) where as the higher slopes produced features with single and straight termination lobes (right).

**Features produced at low viscosities**

Fluids between 0.001 Pa s and 0.004 Pa s were erosive in nature, carving a path in the sand substrate. When the fluids lost the available energy, the sand entrained in the fluid was deposited as aprons and levees. Simulations run at both slope angles produced features with three distinct sections (alcove, channel and apron); however, simulations at low slope produced features that most distinctly resembled martian gullies (Figure 20). Due to previous experimental work (Coleman *et al.*, 2009; Rivera-Valentin *et al.*, 2008; Benison *et al.*, 2008), it was expected that the low viscosity simulations would produce flow features that resembled martian gullies.
Examples of low viscosity fluids include water, low sediment concentration debris and slush flows and low concentration brines (Pierson and Costa, 1987 and Chevrier et al., 2009).

**Alcove**

As the low viscosity fluid left the tubing, it eroded into the substrate and created an alcove feature. The alcove was formed by the action of the water leaving the tube and eroding the surface. As the water poured from the tube to the substrate, it cut a tear dropped shaped alcove. The depth of the alcove was favorable for the water to pool until it filled the alcove and breeched the widest part of the alcove, which was located at the furthest down slope section. At times, there was some undercutting of the alcove ledge, which left the tubing protruding slightly into the alcove. When this happened, an increase in alcove depth was observed and the alcove shape became less tear drop and more rounded. As undercutting progressed, the alcove became more elongated due to the backward erosion. The erosion was a function of the velocity of the fluid and the loose packing of the sand and might be envisioned to be similar to a melt water spring emerging into unconsolidated regolith. During and after the fluid was active in the simulation, there was some infilling from the alcove wall into the bottom of the alcove; this occurred at both slopes. Infilling is also observed in martian gully alcoves (Malin and Edgett, 2000).

Although alcoves of both high and low slopes formed roughly tear dropped shapes, the higher slopes did form more elongated alcoves due to the greater energy available for erosion. Simulated flow features with elongated alcoves most closely match the alcoves from martian gullies (Malin and Edgett, 2000), but due to the range of simulated alcove shapes and lack of consistent reproduction of those shapes, the alcove section appears to be the least useful.
morphological feature to assist in determining the viscosity of fluids creating flow features on Mars.

**Channel**

During the simulation, when the fluid breeched the alcove lip, it spilled over the lip and gained energy to erode the substrate and create a channel. As the fluid overfilled the channel, it lost energy and deposited levees on the sides. This occurred at both low and high slopes but was more pronounced at low slopes. The levees in the low slope simulations were obstructive enough to slightly divert the flow sideways. After the levee deposition, the fluid no longer had the energy to flow over the raised area and so was diverted slightly around it, creating slightly sinuous channels. At the higher slope simulations, this also occurred but to a lesser degree, resulting in straighter channels. Both straight and sinuous channels are seen in martian gullies (Malin and Edgett, 2000; Costard et al., 2002). With knowledge of the slope that martian gullies form on and identifying the sinuosity, it is possible that, with more research in the low viscosity fluid range, the combination may be useful to narrow the viscosity range of fluids that create martian gullies.

**Apron**

During the low slope simulations, the low viscosity fluid was carried down slope at a slightly slower rate than the higher slope resulting in slightly less available energy. This resulted in deposition of the entrained particles at a shorter distance down slope when compared to the high slope simulations. The simulation was not complete when the fluid began to deposit material as there was still fluid flowing from the delivery system. If the fluid had sufficient energy to continue traveling down slope but could not breech the initial apron, it diverted sideways. This
diversion created a new path for the fluid to follow. While the fluid still had energy to erode in this new path, another channel was formed. Eventually the fluid would lose the energy needed to carry the sand it entrained and would create a new apron. The number of times the fluid was diverted was reflected in the number of fingers in the digitate apron.

During the high slope simulations, a single linear apron generally formed. As the fluid source ran out (or on Mars, dried up or froze), the flow lost energy and began to deposit material into the channel it had created and back fill the channel, creating a single linear apron. Although there are martian gullies that have linear, single digit aprons, the more common aprons have a greater range of morphologies (Malin and Edgett, 2000). The aprons created by low viscosity and high slopes produced planar shapes more resembling martian slope streaks than gullies (Sullivan et al., 2001). One important difference between martian slope streaks ends and the low viscosity, high slope simulations aprons is the presence of discernable relief. The simulated features had ends with measurable height while martian slope streaks do not produce depositional features.

Simulated features at low viscosity and low slope are distinctly gully-like features. Those at high slope simulated features with a combination of gully and slope streak features. The combination of morphologies may point to a potential link between slope streak and gully formation. Slope streaks and gullies form in very similar locations and HiRISE images show some potential links between the two (Figure 21). Data from this study suggests that the lower slopes create gully-like features while the higher slopes create slope streak like features; if the same fluid that produces a slope streak at a high slope were to emerge onto the surface at a lower slope, a gully may form.
instead. Although suggestive of a link, again, further research is needed in this viscosity range to better determine if the features created are a function of viscosity or slope.

**Features produced at medium viscosities**

Although covering a wide range, fluids with viscosities between 0.005 Pa s and 0.075 Pa s produced features with little variance. The resulting features resembled martian slope streaks (Figure 22). As the medium viscosity fluid exited the tubing and moved down slope, the fluid overcame the confining pressure of the tube and the frontal lobe widened to a tongue shape. The tongue shaped front continued to spread laterally until it reached its maximum width, at which point, the spreading forces were overcome by consolidating forces and the fluid quickly narrowed into a tear drop shape. A thin, narrow trail of fluid was left behind as the frontal lobe advanced down slope (Figure 14). The tear drop shape front continued to narrow as it lost fluid and energy but the narrowing occurred at a continually decreasing rate and therefore resulted in a short and wide upper section with a long and thin lower section. The narrowing of the flow occurred as the fluid lost energy. Even though the fluid did not infiltrate deeply, some fluid was still lost to the substrate, which resulted in a further loss of energy. In addition, friction between the fluid and the sand grains caused a loss of down slope energy. Finally, internal fluid friction would create a situation for energy loss (Miyamoto et al., 2004).

The parameter that changed the most with varying slope using medium viscosity fluid was the average total length. At larger slope, all parameters were larger than those produced at low slope except the levee width, which was the same at both slopes (Table 2). The lower sloped terrain consistently had fewer levees than the high sloped terrain, indicating the high sloped terrain
Figure 21: These images show visually the potential link between martian slope streaks and gullies. Martian slope streaks and martian gullies form in similar geographic areas. These images show martian gullies (top left) and slope streaks (top right) in craters of similar scale in the southern hemisphere. The martian gullies in this image (bottom) have very straight, narrow and linear paths that end with more linear than triangular aprons. The morphology resembles slope streaks even though the erosion and deposition resemble gullies. The low viscosity simulations created flow features that also exhibited both gully and slope streak characteristics.
Figure 22: A representative image of features produced by medium viscosity fluids (left) and high viscosity fluids (center) with strikingly similar morphology to martian slope streaks (right top and bottom), indicating a potentially similar formation mechanism.

had more energy to entrain, transport, and deposit material. The similarities between the two data sets indicate that the slope of the surface was not a controlling factor in the flow features produced by medium viscosity fluids.
Medium viscosity simulations consistently produce martian slope streak features. Although similar morphology is not indicative of the same formation process, it is highly suggestive. Examples of fluids at medium viscosities that may have formed martian slope streaks include: Fe$_2$(SO$_4$)$_3$ brines at 38.8%-48.5% salt at temperatures of 262.15K-282.65K (Chevrier et al., 2009); relatively low sediment concentration debris flows (Shroder et al., 2005); grain lubricated creep (Shroder et al., 2005).

**Features produced at high viscosities**

High viscosity simulations, with viscosities 0.075 Pa s to 1.1 Pa s, consistently produce martian slope streak features. Again, although similar morphology is not indicative of the same formation process, it is highly suggestive. Examples of fluids at high viscosities that may have formed martian slope streaks include: Fe$_2$(SO$_4$)$_3$ brines at 48.5%-58.2% salt at temperatures of 262.65K-282.65K; relatively high sediment concentration debris flows (Shroder et al., 2005); grain lubricated creep (Shroder et al., 2005).

The high viscosity fluid exited the tube, flowed down slope, widened and then narrowed, creating a similar planar shape to the medium viscosity fluid simulation (Figure 22). As the fluid existed the tube, it spread laterally much quicker than the medium viscosity fluids (Figure 23). This resulted in the maximum widths of the features being reached closer to the point of origin than the medium viscosity fluids. Although martian slope streaks reach their maximum widths before the half length measurement (Sullivan et al., 2001), both high and medium viscosity fluids generally produced features that have a maximum width very close to the point of origin; the medium viscosity fluids, however, create a better match to martian forms than the high...
viscosity fluids. It is likely that environmental conditions of the simulations do not match Mars conditions (i.e. gravity, regolith saturation and grain size) closely enough to simulation the appropriate distance the maximum width is reached. It is significant, though, that the maximum width of simulated slope streaks is reached before their half-length measurement.

Figure 23: The high viscosity fluid emerges from the tubing (A) and immediately widens (B). The maximum width is reach quickly (C) and then steadily narrows (D) until a tear drop shaped frontal lobe forms (E). The high and medium viscosity simulations form similarly shaped features. After the medium viscosity fluid emerges from the tubing, it does not spread laterally as quickly as the high viscosity fluid (shown here).

As the fluid glided over the substrate, it incorporated only a few sand grains at a time. The sand grains were picked up by the sides and transported slightly inwards, but not upwards. The lack of
upward transport of the incorporated grains indicates the high viscosity fluid was dominated by laminar flow (Pierson and Costa, 1987). This type of flow on the grains created the depression and ridge system. The grains that were removed created a grain-deep depression and were deposited in a grain-high ridge.

The higher viscosity fluids were less mobile than the medium viscosity fluids and created shorter simulated slope streaks (Table 3). Martian slope streaks can be hundreds of meters long or a few tens of meters long (Chuang, et al., 2007). This range could be explained by the difference in concentration of salt or temperature of the brine involved in the martian slope streak formation process. The higher concentrated the brine, the more viscous it is (Chevrier et al., 2009); greater sediment concentration also creates more viscous fluids (Pierson and Costa, 1987). Research here indicates that one possibility for the range of martian slope streak length may be the viscosity of fluid involved, where the higher viscosity fluids created the shorter martian slope streaks and the medium viscosity created longer martian slope streaks.

**Comparison to martian slope streaks**

Fluids with viscosities of 0.005-1.2 Pa s. flowing down slopes of 10° and 20° resemble the morphology of martian slope streaks (Figure 22) While at high slope, fluids with viscosities less than 0.004 Pa s. produced aprons that resembled martian slope streaks, their over all form was that of martian gullies (Figure 20). It is possible that features simulated at low viscosity and high slope represent the middle of a spectrum of slope streaks to gullies, where gullies and slope streaks are two end members of the same formation process (i.e. the features start as slope streaks and erode to gullies) or are two end member of viscous fluid types (i.e. gullies formed by
low viscosity and slopes streaks by high viscosity fluids). The following discussion examines characteristics of the medium and high viscosity simulations and how they compare to martian slope streak characteristics.

**Point of origin**

The tubing delivery device used in simulations in this study leads to a natural bias for the point of origin of the simulated slope streaks to resemble the point source for martian slope streaks (Figure 24). It is possible the point source of the martian slope streaks due to an area of localized snow accumulation that has melted, as has been suggested for martian gullies (Christensen, 2003 and Marchant and Head, 2007; Levy *et al.*, 2009). The simulation delivery device essentially mimics this type of fluid release. How the fluid behaves after exiting the tubing device helps define which characteristics best match martian slope streaks. By this logic, the delivery device design is justified in simulating martian slope streaks but is not relevant for comparison purposes.

**Lobate termination**

The termination of martian slope streaks is often described as digitate (Sullivan *et al.*, 1991). Although martian gully morphology can also be described as digitate (Malin and Edgett, 2001), slope streak digitate termination points differ from gullies in that they produce no relief (Head *et al.*, 2007). The low viscosity simulations did produce digitate aprons and their termination section had relief to them. Both high and medium viscosity simulations produced digitate termination sections that had no relief in the resulting feature and had bulb shaped ends the same shape as the advancing front.
Figure 24: Comparison between simulated slope streak point of origin (left) and martian slope streak point of origin (right) illustrating the similarities between point sources that are a direct result of the experimental set up. Since martian slope streaks originate from a point source, it is reasonable to create an experimental set up that reflects this.

Simulated slope streaks resulted in only one point of termination, unlike those on Mars that can show multiple digitate termination lobes (Sullivan et al., 1991). Assuming liquid involvement in martian slope streaks, it is possible the source of fluid had multiple activation periods. Each period may have originated from the same point source but taken a slightly different path. The adjacent termination lobes could result in a digitate shaped end. It was beyond the scope of this research to simulate this scenario.
Another explanation for the discrepancy of the multiple and single termination lobes of the martian slope streaks compared to the simulated streaks is the diversion of the fluid around obstacles. Martian slope streaks will divert around objects and the multiple branches in the termination end may be the fluid moving around objects (Figure 25). In a preliminary experiment using more fluid, the fluid split into two fronts as it diverged around an accumulation of larger sand grains. This created a termination section that resembled slope streaks with multiple digits (Figure 25).

Figure 25: During a preliminary trial, using 200ml of viscous solution ~1.0 Pa s, the fluid the fluid encountered a large accumulation of large sand grains shortly after exiting the point source (left). The fluid diverted around the cluster, much like slope streaks divert around boulders in their path on Mars (right).
Figure 26: The high viscosity fluid (left) emerges from the tubing and widens to its maximum width almost immediately. The medium viscosity fluid (center) reaches maximum width more down slope than the high viscosity fluid. Martian slope streaks (right) more resemble the medium viscosity behavior but tend to reach maximum width even farther down slope.

Midsection

Both medium and high viscosity simulations created narrow, straight streaks. The medium viscosity fluids widened at a slower rate than the fluids of high viscosity when first exiting the tubing. This resulted in the medium viscosity fluids reaching its maximum width 10-15cm from the point of origin and the high viscosity fluids reach the maximum widths 0.5-5cm from the point of origin. Although no measurements have been taken, visual examination of HiRISE
images shows that the widest section of the martian slopes streaks occurs down slope of their point of origin but before the half length measurement (Miyamoto et al., 2004). In this sense, the medium viscosity fluids (Figure 26) better simulate the distance at which the widest part of the feature forms.

Sensitivity to topography

Martian slope streaks commonly reflect the terrain over which they form (Sullivan et al., 2001), leading to branching and diverting of martian slope streak paths (Figure 27). In preliminary simulations, the amount of fluid used was 200mL. During one of those experiments, the fluid encountered a small accumulation of large sand grains and split into two lobate advancing fronts (Figure 25), similar to what occurs with martian slope streaks.

Slope streaks on Mars are often seen to have textured terrain inside the streaks that match the adjacent terrain (Sullivan et al., 2001), indicating that as they flow over the terrain, the fluid interacts minimally with the surface and in doing so preserves the texture. The preservation of underlying textures indicate slope streaks are formed by a ground hugging material with low kinetic energy that can easily be diverted around objects or into depressions (Sullivan et al., 1991). Due to experimental set up, the flume would occasionally be slanted to one side. In these cases, the fluid always flowed with the slope (Figure 28). Smoothing the surface was done by hand and subjected to occasional error. In the cases where depressions or ridges were inadvertently created, the fluid would flow into or around the obstacles. The depressions or ridges would be analogues to patterns on the martian surface that slope streaks are known to flow over without altering.
Figure 27: Martian slope streaks follow the slope of the terrain. They will also flow over any textured ground in such a way as to preserve the pattern of the terrain. This leads to branching and patterned slope streaks.

Figure 28: When the surface was not completely level, the viscous solutions sloped with surface (A and B). If there were any depressions in the surface, the fluid would fill in the depression (C) and then flow out of it. If there were any ridges, or even small clusters of larger sand grains, the fluid would be diverted around the obstruction (D).
Length to width (L/W) ratio

The simulated slope streaks are at the meter scale, whereas slope streaks on Mars range from 10s-100s of meters, which makes directly comparing the measurements from the simulations and martian slope streaks difficult. In order to bypass the scale issue, the ratio of the length to the width of the features created in the simulations is compared to the same ratio of martian slope streak. The morphology of the features resulting from the low viscosity simulations make the comparison of length to width ratios (L:W) to martian slope streaks and simulated slopes streaks inappropriate. The low viscosity L:W ratios were highly varied. This was expected from previous work (Coleman et al., 2009) and the observation of the features during the experiments. The medium and high viscosity fluids resulted in features very linear, making L:W ratios easily calculated.

L:W ratios of MOC images of slope streaks ranged from 5 to 30 (Sullivan et al., 2000). Using ENVI software and HiRISE data, the L:W ratios of martian slope streaks were measured in this study and found to agree with this range, as L:W ratios ranged from 6.07 to 35.33. Average medium viscosity slope streaks simulated were 35.83 at low slope and 35.86 at high slope, slightly higher L:W than those reported on Mars. High viscosity simulations, on the other hand, produced average L:W ratios of 12.38 at low slope and 14.94 at high slope, more towards the middle of the range determined for Mars. This indicates that the horizontal and vertical forces acting on the fluids creating martian slopes streaks and high viscosity simulations are more similar, where as the medium viscosity fluids have a more dominate vertical force than the fluids creating martian slope streaks. Both the medium or high viscosity fluids created features with
consistent L:W ratios but the features resulting from high viscosity fluids more closely matched those in the literature.

The difference between the L:W ratios of high slope and low slope of the same viscosity were minimal. The difference between the L:W ratios of the same slope value but different viscosities was more significant. This indices that slope does not affect L:W ratios as significantly as the viscosity of the fluid, which justifies the comparison between the slopes tested here and those on Mars which are not always known.

**Feature edges**

The edges of slope streaks are straight and sharp from top to bottom and contrasts in albedo from the surrounding environment by about 10% (Sullivan *et al.*, 2001). The sharpness of the edges indicates that there is little interaction between the edge of the flow and the substrate adjacent to the flow. This could be caused by a fluid that does not infiltrate into the surface and spreads laterally. Fluid that spreads laterally in the near surface creates areas that decreases in moisture away from the feature (Coleman *et al.*, 2009) where as fluids that do not spread in the subsurface have no lateral moisture gradient. Unless the fluid infiltrated deep into the surface before moving sideways, it would likely leave evidence of blurred edges or depressions where the fluid compressed the underlying grains and the surface sunk slightly.

In the reported experiments, the contrast in color between the fluid and substrate was artificially created with food coloring. Although the color was artificial, the sharp contrast between the flow and the substrate was not. At low viscosity, the edges of the flow were not sharp but fuzzy. The
fuzziness was due to the lateral infiltration of the fluid into the sand substrate. The medium and high viscosity simulations, on the other hand, had sharp edges to their flow, suggesting minimal interaction between the fluid and the subsurface.

**Variation in martian slope streaks**

Although all slope streaks share general overall characteristics, there does exist some texture differences seen in the martian slope streaks (Figure 29). These patterns were not reproduced in the lab, although this can be explained by the simple substrate used. Martian slope streaks form over a variety of rough and smooth terrain and only the smooth terrain was tested. In addition, some martian slope streaks form over surfaces that have pre-existing patterns. These patterns are preserved in the slope streaks, giving the features textures, again that were not tested in the laboratory.

Although slope streaks are believed to be uniform in color within an individual streak, there are some examples of slope streaks with some internal albedo variation (Figure 26 and 29, for example). This could be explained by different flow events. Each flow event may have slightly different fluid chemical or physical make up that would create a slightly different surface signature. This would also allow for the events to be similar in make up so that at some resolutions, differences can not be seen and the streak appears uniform. It is also not unusual for a group of related geological features, such as gullies or slope streaks, to be classified based on slightly different patterns of formation (Coleman and Dixon, 2009; Mangold et al., 2003; Shroder et al., 2005).
Figure 29: A: On the left edge are two slope streaks of different albedo merging into one streak. The termination end of the streak is digitate, possibly from multiple events. It is also possible the multiple digits are due to the pattern of the surface it flowed over, as it shows preservation of the terrain. B: These streaks also have less distinct edges than other slope streaks. This appearance might be linked to a lower viscosity fluid, as the low viscosity simulations in this study have blurry edges. C: Many streaks in this image have a variety of colors within the streak. The color variance is often linear, suggesting there may have been multiple events to form the streak. D: At the top of the image is a slope streak that appears to have one point source and multiple digits, each a slightly different albedo, suggesting reactivation of a site. Each digit follows a similar shape as simulated slope streaks. At the bottom of the image are slope streaks that resemble braided channels, where each section is diverted by a boulder in the slope streak’s path.
**Potential sources for martian slope streaks**

Pure water in a liquid state is unlikely to be present on the surface of Mars (Mellon and Phillips, 2001; Mellon *et al.*, 2004; Tosca *et al.*, 2008; Carr and Head, 2003). In addition, the low viscosity of water would appear to make it an unlikely candidate for slope streak formation based on the results of this study. Neither the medium or high viscosity fluids create features precisely resembling martian slope streaks but both produce remarkably similar features to each other and to martian slope streaks. The overall shape, as well as key characteristics of slope streaks, is produced by both medium and high viscosity fluids (Table 5). Discrepancies between fluids tested and martian slope streak characteristics could potentially be due to: the experimental nature of the simulations (i.e. inability to simulation martian gravity and temperatures); the exact viscosity of the fluids forming martian slope streaks were not tested; and differences between the substrates and environmental conditions (i.e. temperature) in the lab and on Mars.

Salts, which are known to be on the surface of Mars, would increase the stability of the liquid as well as the viscosity (Chevrier *et al.*, 2009). Cooler temperatures, such as those on Mars, would also increase the viscosity of the fluid (Chevrier, 2008). The viscosity of concentrated brines of Fe$_2$(SO$_4$)$_3$ at martian temperatures (262.15K-282.65K) are consistent with viscosities simulated here at concentrations at 38.8%-48.5% (medium viscosity) and 48.5%-58.2% (high viscosity) (Chevrier and Altheide, 2008). The addition of sediment in the brine would increase the viscosity of that brine at that temperature (Pierson and Costa, 1987), which would then reduce the amount of salt required to make a viscous fluid.
Table 5: Comparison of martian slope streaks, experimental simulations and theoretical works

<table>
<thead>
<tr>
<th>Martian slope streak characteristics</th>
<th>Viscous liquids</th>
<th>Run away percolation</th>
<th>Dry dust avalanche</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Viscous liquids</td>
<td>Run away percolation</td>
<td>Dry dust avalanche</td>
</tr>
<tr>
<td></td>
<td>this study</td>
<td>Kreslavsky and Head, 2009</td>
<td>Sullivan, et al., 2001</td>
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<td>Narrow, linear, parallel planar shapes</td>
<td>yes</td>
<td>yes</td>
<td>more triangular in shape</td>
</tr>
<tr>
<td>Originates at point source</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
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<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Constant albedo within feature</td>
<td>yes; artificially created</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Distinctive and sharp edges to feature</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Lacks discernable relief associated with feature</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Single and multiple branches possible</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Preserves underlying texture</td>
<td>maybe; not simulated</td>
<td>maybe</td>
<td>no</td>
</tr>
<tr>
<td>Diverted around topographic highs</td>
<td>yes</td>
<td>maybe</td>
<td>yes</td>
</tr>
<tr>
<td>Restricted by temperature</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
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<tr>
<td>Can form in variety of geological settings</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Length varies from meters to hundreds of meters</td>
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<td>yes</td>
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<tr>
<td>Can form on shallow and steep slopes</td>
<td>yes</td>
<td>yes</td>
<td>no; shallow slopes need trigger event</td>
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</table>
**Connection between martian gullies and slope streaks**

Assuming slope streaks and gullies are both formed by a fluid with a liquid component, it is possible they represent two ends of a morphological spectrum. One way to classify terrestrial mass movements is using the amount of water versus sediment in the fluid involved (Pierson and Costa, 1987; Shroder et al., 2005); terrestrial features vary depending on the amount of fluid involved in the formation and so could martian features. Slope streaks and gullies both form where liquid water is potentially present in the near surface on Mars (Schorghofer, 2002). It is unknown what proportion is liquid water and what the salt or sediment concentration in it would be should it melt. As the salt or sediment concentration of a fluid increases, so does the viscosity (Chevrier et al., 2009). The low viscosity experiments produced gullies (analogous to low concentration of salts/sediments) and the medium and high viscosity experiments produced slope streaks (analogous to high concentration of salts/sediment), it is possible this may be true on Mars (Figure 30).

Both gullies and slope streaks have been seen to form in the span of only a few years. Gullies have been seen to deposit new material and slope streaks to form new streaks. Slope streaks and gullies form in similar geographical and geological locations (Schorghofer et al., 2007; Balme et al., 2006), so is possible that slope streaks are the beginning stages of gullies. The lack of the in-between stage makes this theory difficult to validate. Although the majority of slope streaks do not have any relief associated with them, detailed analysis of a few images has shown some lowering of the surface (Chuang et al., 2007), which may indicate the in-between stage if there is one. If a small amount of fluid is released periodically over a period of time, the resulting feature may change over time. Gullies and slope streaks form were liquid may be present in an unknown
quantity. If an area that lacks the amount of liquid needed to entrench the regolith, slope streaks may result instead of gullies. As the area is reactivated, it may create gullies out of slope streaks (Figure 30).

Figure 30: Martian gullies are associated with a liquid component for their formation (Malin and Edgett, 2000; Mangold et al., 2003; Kossacki and Markiewicz, 2004; Christensen, 2003). Martian gullies in these images have dark slope streaks within the channel section, indicating that gullies and slope streak may be associated.
**Martian slope streaks and Antarctic Dry Valley slope streaks**

Few terrestrial locations offer appropriate Mars-like conditions and the Antarctic Dry Valleys (ADV) represent one of the best candidates (Marchant and Head, 2007; Levy et al., 2009). Slope streaks have been identified in the ADV (Head et al., 2007). ADV slope streaks share many characteristics with martian slopes streaks (Figure 31). ADV streaks: have a low albedo compared to surrounding terrain; have no relief associated with their formation; elongate and widen down slope; have length:width ratios that vary from 10-35; new streaks are darker than old streaks; are influenced by the local topography; and have digitate termination lobes (Head et al., 2007).

Figure 31: Martian slope streaks (left) and terrestrial Antarctic Dry Valley slope streaks (right-images from Head et al., 2007) illustrating the similarities between the features.
Unlike martian slope streaks, field observations of the ADV were made (Head et al., 2007). In areas where ADV slope streaks were present, there were depression areas on the scarp walls that allowed for windblown snow to accumulate in the winter months. The snow in these areas remained through most of the summer season. The sharp edges of the ADV slope streak as well as the lack of erosion (i.e. channels) and deposition (i.e. snow or dust deposits) were confirmed by ground observations. The only difference between soils in and outside the ADV streaks was the water content; outside the streak was dry from the surface to ice table where the soil from inside the streak were moist from the surface to the ice table. The ice table depth, 20-40cm was too deep to be seasonally effected to a degree that would act as a water source for the ADV slope streaks.

These observations lead to the following proposed formation mechanism for ADV slope streaks: 1) winter snow accumulation is sublimated in the summer unless it is protected or covered; 2) the snow that accumulates in alcoves or in shadowed regions melts and percolates down toward the ice table through the high porosity colluvium; 3) when the moisture reaches the finer grained colluvium, grain boundary contact wicks the moisture towards the surface, which wets the surface (Head et al., 2007).

Although the environmental conditions in the ADV do not exactly match Mars, the similarities in the martian and ADV slope streaks are distinct enough that the wet formation mechanism of the ADV should be considered for martian slope streaks. Martian slope streaks are found in areas associated with elevated hydrogen levels (Feldman et al., 2002), where the peak temperatures
reach above the freezing point of water (Schorghofer et al., 2006) and in areas that seasonal and local snow precipitation is possible (Forget et al., 2006), which all support a possible correlation between the formation of ADV slope streaks and martian slope streaks.

Experimental simulation here supports the hypothesis of local surface wetting forming slope streaks. The point source of the delivery device would be analogs to where the moisture began to wick to the surface and create a wetted surface. The emptying of the delivery device would be analogs to the limit of the amount of snow accumulation in the protected region as the length and width of the ADV slope streaks were controlled by the amount of available melt water from the snow (Head et al., 2007). The experimental simulations would be analogues to the post-wicking processes, where the surface has been wetted and the top layer of finer grained material is lubricated by a viscous fluid.

The amount of fluid controls the length and width of the ADV slope streaks and it is reasonable that martian slope streaks would also be controlled in such a way (Head et al., 2007). Mars does not have a current climate conducive to an abundance of water so any analogue would have to account for long slope streaks to be created from a small liquid reservoir. The high viscosity fluids created longer simulated slope streaks with the same amount of fluid as the medium viscosity simulations. High viscosity fluids, in the form of a brine or debris flow, would allow for a wet formation with little liquid required (Kreslasky and Head, 2009).
Chapter 5

Conclusion

Viscosities lower than 0.004 Pa s produced features in the flume that resemble small scale martian gullies. This is consistent with previous experiments simulating martian gullies using pure water (0.001 Pa s). At 20° conditions at the upper end of the low viscosity range, there were some characteristics of slope streaks beginning to emerge. Slope streaks and gullies have been imaged in similar geological settings on Mars. The combined experimental and imagery evidence suggests there is a connection between martian gullies and slope streaks but it is still unclear how they may be connected. Simulations presented here show that the same viscosity fluid at different slopes can produce slightly different morphologies, making it plausible that gullies and slope streaks may form from similar fluid but under different environmental conditions.

Viscosities of 0.005-1.0 Pa s produced features that strongly resembled martian slope streaks at both 10° and 20° slopes. Differences in features produced by high and medium viscosities were slight but important. Fluids of 0.005-0.075 Pa s produced features that had slight levees where as the higher viscosities solutions produced only grain sized depressions and ridges at the edge of the fluid. In this sense, the high viscosity fluids match better the martian slope streak characteristics. The high viscosity fluids match better the length:width ratios observed on Mars,
suggesting high viscosity fluids create simulated slope streaks that better match martian slope streaks. Medium viscosity fluids better match the martian slope streaks in reference to the maximum width occurring down slope of the point source. Since neither viscosity range exactly matches all characteristics of martian slope streaks, the viscosity range may need to be refined.

The differences in the simulated slope streaks may also offer an explanation to why not every slope streak on Mars is the same as the next. The slight differences in Mars slope streak morphology may be due to slight differences in the viscosity of the fluid forming martian slope streaks. The viscosity of a brine is controlled by the salt concentration and the temperature at which it formed. Since weather conditions are not the same everywhere on Mars and the mineralogy may varying as well, it is reasonable to suggest that the variation in slope streaks are formed by fluids of slightly different viscosities or temperatures. The range of viscosities used the simulations represent a range of brine temperatures and conditions. Some martian slope streaks are more triangular and may be formed by a different viscosity fluid than those reported on here. It is possible that these slope streaks are formed by a more dry process, such as dry avalanches.

Most of the martian slope streaks are not triangular in shape and resemble the slope streaks simulated using viscous fluids. Viscous fluids do not have to contain copious amounts of water, which is consistent with current conditions on Mars. The Antarctic Dry Valley (ADV) has features that resemble martian slope streaks and simulated slope streaks. ADV slope streaks form
from winter snow melting creating a small layer of wetness that drives the slope failure. With the locations and amount of liquid available, this is a likely analogue for martian slope streaks.

This work does not definitively answer the origin of slopes streaks on Mars. It does, however, show that there is a strong resemblance between martian slope streaks and features produced by viscous fluids. The similarities between experimental simulations and martian slope streaks is strong enough that the viscous fluid theory should be considered along with the other slope streak formation theories for martian slope streaks (Table 5).
References


Christensen, P. R., 1986, Regional dust deposits on Mars-physical properties, age, and history, Journal of Geophysical Research, v. 91, 3533


Roger Gilmont Instruments, Inc. user manual


<table>
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<th>Run</th>
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# Curves

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Appendix A: Low Viscosity Simulation data
### Appendix: Medium Viscosity Simulation data

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Appendix C: High Viscosity Simulation Data