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Experimental Simulations of Recurring Slope Lineae on the Surface of Mars

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EXPERIMENTAL SIMULATIONS OF RECURRING SLOPE LINEAE ON THE SURFACE OF MARS

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Abstract

Recurring Slope Lineae (RSL) are active surface features found on rocky Martian slopes commonly in the southern hemisphere equatorial to mid-latitude regions. These low albedo, dark streaks on Mars demonstrate seasonal characteristics; they appear and grow darker and longer in warm months and fade to possible disappearance in colder months. One proposed mechanism for the formation and evolution of these features by McEwen et al. (2011) is the melting of subsurface water on Mars. The goal of this study was to test this hypothesis by reconstructing features similar to RSL in the lab that display the same seasonal characteristics as a result of freezing and thawing cycles creating a source of subsurface liquid. Laboratory experiments were conducted at both the Arkansas Center for Space and Planetary Sciences and at Connecticut College using small open-topped and insulated boxes filled with saturated regolith. The two main constraints that were identified in these simulations were the effects of topographic distribution of regolith and of large boulders on the overall thawing of the system and production of features. Results showed that dark wet streaks could appear along the slope as a result of capillary rise through a thin dry overburden of sediment, but there must be some sort of anisotropy introduced into the system in order for the dark line to occur in a linear trend, such as the generation of a small channel extending down the slope. Additional results indicated that different heat transfer properties of larger particles could initiate subsurface thawing from a point along the slope. The lack of recurrence of slope lineae in these experiments suggests a need for larger scale varying topography experiments or a possible limitation due to the size of the small boxes not reaching the critical length necessary for features to form.

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Chapter 1
Introduction

For decades, Mars has been a focal point of solar system research. The fourth planet away from the sun, our neighboring rocky planet has sparked a broad scientific interest to dig deeper into its past and to search for the possibility of liquid water. Water is a principle component for the survival of life on any planetary body, making it a common point of interest for research when searching for potentially habitable bodies both in and out of the solar system. Not only has the possibility of water, in any physical state, made Mars a particularly interesting planet to study, but the close proximity of Mars to our own planet has created an especially intriguing component to both the search for life off of our own planet as well as the search for a body that could potentially host our own life in the future. Studies of, and missions to, Mars have shown that the Red Planet, while cold and dry, is not a completely inactive planet.

This study focuses on one of these active features, called recurring slope lineae, often referred to as RSL. Experiments were conducted at both the Arkansas Center for Space and Planetary Sciences and at Connecticut College. They were aimed at recreating features in the lab with similar characteristics to RSL. Although other mechanisms of formation have not been completely ruled out, this study concentrated on the hypothesis proposed by McEwen et al. (2011) and Levy (2012) that RSL form as a result of liquid water processes on and/or below the surface of Mars. The formation mechanism studied in the lab focused on the freezing and thawing cycles that could potentially produce a source of liquid water to form RSL. Experimental simulations were designed to identify controlling factors in the recreation of RSL. Based on the presence of channels and boulders on the steep slopes on which RSL form, we hypothesized that by including these features in our experimental simulations and placing them through freezing and thawing cycles we could recreate RSL in the laboratory and define additional constraints on their formation.

Section 1.1: The Motivation for Studying Mars

Because of both its similarity and proximity to Earth, studying Mars up close has been an important and attainable goal of space exploration. Multiple countries have successfully orbited and landed on Mars to examine and analyze the planet's atmospheric and surface properties since the first successful fly by of Mars made by the United States in 1965 and orbit of Mars made by the United States in 1971 (NASA Program and Missions, 2015). Some of the most important Mars missions, such as the Mars Science Laboratory on the Curiosity rover that reached the Red Planet in 2012, are still in operation, providing a constant source of new information about the planet. Another important and currently operational mission is the Mars Reconnaissance Orbiter, equipped with the High Resolution Imaging Science Experiment (HiRISE) camera, which sends back important images for both scientific analysis and for determining landing sites for future Mars missions (NASA Program and Missions, 2015). Both of these currently operating missions are especially important in this study, as they provide data and observations necessary for identifying features and processes related to RSL.

Given the known importance of water to sustain terrestrial life, the search for water is essential in the search for habitable planets. One method for searching other celestial bodies for water focuses on analyzing the atmosphere and surface composition of a body for the hydrogen and oxygen components that make up water molecules (Bennett and Shostak, 2012). Another method, however, is to examine the surface of a planet for features that resemble those on Earth that are associated with water processes (Bennett and Shostak, 2012). Identifying terrestrial analogs to Martian features allows scientists to make hypotheses regarding the possible forces driving the formation and evolution of similar features on Mars. Given our ability to examine

Mars in detail with orbiters, landers, and rovers, surface features can be thoroughly observed. These observations are extremely useful in combination with spectroscopy and other chemical analyses when searching for the presence of water on the planet. Additionally, because Mars is not currently tectonically active (Marshak, 2012) and has not been very active for billions of years, old features that were created by past flowing water could be preserved on the surface of the planet even if water is no longer present. Observations of the surface of Mars through various orbiting and landing missions have revealed both old and currently active features that could potentially be associated with water-related events.

Section 1.2: An Introduction to Recurring Slope Lineae

RSL are currently active surface features on Mars that have gained much attention since the first observations of these features were made in 2006 (McEwen et al., 2011). RSL appear in HiRISE satellite images taken by the Mars Reconnaissance Orbiter as dark, narrow lines with low albedos compared to the surrounding area on rocky Martian slopes. The term RSL is used to describe these slope streak-like features that exhibit seasonal properties; the lineae appear and grow both darker and longer during warmer months, fade to possible disappearance during cooler months, and reappear following the same seasonal cycle in the following year (McEwen et al., 2011). To be classified as a confirmed RSL, the slope lineae must show the same pattern of seasonal appearing and

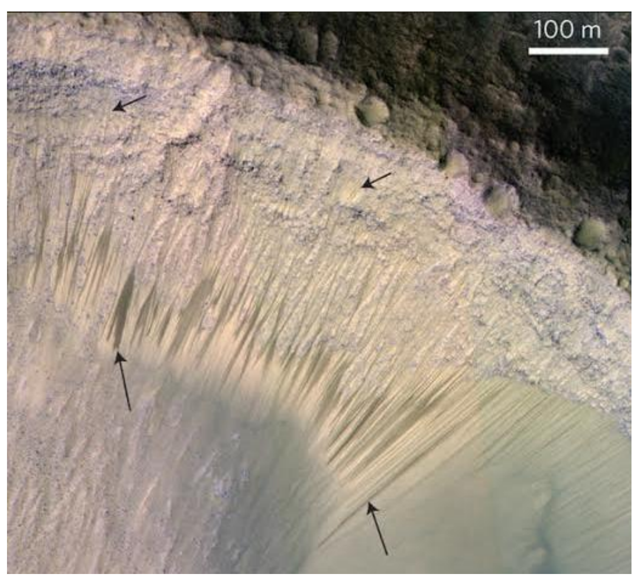


Figure 1.1: HiRISE image of recurring slope lineae extending downslope on a crater wall in Valles Marineris (McEwen et al., 2013).

disappearing over multiple Mars years (Ojha et al., 2014). The locations of RSL tend to be in the equatorial and mid-latitude regions, mostly on equator facing slopes, especially in the southern hemisphere (McEwen et al., 2011). The image in Figure 1.1 shows a set of RSL extending downslope from a rocky outcrop in the southern hemisphere during their active season from early spring into the summer.

Many mechanisms have been proposed for the formation of RSL. Because of their locations on steep rocky slopes, some scientists have proposed dry or granular flows (McEwen et al., 2011) for the formation of RSL. However, given the strong seasonal characteristic of RSL, there is likely an important dependence on temperature for the yearly recurrence of these particular slope streaks. This suspected reliance on temperature has led scientists to a stronger proposed mechanism focused on a presence of liquid during certain seasonal time periods (McEwen et al., 2011; Levy, 2012). Warmer temperatures create a more suitable environment in favor of liquid water or liquid brine. Brine is water with an extremely high salt content, which depresses the melting point of the water, making it a likely candidate as a source for RSL on Mars (Levy, 2012; Chevrier and Rivera-Valentin, 2012). Much is still unknown about the formation and evolution of RSL. Through research and experimentation, including those involved with this study, RSL may prove to be features dominated by liquid processes on Mars.

Section 1.3: The Goals for this Study

Initial experiments were conducted at the Arkansas Center for Space and Planetary Sciences in the summer of 2014, and were followed up at Connecticut College in the following fall. The RSL experiments required a constant changing of variables in an attempt to create RSL-like features within a small box filled with regolith and water. Different factors were varied throughout the experimental process to observe the effects of these factors when determining the necessary conditions for RSL to form. Variables used included the properties and grain size of the regolith and the overall topography. The experiments generally contained a frozen layer of regolith previously saturated with water, accompanied by an overlying layer of dry regolith on the surface. Specifically, experiments were aimed at determining the controlling factors of the topographic distribution of regolith and of the presence of large particles because of the formation of RSL on rocky slopes. These factors were varied in accordance with possible conditions on Mars. Different boxes were put through cycles of freezing and thawing on various slopes. The results of each individual experiment were then used to prepare the next set of experiments in an attempt to create features most similar to those of observed RSL.

The overall goal of these experiments was both to test the leading hypothesis that the driving mechanism for forming RSL is the seasonal thawing of liquid brine and to create these features on slopes as reappearing dark lineae in repeating cycles as a result of freezing and thawing. The variation of the regolith properties, including topographic distribution and particle size, yielded results that gave insight into the degree of control each of these factors have on the formation of RSL.

Chapter 2
Background

Mars is classified as one of the four inner terrestrial planets and exhibits some characteristics similar to those on Earth, with some important differences to note. The National Aeronautics and Space Administration (NASA) publically distributes information about all of the solar system's planets, via their website, including the following facts and values which were used as background knowledge in this study (NASA Mars Facts, 2015). Sitting at an average distance of about 142 million miles from the sun (1.5 AU), Mars is a cold body compared to Earth with an average surface temperature of -63 degrees Celsius (210K). The diameter of Mars is 3390 km, about half that of Earth, and it exerts a force of gravity of about a third of that of Earth. The length of one day on Mars, referred to as one sol, is 24 hours and 37 minutes, so it experiences a diurnal cycle similar to that on Earth. However, being on average 1.5 times further from the sun than Earth, a Mars year is nearly two times as long as that on Earth, at 687 Earth days. Because Mars rotates on an axis tilted at 25 degrees, the surface of Mars experiences seasonal changes throughout its yearly orbit around the sun (NASA Mars Facts, 2015). These seasonal changes exhibit greater variation than those on Earth, due to the greater eccentricity of the orbit of Mars, which is further described in Section 2.2.

Section 2.1: The Surface and Atmosphere of Mars

The surface of Mars is littered with impact craters, indicating a geologically inactive surface. If the surface of Mars were dominated by plate tectonics, a constant recycling of surface material would wipe away such an abundance of craters that have accumulated over time, as it does on Earth (Marshak, 2012). Mars does contain mountains, including Olympus Mons the highest mountain in the solar system, as well as a large rift valley, Valles Marineris, suggesting that the surface was at one time active (Bennett and Shostak, 2012). Given its small size relative to Earth and greater distance from the sun, Mars likely cooled much more rapidly than Earth. This inhibited any tectonic activity from dominating because of a lack of a hot, plastic-like layer for plates to be able to move on top of and a heat-generating interior to drive the movement (Marshak, 2012). Craters on the surface of Mars imply a very old surface. The inactivity of any possible plate tectonics in recent geologic history indicates that the very old surface is mostly comprised of rocks that are igneous in origin due to a lack of processes that could have metamorphosed existing rock. Therefore, the composition of the surface of Mars is dominated by iron-rich basaltic rock, which is igneous in origin from the short period of time when the interior of this planet was still warm enough to produce mantle plumes that could drive volcanic activity (Bennett and Shostak, 2012).

Sedimentary deposits also exist on Mars, many a result of wind-driven processes currently active on the surface. A lack of vegetation and limited water encourage large dust storms that can cover vast areas of the surface (Marshak, 2012), resulting in the erosion and deposition of surface material. Landers and rovers on the Mars surface have recently provided observations of additional sedimentary deposits on the surface. These deposits present a connection to fluvial processes, or those associated with rivers and streams (Ritter et al., 2011), and other water deposition. Specifically, the Mars Science Laboratory on board NASA's Curiosity rover is currently analyzing fluvial deposits at Mount Sharp in Gale crater providing important insight into the past conditions on Mars and its ability to host liquid water (NASA/JPL Mission, 2015). These deposits are not unexpected, given the appearance of geomorphic features such as gullies and channels on the surface of Mars that closely resemble fluvial features on Earth (Marshak, 2012).

In addition to basaltic rock outcrops, observations and measurements of the environment of Mars by orbiters and landers indicate a presence of soluble salts in the regolith and on the surface of Mars (Chevrier and Dixon, 2014). Large amounts of salts including sulfates, chlorides, and perchlorates have been confirmed on the surface of Mars in various regions including both the equatorial and higher latitude regions (Bibring et al., 2006; Squyres et al., 2004; Wang et al., 2006). The abundance of these salts play an extremely important role in the potential development of features on Mars, especially related to water and fluvial processes. The availability of soluble salts greatly influences the properties of any water forming on Mars, and is further discussed regarding the formation of liquid brines, or water with an extremely high salt content.

The thin atmosphere of Mars is dominated by carbon dioxide (CO_2). According to Sharp (2012), the composition of the Martian atmosphere is composed of at 95.32% carbon dioxide. Nitrogen makes up an additional 2.7% of the atmosphere and argon 1.6%. Oxygen is 0.13% of the atmosphere and carbon monoxide is 0.08%. The remainder of the atmospheric composition is made of trace amounts of other elements and compounds such as water and nitrogen oxide (Sharp, 2012).

Some current surface features are presumably driven by CO_2 activities, specifically CO_2 frost and sublimation, especially in the higher latitudes and near the polar ice caps, which are made mostly of carbon dioxide (Sylvest, 2013). The abundance of carbon dioxide in the atmosphere and ice caps results in a cycle similar to that of the hydrologic water cycle on Earth, but dominated by CO_2 rather than H_2O (Marshak, 2012). The lack of water and extremely dry atmosphere results in high evaporation rates on Mars, which will play a role in the stability of water on the cold and dry planet. According to Sears and Moore (2005), pure water evaporates under Martian conditions at a rate of approximately 1 mm/hour at a temperature of 273 K.

Section 2.2: Martian Seasons

Seasons are a direct result of the tilted axis of a planetary body. The tilt of the rotational axis causes different regions of a planet to receive radiation from the sun at different intensities and durations depending on the orientation of the axis at different points throughout the orbit. Summer in either the northern or southern hemisphere of a planet occurs when the tilt of the planet is pointing that hemisphere towards the sun, while the other hemisphere is tilted away from the direction of the sun and, therefore, experiences winter (Freedman and Kaufmann, 2005).

Additionally, planetary bodies do not orbit the sun in perfect circles, but rather in ellipses, as discovered by astronomer Johannes Kepler (Freedman and Kaufmann, 2005). This causes the distance between a planet and the sun to vary throughout a planet's orbit. Kepler's second law of planetary motion states that a line segment connecting the sun to a planetary body in an elliptical orbit sweeps out segments of equal areas over equal intervals of time (Freedman and Kaufmann, 2005). Newton's subsequent law of gravity states that the gravitational force between two objects responsible for planetary orbits is inversely proportional to the square of the distance between the two objects. Based on the combination of Kepler's and Newton's laws, we know that planets must be orbiting with a higher velocity when near perihelion, the closest point in the elliptical orbit to the sun, compared to aphelion, the furthest point in the orbit from the sun (Freedman and Kaufmann, 2005). The eccentricity of Mars's orbit has a value of 0.093, compared to a value of just 0.017 for Earth's orbit (NASA Mars Facts, 2015). According to Freedman and Kaufmann (2005), this higher eccentricity causes more dramatic seasonal effects on Mars. In the case of Mars, perihelion, or the closest distance between the sun and the Mars orbit, occurs during northern winter and southern summer, when the northern hemisphere is tilted away from the sun.

Aphelion, or the furthest distance between Mars and the sun, occurs during southern winter and northern summer (Freedman and Kaufmann, 2005).

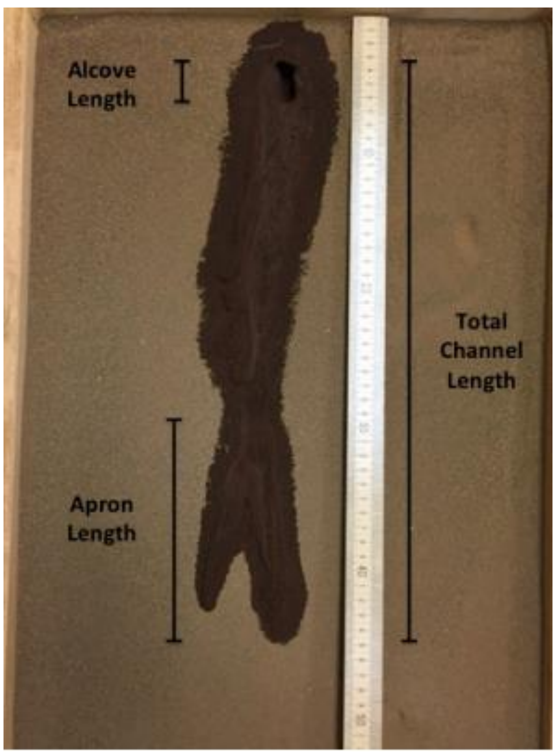
Combined with the greater eccentricity of the Mars orbit, this difference creates a larger variation in seasons depending on hemisphere. The southern hemisphere of Mars experiences more drastic changes between summer and winter temperatures because, during the summer when days are longer and solar radiation is more direct, the planet is also closer in orbit to the sun (Freedman and Kaufmann, 2005). Conversely, the northern hemisphere experiences milder seasonal differences than the summer hemisphere, not getting as cold in the winter or as hot in the summer. This difference is important when further discussing the range in temperatures of different regions of Mars during different times of the year and the possibility for liquid stability on Mars at different times of the Mars year.

Section 2.3: Mars Geomorphology and the Stability of Water and Brines

Surface features and landforms on Mars indicate both past and present processes taking place on the cold planet. Features such as gullies and channels are especially indicative of water and fluvial processes given their association with these eroding processes here on Earth (Ritter et al., 2011). Many of these features were likely initially created in the past when Mars contained a more conducive environment to hosting liquid water (Bennett and Shostak, 2012). Some of these features indicate more recent periods of erosion and development, which imply that the surface of Mars can still be active and that there must be some other driving force or processes besides wind that are playing roles in further evolving these features.

Gullies are slope features that exhibit very unique morphologies. They contain an upper alcove, transport channel, and lower depositional fan or apron (Heydenreich et al., 2015). Figure 2.1 details features of gullies as they were developed in laboratory experiments conducted by

Heydenreich et al. (2015). Figure 2.2 shows well-developed gullies on the surface of Mars (Coleman et al., 2009). Gullies are very closely associated with fluvial processes on Earth (Ritter et al., 2011). It is likely that these processes were also responsible for forming ancient gullies on relatively low slopes on Mars (Heydenreich et al., 2015). Because of the location of these slope features in higher latitudes and the lack of any possibility for stable water in these cold regions, some hypotheses for gully erosion include the use of a CO_2 frost active layer (Dundas et al., 2010; Sylvest et al., 2013). Experiments have been developed to test this hypothesis such as those by Sylvest et al. (2015) in their study of gully erosion as a result of rapidly sublimating CO_2 frost, which can trigger mass wasting events in gully alcoves.



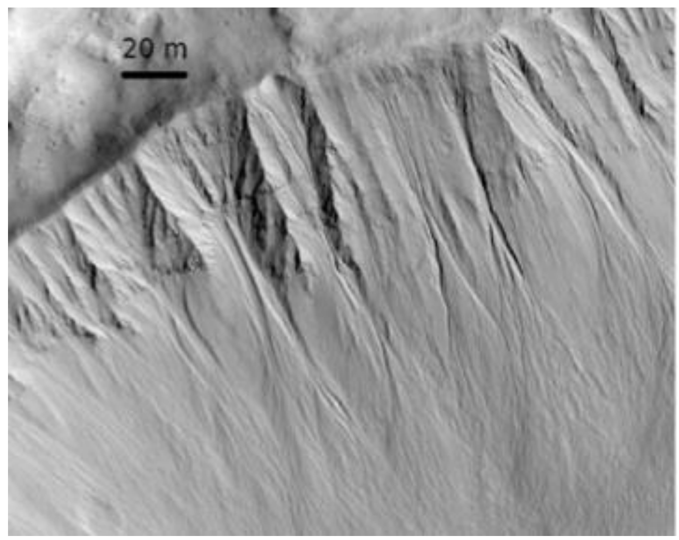


Figure 2.1 (left): Experimentally simulated gully with distinct alcove, channel, and apron (Heydenreich et al., 2015).

Figure 2.2 (above): HiRISE image of gully formation on a crater wall on Mars (Coleman et al., 2009, Image credit: NASA/JPL/University of Arizona).

Current average surface temperatures of Mars indicate an unlikely environment for the formation of liquid water, especially at high latitudes, which generally freezes at a temperature of 273 K. However, the addition of dissolved salts to liquid water both decreases the freezing point and the evaporation rate (Sears and Chittenden, 2005; Chevrier and Altheide, 2008) making salty water a much better candidate for obtaining stable conditions on Mars in the equatorial and lower latitude regions which can reach peak temperatures in the range of 250 K (McEwen et al., 2011). Brines contain an extremely high content of dissolved salts in liquid water; the ions in the water supplied by the dissolved salts serve to significantly decrease the freezing point and evaporation rates of salt-rich fluids (Brass, 1980). The detection of salts on the surface of Mars is necessary for the formation of liquid brines. Orbiters and landers have both indicated that there are no soluble salts in the Martian regolith. It is therefore expected that any water flows existing on the surface of Mars would include dissolved salts, so it is acceptable to assume a significantly decreased freezing temperature for this liquid on Mars (Chevrier and Dixon, 2014).

Section 2.3.1: The Formation of Liquid Brines through the Process of Deliquescence

The formation of liquid brines requires its own driving mechanism in the harsh environment of Mars. Although observations have identified soluble salts on Mars that would easily dissolve into any available water, the source of water remains a limiting factor. The newest analyses of results from the Mars Science Laboratory conducted by Martín-Torres et al. (2015) suggest the process of deliquescence in the formation of liquid brines in the equatorial region. The Mars Science Laboratory is part of the Curiosity rover, which has been exploring the equatorial region of Mars since it landed inside Gale Crater in August 2012 (NASA/JPL Mars Missions, 2015). These most recent analyses have identified perchlorate salts (ClO_4^-) in the equatorial regions, which are particularly associated with deliquescence, a process that could be responsible for the formation of liquid brines (Martín-Torres et al., 2015).

Deliquescence involves the absorption of water vapor out of the atmosphere onto certain salt molecules. Perchlorates are one of the salts that are particularly effective at this process (Martín-Torres et al., 2015). According to their recent study analyzing the environmental conditions of the Mars Science Laboratory site where perchlorates have been identified in Gale Crater, the conditions may be stable enough during some times of the year for perchlorates on the surface of the regolith to deliquesce water vapor out of the atmosphere therefore forming liquid brine which could seep deeper into the regolith through the open pores.

Section 2.4: Recurring Slope Lineae

RSL are evidence of another currently active process on the surface of Mars. The most defining characteristic of RSL is their seasonality. According to McEwen et al. (2011), RSL occur on steep rocky slopes during warm summer months and appear to grow darker and extend longer down slope until the cooler winter months in which they fade to potential disappearance. The slope streaks then reappear, in the same location, cyclically in a similar fashion during the following summer months (McEwen et al., 2011). Figure 2.3 shows the seasonal growth of RSL during the active late spring and summer season. The size of RSL range from 0.5 to 5 meters in width and can extend anywhere for tens to hundreds of meters in length. Initial confirmation of RSL sites by McEwen et al. (2011), indicated that these features have a tendency to form on equator facing slopes

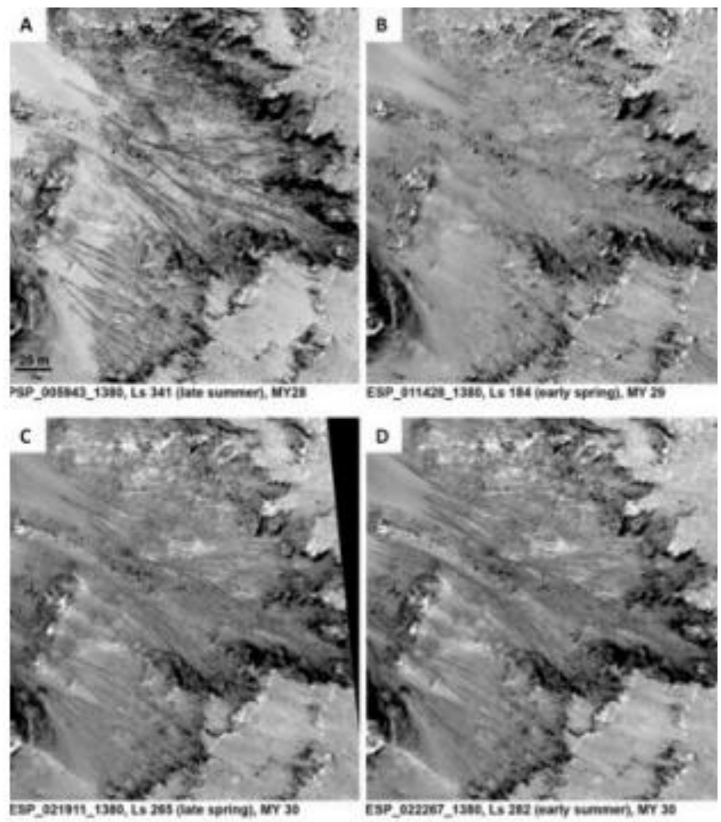


Figure 2.3: HiRISE image of a set of RSL seasonally varying over multiple Mars years: (A) shows dark long streaks in the late summer, (B) shows the very early following spring where streaks have faded, (C) shows gradual darkening and lengthening during late spring and (D) shows dark streaks again in a following summer (McEwen et al., 2011).

between 48^{o} and 32^{o} south latitudes. Since the initial detection of these features in 2006, the HiRISE instrument on the Mars Reconnaissance Orbiter has closely monitored their recurrence (McEwen et al., 2011; Ojha et al., 2014). RSL sites are not confirmed by the HiRISE team until these features are observed to both grow incrementally and reappear in consecutive years (Ojha et al., 2014). Although initial observations confirmed mostly the southern mid-latitude RSL sites, additional observations have continued to identify more candidate sites in the equatorial and northern mid-latitude regions as well. Analyses conducted by Ojha et al. (2014) identified possible RSL locations in both equatorial regions and as far north as 19^{o} north latitude.

The appearance of RSL during the spring and summer suggests an important dependence on temperature in the formation of RSL (McEwen et al., 2011). Equator facing slopes obtain the most direct solar radiation, especially during the summer. This temperature dependence of RSL is further exhibited by their dominance in the southern hemisphere compared to northern latitude regions. Because of the elliptical orbit of Mars, the southern hemisphere summers are longer than the northern hemisphere, so the southern hemisphere regions experience longer warm seasons compared to the northern hemisphere (Freedman and Kaufmann, 2005). This allows the southern hemisphere extended exposure to more direct sunlight for a longer part of the year, and warmer temperatures compared to northern summers. This accounts for a much wider majority of RSL to appear in the southern latitudes. They appear up to 19^{o} in the northern hemisphere compared to as far south as 48^{o} in the southern hemisphere (Ojha et al., 2014).

According to the initial study by McEwen et al. (2011), the slopes that RSL appear on are both extremely steep (25^{o} – 40^{o}) and relatively rocky, including bedrock outcrops that some RSL appear to extend from. Some of the slopes are also associated with small channels (McEwen et al., 2011). RSL mostly appear in large groups of lineae, as depicted in Figure 1.1, which shows a large group of RSL extending downslope on a crater wall in Melas Chasma, within Valles Marineris just south of the equator of Mars.

Section 2.4.1: Potential Formation Mechanisms for RSL and the Antarctic Analog

All of the characteristics and properties of the Mars surface and atmosphere described in the previous sections play important, interconnected roles in hypotheses for potential mechanisms that could form RSL features. The formation mechanism for RSL is still unknown, though there are four leading hypotheses based on both the general appearance and characteristics of the features and the environmental conditions of the regions in which they form. These hypotheses include both dry/granular and aqueous flows on the surface of Mars. One hypothesis involves CO_2 activity such as that which is thought to influence the erosion of gullies (McEwen et al., 2011). However, the temperatures of the regions in which RSL appear in the summer months are too high for sublimating and freezing of CO_2 frost (Chevrier and Dixon, 2014). Mass wasting, as a result of dry processes, also provides a potential mechanism, but dry mass wasting does not demonstrate the same seasonality that is so characteristic of RSL (McEwen, 2011). Pure water aqueous flows have also been proposed because of the possibility of peak temperatures reaching above the melting point for pure water of 273 K for some of the regions in which RSL form (McEwen et al., 2011). However, the time period for these regions to reach peak temperature would be very short and would not provide high quantities of water, which, according to McEwen et al. (2011) would be necessary for pure water to be creating these features.

Based on the temperature dependence of RSL, it seems apparent that some form of liquid or aqueous solution is being made available on a seasonal basis for RSL to form and availability is being cut off when temperatures drop again (Chevrier and Dixon, 2014). This leads to the most important hypothesis for the experiments conducted in this study; RSL could be the result of viscous flows of liquid brines that are supplied to the subsurface and surface of these rocky slopes when temperatures are sufficient enough to reach the associated melting point for this salt-rich water composition (McEwen et al., 2011; Levy, 2012; Chevrier and Dixon, 2014). When peak temperatures begin to decrease with the end of the summer season, the brines refreeze and evaporate, diminishing the appearance of the slope streaks. The growths of RSL have been classified as exhibiting low apparent speeds, extending downslope on the order of only one meter per sol (Grimm et al., 2014). A study by Grimm et al. (2014) compare this rate to that of subsurface flows rather than surface runoff that would occur much more rapidly, leading to the briny subsurface flow hypothesis. According to experimental simulations conducted by Chevrier et al. (2009), increased salt concentration in water also increased the viscosity of the fluid, especially at low temperatures such as those experienced on Mars, and would further decrease the speed of flow feature growth on Martian slopes.

Because previous observations of Mars have identified the presence of subsurface ice, this is a likely source for the dark streaks observed as RSL in the HiRISE images. Levy (2012) used water tracks in Antarctica to propose a useful terrestrial analog for RSL. Water tracks are features that develop in association with thawing permafrost environments in the arid polar climate, and exhibit the same seasonal characteristics as RSL. Figure 2.4 shows water tracks extending downslope in the McMurdo Dry Valleys of Antarctica. Through noticing the similarity in both the appearance (darkening of the surface, mostly linear features) and their seasonal characteristics, these water tracks presented a good analog for the formation mechanism of subsurface flows. Most importantly, water tracks are known to appear as a result of the seasonal thawing of the active layer of subsurface permafrost (Levy, 2012). This supports the hypothesis that liquid brines could be supplied to create RSL from a subsurface layer of frozen water and regolith that only thaw during peak warm months.

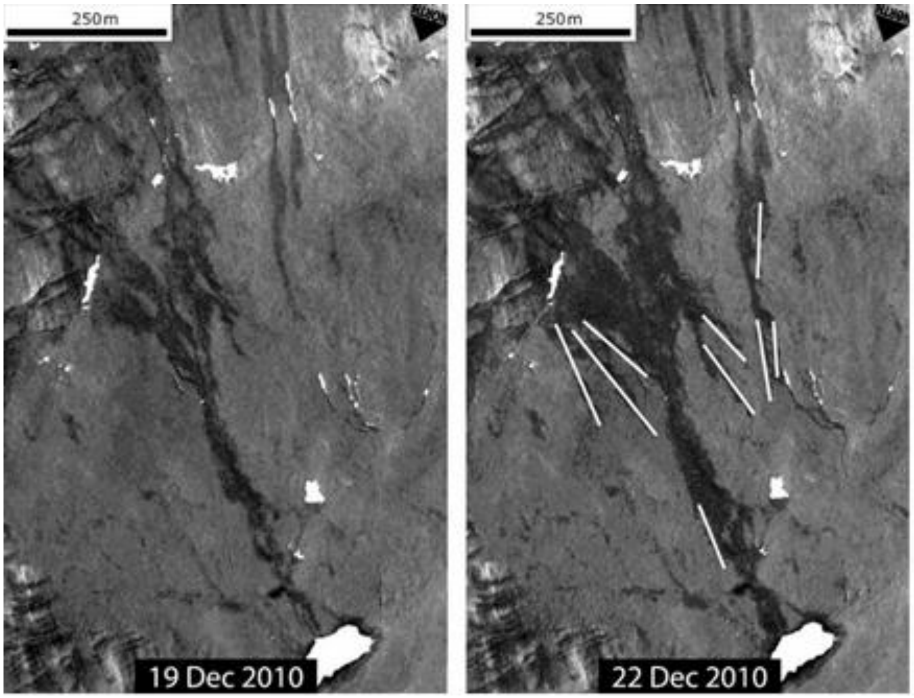


Figure 2.4: Water tracks extending downslope in the McMurdo Dry Valley region of Antarctica. Right image shows lengthening of dark streaks in the downslope direction compared to left image (Levy, 2012).

When discussing the thawing processes in the formation of RSL, the properties of the regolith and surface of the slopes should also be considered. As previously described, the slopes on which RSL appear tend to be both steep and rocky. Large boulders and outcrops have been proposed by McEwen et al. (2011) and by Chevrier and Dixon (2014) to potentially begin thawing of the subsurface frozen layer, creating an initiation point for RSL to be able to begin to form. The surface of regions in which RSL form exhibit relatively low albedos (McEwen et al., 2011), absorbing more of the incoming radiation than some surrounding areas (Freedman and Kaufmann, 2005). Additionally, boulders on the rocky surface generally exhibit higher thermal inertias according to McEwen et al. (2011). Thermal inertia considers the ability of a given material or objects to retain heat and is a measure of how quickly an object reaches thermal equilibrium with its surrounding environment (McEwen et al, 2011). Boulders with higher thermal inertias than the surrounding regolith take longer to reach equilibrium and therefore retain heat better. Because of this, Chevrier and Dixon (2014) suggest that that boulders and bedrock outcrops in contact with the permafrost-like layer on Mars can warm up more quickly, thawing that particular area more rapidly.

Section 2.5: Previous Research and Laboratory Simulations

The Arkansas Center for Space and Planetary Sciences, as well as other institutions such as Open University in the UK, have conducted multiple studies on the development and evolution of various Martian surface features and properties, including those initiated by liquid water and brines (Conway et al., 2011; Sylvest et al., 2015). Previous research has especially focused on the formation and erosion of gullies and the impact of various viscous flows on their morphologies, specifically how different viscosity fluids affect the alcove, channel, and depositional fan features of gullies (Coleman et al., 2009; Addison et al., 2010). Laboratory simulations of flows at the Arkansas Center have used both sand and other Martian regolith simulants, including Mojave Mars Simulant (MMS) and JSC Mars-1, developed by Johnson Space Center (Heydenreich et al., 2015).

Although many previous groundwater flow simulations have been conducted, they have all largely focused on the development of features resulting from a point source of water intended to provide water to the subsurface of the regolith (Coleman et al, 2009; Conway et al., 2011; Heydenreich et al., 2015). For example, Conway et al. (2011) introduced water into the system via a pipe into their Martian environment chamber for experiments that created features with similar morphologies to RSL at extremely low temperatures and low pressures. These experiments are important because of the lack of current understanding of the source of water or brine that could be creating these features. The hypothesis developed by McEwen et al. (2011), and supported by the water track analog (Levy 2012), implies a source of liquid in the form of an underlying layer of permafrost. Based on this hypothesis, some additional useful experiments would include a full layer of subsurface frozen regolith rather than the simple placement of a hose or pipe under the surface of the regolith that would create a single point source of liquid into the system. The successes of subsurface flows in these experiments from a point source also raise the possibility of a point source being created from a specific location within the subsurface permafrost layer.

Grimm et al. (2014) conducted modeling of the water budget for RSL considering a groundwater-flow mechanism for the formation of the seasonal dark streaks. This study considered both pure water and brines, and results showed that pure-water flows would require a shielding layer of dry regolith above the water to prevent the rapid evaporation of pure water from inhibiting the continuation of the flow. Given the strong support for briny water, however, the results for this type of flow were more useful to the development of the experiments in this study. The research concluded that in order for features to form on the scale that RSL form on Mars, the source of briny water that form the features must be extremely close to the surface because of the large amount of aqueous fluid that would be needed to create the features and the small amount of water that would be expected to actually melt out of the permafrost layer and become subject to evaporation (Grimm et al., 2014).

When conducting Mars simulations in the laboratory, experiments need to consider the formation of features under lower pressures because of the weaker Martian atmosphere. Although some institutions have the resources to model the environmental pressure of Mars in a simulation chamber, it is generally difficult to simulate 7 mb of pressure. Previous experiments conducted in these environmental chambers have indicated that the lower pressure environments do not greatly influence the morphologies of features that form compared to those at Earth atmospheric pressure (Jouannic et al., 2015).

The experimental setups for the simulations conducted in this study were modeled based on the briny subsurface liquid hypothesis and the water track terrestrial analog to RSL. Experiments were designed to mirror known Mars conditions in the equatorial and mid-latitude regions in which RSL form and the Antarctic environment in which water tracks form. These conditions included shallow to steep slopes, placement of model boulders, and variation in topographic distribution.

Chapter 3
Experimental Methods

The simulation of the formation of RSL were broken up into four major sets of experiments, with slight adjustments to the experimental setup for each set to try to obtain the best results. The two major variables tested were changes in the topographic distribution of the regolith used and the effects of the placement of larger particles in the regolith, simulating the existence of boulders on Martian slopes where RSL appear. The main goal of these experiments was to determine the most probable topographic distribution and variation in particle size size to recreate RSL in a laboratory setting. Insight obtained into how these variables control the formation of RSL allowed connections to be drawn into the formation of RSL on Mars. Based on those results, further development of experimental simulations was established.

All of the experiments in this study utilized small, open top boxes in which a permafrost layer of regolith was created in the bottom of the boxes by freezing a mixture of sediment and water. The boxes were put through cycles of freezing and thawing to simulate the possible diurnal and/or seasonal melting of the underlying frozen regolith that could produce RSL. Throughout each experiment, extensive observations were made of any features that formed during the thawing of the permafrost within the small box system. Photographic evidence was taken to support all observations. Tables 3.1, 3.2, 3.3, and 3.4 describe the experimental setup for each individual experiment within Sets 1, 2, 3, and 4, respectively. Variations within the setups include the box used, the regolith type, the slope that the box was placed on for thawing, as well as the environment and temperature in which freezing and thawing occurred.

Section 3.1: Topographic Distribution Variations with Thawing at Ambient Temperature

The first set of RSL experiments was conducted at the Arkansas Center for Space and Planetary Sciences, using a Plexiglas, open top box shown in Figure 3.1. This box measured approximately 30-cm long, 10-cm wide, and had sloping sides from 15-cm to 3-cm high. The first four experiments were put through freezing cycles using a domestic freezer at about -18^{o} C, and were thawed at ambient temperatures of approximately 20^{o} C. Poorly sorted quartz, playground sand was used as the first regolith and mixed with tap water. A frozen permafrost layer was prepared in the Plexiglas box by filling the bottom evenly with about three centimeters of playground sand and fully saturating the layer with tap water. When the sand was sufficiently saturated, with minimal presence of excess water on the surface, the box was placed in the freezer to create the permafrost layer.

Figure 3.1: Plexiglas box with sloped sides.

For Experiments 1.1–1.4, the box was removed from the freezer once the permafrost layer was completely frozen and an overburden of dry sand was spread on top in four different topographies. The system was only refrozen during experiments in which some indication of linear features formed. With each subsequent experiment, a new topography was chosen based on the results of the previous experiment. The topographic distribution of the overburden sand in Experiments 1.1–1.4 included, respectively, a flat, even distribution on top of the entire permafrost, a sloped overburden with approximately eight centimeters at the top of the box down to the level of the permafrost at the front of the box, a sloped overburden across the width of the box, and an overburden in which a small depression was implemented down the center of the box. All of these setups are shown in Figure 3.2 and described in Table 3.1.

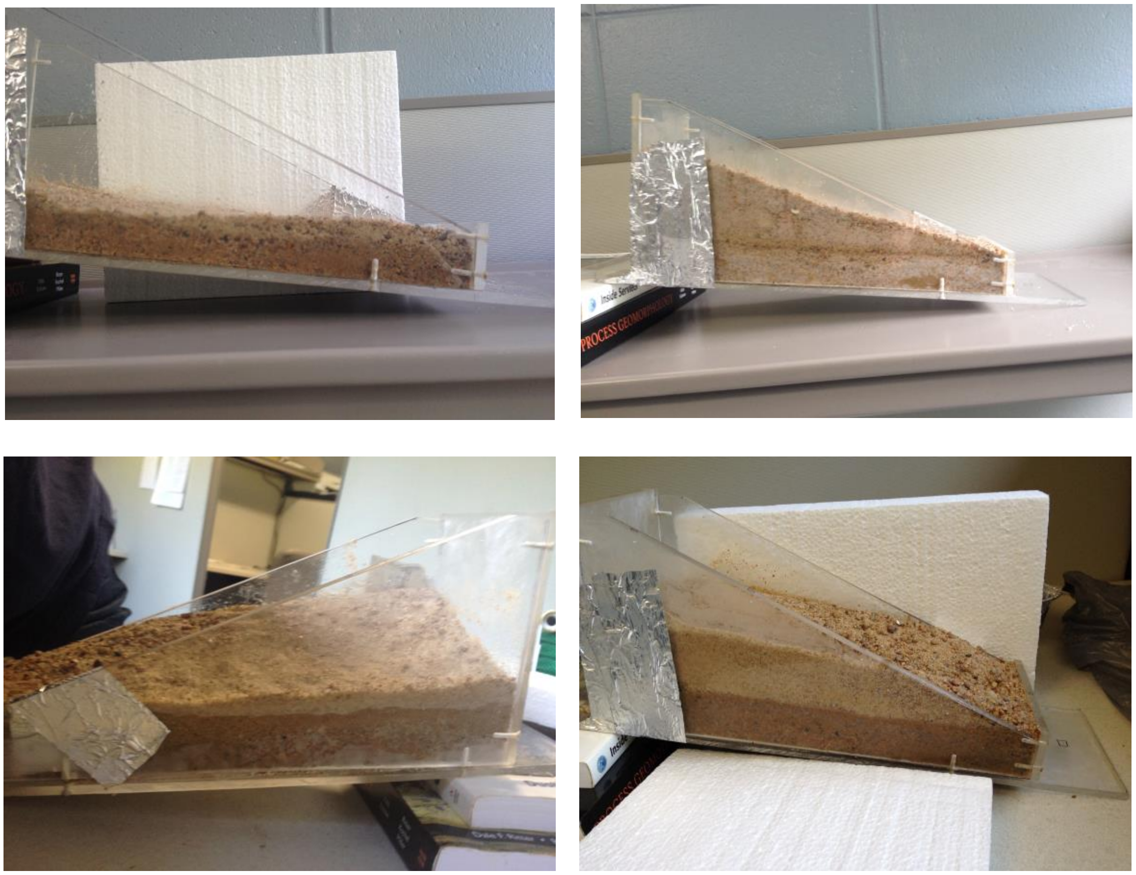


Figure 3.2: Topographic distribution of regolith in Plexiglas box for Experiment 1.1 (top left), 1.2 (top right), 1.3 (bottom left), and 1.4 (bottom right).

Table 3.1: Experimental setups for Set 1 of RSL experiments.

Experiment	Box Apparatus	Regolith Type	Slope	Freezing and Thawing Conditions	Regolith Distribution and Overburden Conditions
1.1	Plexiglas	Poorly sorted quartz sand	12^{o}	-18^{o} domestic freezer, 20^{o} C ambient thaw	Flat layer, approximately 1 cm deep
1.2	Plexiglas	Poorly sorted quartz sand	12^{o}	-18^{o} domestic freezer, 20^{o} C ambient thaw	Sloped along slope of box, 8 cm deep at the top
1.3	Plexiglas	Poorly sorted quartz sand	12^{o}	-18^{o} domestic freezer, 20^{o} C ambient thaw	Sloped across width of the box
1.4	Plexiglas	Poorly sorted quartz sand	12^{o}	-18^{o} domestic freezer, 20^{o} C ambient thaw	Linear depression down center of the box

After the dry layer was distributed on top of the permafrost, the box was placed at ambient temperature on a slope of about 12° to thaw. Although this slope is relatively low compared to those of RSL, which tend to be steeper slopes of about 25° - 40°, a 12° slope was initially used as a representation of the lower slopes where water tracks, the Antarctic analog to RSL, form. This slope remained constant for Experiments 1.1-1.4. Because RSL appear on continuous slope surfaces without edges, pieces of Styrofoam were used to surround the sides of the box to insulate the system and to maximize melting from the surface rather than the edges. Observations were made during the thawing process of the permafrost. As melting progressed and features formed, photos were taken and used for comparison of the results. For experiments in which linear features formed, the partially thawed permafrost was placed back into the freezer for another cycle of freezing and thawing. In the second thaw process, observations were made of the subsequent features forming and additional photos were taken for comparison with the original thaw cycle. Following the completion of an experiment, sand was generally removed from the box and left out in aluminum pans to air dry before being reused in a later experiment.

Section 3.2: Cold Room Cycles at Arkansas Center for Space and Planetary Sciences

The second set of experiments differed from the others in that freezing and thawing cycles used a set of two cold rooms at the University of Arkansas. These setups are described in Table 3.2. The cold rooms were connected and included one room at 4° C with an adjacent cold room at -20° C to simulate conditions more similar to the Mars surface in the equatorial to mid-latitude regions in which RSL form. A 150-Watt heat lamp was used in some experiments in the 4° C room for thawing to simulate direct radiation from the surface. Experiments conducted in these rooms included both another topographic distribution experiments similar to Experiment 1.4 followed by the first of the simulated boulder experiments.

Table 3.2: Experimental setups for experiments conducted in Set 2 using cold rooms at University of Arkansas.

Experiment	Box Apparatus	Regolith Type	Slope	Freezing and Thawing Conditions	Regolith Distribution and Overburden Conditions
2.1	Plexiglas	Poorly sorted quartz sand	12^o	-20^o C and 4^o C cold rooms; last thaw used 150-W heat lamp	Linear depression down center of box, as in 1.4.
2.2	Copper	Poorly sorted quartz sand	12^o	-20^o C for freezing 4^o C with 150-W heat lamp for thawing	1.5-cm metal nuts and 2.5-cm metal cap embedded in permafrost Overlying dry layer approximately 1-cm deep.
2.3	Copper	Poorly sorted quartz sand	12^o	-20^o C for freezing 4^o C with 150-W heat lamp for thawing	1.5-cm metal nuts, 2.5-cm metal cap, and <1-cm metal spheres embedded in permafrost. Slight coating of dry regolith overburden.
2.4	Copper	Poorly sorted quartz sand	12^o	-20^o C for freezing 4^o C with 150-W heat lamp for thawing	5-cm diameter steel sphere embedded in permafrost. Slight coating of dry regolith overburden.
2.5	Copper	Poorly sorted quartz sand	12^o	-20^o C for freezing 4^o C with 150-W heat lamp for thawing	5-cm diameter steel sphere embedded in permafrost Dry overburden layer approximately 0.5-cm deep.

Section: 3.2.1 Topographic Distribution Experiment

The additional topography experiment, Experiment 2.1, was carried out in the cold rooms in order to investigate the effects of the same topographic overburden used in Experiment 1.4 under the cold room conditions. Experiment 1.4 cycled through multiple freezing and thawing periods in which thawing occurred in the 4^o C cold room on a 12^o slope during the day and freezing took place on the same slope in the -20^o C cold room for extended periods. Additionally, the 150-Watt heat lamp was introduced into the thawing process during the last thaw cycle. The heat lamp was placed approximately 30 cm above the surface of the box, as shown in the setup in Figure 3.3. The heat lamp was used during thawing in the 4^{o} C cold room to simulate direct heating from the surface down through the regolith, as would occur on the surface of Mars from solar radiation, rather than from the sides. Observations were made and supported with photos in the same manner as in the first set of topography experiments.

Figure 3.3: Thawing setup in the 4^{o} C cold room with heat lamp applied approximately 30 cm from the surface.

Section 3.2.2: Simulated Boulder Experiments

Following Experiment 2.1, adjustments were made to the methods for the following cold room experiments, which focused on the effects of different particle size and materials in the regolith. A new, slightly wider, copper metal open top box was used for Experiments 2.2–2.5. This box measured 30-cm long, 15-cm wide, and also had sloped sides that ranged from 12.5 cm at the top to 2.5 cm at the bottom. The metal box was placed in the -20^{o} C cold room with a mixed, saturated layer of poorly sorted quartz sand and water, similar to the permafrost layer in previous experiments. In these experiments, the overburden layer of sand and additional large particles were introduced into the system after the bottom layer was frozen and the whole box remained in the -20^{o} C room to allow the dry layer to reach the same temperature as the permafrost before thawing. Additionally, the 150-W heat lamp was used in all thawing processes at a height approximately 30 cm above the surface of the regolith.

Experiments 2.2–2.5 used various metal pieces to examine the role of boulders on the rocky slopes that form RSL. Table 3.2 details the specific metal hardware and spheres used in each of these individual experiments. Experiments 2.2 and 2.3 used a variety of metal nuts and metal caps. These small pieces varied in both size and color and included a 2.5-cm dark metal cap, two 1.5-cm metal nuts, one that was light gold in color and one that was rusted and, therefore, darker in color, and a small silver nut. In Experiment 2.3, two small metal spheres were added, one that was silver and one that was rusted into a darker color. All of these pieces can be seen in Figure 3.4. In Experiments 2.4 and 2.5, only a steel sphere with a 5-cm diameter was used to represent a large boulder. This sphere was centrally embedded in the permafrost at the top of the slope.


Figure 3.4: Metal hardware partially embedded in regolith to simulate boulder effects. Left to right: 1.5-cm light gold nut, rusted metal sphere (<1 cm), 2.5-cm dark metal cap, silver metal sphere, and 1.5 cm rusted metal nut.

In Experiments 2.2–2.5, any of the metal pieces used were placed into the box at the same time as the mixture of sand and water that created the permafrost. They were partially embedded in the top of the mixture and then placed into the -20^{o} C cold room to freeze. While still in this room, a thin and evenly spread dry layer or coating of sand was spread on top of the frozen permafrost and allowed to reach the same temperature as the frozen regolith. Then the entire box was removed to the 4^{o} C room for thawing with the heat lamp. For experiments in which more than one metal piece was used, the pieces were placed across the width of the box, as can be seen in Figure 3.4, in order to avoid interference between different potential linear features that would form down slope in the box. Photos and extensive notes were again taken during the thawing process to describe the way in which the permafrost melted, paying close attention to the regolith immediately surround the metal pieces and spheres in the box.

Section 3.3: Continued Topography Experiments at Connecticut College

The first set of topographic experiments was followed up at Connecticut College in the fall of 2014 with Experiments 3.1-3.3, described in Table 3.3. Experiments conducted at Connecticut College utilized a cut down Styrofoam cooler. This box had inner dimensions of 32-cm in length and 24-cm in width, with 2-cm of Styrofoam insulation on all sides. This Styrofoam open top box was chosen to eliminate the problem of finding sufficient insulation so that the majority of thawing would happen from the surface down rather than from the sides and bottom. It was also reinforced with fiberglass strand tape around the outside to avoid cracking of the box during freezing and thawing cycles.

Table 3.3: Experimental setups for RSL experiments conducted in Experiment Set 3 at Connecticut College, following initial topographic distribution experiments of Sets 1 and 2.

Experiment	Box Apparatus	Regolith Type	Slope	Freezing and Thawing Conditions	Regolith Distribution and Overburden Conditions
3.1	Styrofoam	Loess	30^{o}	-18^{o} domestic freezer, 20^{o} C ambient thaw	Distinct linear depression down center of box
3.2	Styrofoam	Loess	30^{o}	-18^{o} domestic freezer, 20^{o} C ambient thaw	Slight central swale
3.3	Styrofoam	Fine-grained quartz sand	30^{o}	-18^{o} domestic freezer, 20^{o} C ambient thaw	Slight central swale

Experiments 3.1-3.3 were conducted in this Styrofoam box using a domestic freezer for freezing and a laboratory at ambient temperature for thawing. Figure 3.5 shows these experiments thawing on a slope of 30^{o} during thawing, which is more comparable to the steep slopes on which RSL form. Experiments 3.1 and 3.2 used loess obtained from the Connecticut College Arboretum, with a composition of 60% sand, 30% silt, and 10% clay. The samples were sieved with a 4.00-mm diameter sieve before use to remove any large particles and left out to dry

before using. The preparation of a permafrost layer was similar to those in Experimental Sets 1 and 2. A layer of loess was spread evenly across the bottom of the Styrofoam box to a depth of 3-4 cm and then saturated with tap water. After evenly mixing and distributing the water and loess, the box was placed into the freezer overnight. After the layer was frozen, the box was removed and an overburden of dry loess was spread on top of the permafrost. The whole system was then placed back into the freezer to prevent melting from the warmer overburden on top.

Figure 3.5: Styrofoam box set to thaw at ambient temperature on 30^{o} slope in the lab at Connecticut College.

In Experiment 3.1, the topography of the overburden included a depression down the center of the box with the highest depth of dry loess on the sides at an additional depth of about 3-4 cm. In Experiment 3.2, the overburden of loess was very thin on top of thicker permafrost, with only a slight swale down the center of the box. A swale is a very gentle slope, creating just a slight depression in the ground surface. Experiment 3.3 was set up the same way, except well-sorted, fine-grained quartz sand was used as a regolith. The permafrost layer of sand was 100% saturated with pure water before freezing. During the freeze cycle in Experiment 3.3, a thin overburden of dry sand was spread on top of the permafrost with a very slight swale down the center. The box was refrozen with the overburden in place in order to allow the layers to reach the same temperature. Upon removing the box for thawing in Experiments 3.1-3.3, it was placed on a slope of 30^{o} and observations were made in a similar manner to the previous sets of experiments. Photographic evidence was taken to support consistent and detailed observations of the melting process and of any features that developed in the system.

Section 3.4: Continued Simulated Boulder Experiments at Connecticut College

The fourth and final set of experiments was conducted for this research at Connecticut College and was a continuation of the preliminary simulated boulder experiments done in Experimental Set 2. In this set of experiments, detailed in Table 3.4, the same Styrofoam box setup was used. Initially, a permafrost layer was generated using a 3-cm deep, even layer of fine sand. It was fully saturated with tap water in the lab. In Experiment 4.1, four marbles of different size and color were embedded in the permafrost in a line at the top of the slope during the thawing cycle. The marbles had diameters of 1.0 cm, 1.5 cm, and 2.5 cm. The colors of the marbles were not intended to influence the system or to be tested as particular variables. The important characteristic of the marbles was their varying sizes, and the different sizes used happened to be different colored marbles. Experiments 4.2 and 4.3 were similar to Experiment 4.1, but used more marbles, which were all still the same three sizes. These marbles were embedded into the permafrost layer before freezing as shown in Figure 3.6. The overlying dry layer of regolith was spread after the permafrost layer had frozen, and replaced into the freeze to reach the same temperature. The overlying sand in these three experiments were distributed as lightly and evenly as possible in order to strictly examine the effects that the large particles had on the system during thawing.

Figure 3.6: Marbles with 1.0-cm, 1.5-cm, and 2.5-cm diameters embedded in saturated regolith before freezing.

Table 3.4: Description of experimental setups for Experimental Set 4, continued simulated boulder experiments conducted at Connecticut College.

Experiment	Box Apparatus	Regolith Type	Slope	Freezing and Thawing Conditions	Regolith Distribution and Overburden Conditions
4.1	Styrofoam	Fine-grained quartz sand	30^o	-18^o domestic freezer, 20^o C ambient thaw	Marbles embedded in permafrost with 1.0-cm, 1.5-cm, and 2.5-cm diameters Overlying dry layer between 3-6 mm deep
4.2	Styrofoam	Fine-grained quartz sand	30^o	-18^o domestic freezer, 20^o C ambient thaw	Marbles embedded in permafrost with 1.0-cm, 1.5-cm, and 2.5-cm diameters Overlying dry layer between 6-10 mm deep
4.1	Styrofoam	Fine-grained quartz sand	30^o	-18^o domestic freezer, 20^o C ambient thaw	Marbles embedded in permafrost with 1.0-cm, 1.5-cm, and 2.5-cm diameters Overlying thin coating, under 0.5-cm deep throughout

Section 3.5: Large Flume Construction

Following the first set of topography experiments described in Section 3.1, a metal flume was constructed for future use with larger scale RSL experiments at the Arkansas Center for Space and Planetary Sciences. This flume was 1.5-m long by 0.6-m wide and was constructed using aluminum c-channel and aluminum sheeting. The motivation for constructing this flume came from the need for a means to provide longer slopes for RSL to form, in addition to greater topography variation across the width of the slope. Additionally, the design of the flume was initially created to support the flow of liquid nitrogen in the area surrounding the flume for cooling of the regolith in future experiments. The construction process for this flume involved drilling holes in the aluminum c-channel stringers that were then connected to make up a grid-like main structure of the flume, shown in Figure 3.7. Each joint within the grid was further supported by individually made metal blocks. The completed grid frame will be covered with aluminum sheeting when completed. The large, lightweight metal flume will also contain an adjustable arm to create various slope angles for different experiments. The results from this study will be used to determine experimental setups for additional topography and boulder simulation experiments to be conducted in the large cold rooms at the Arkansas Center for Space and Planetary Sciences.

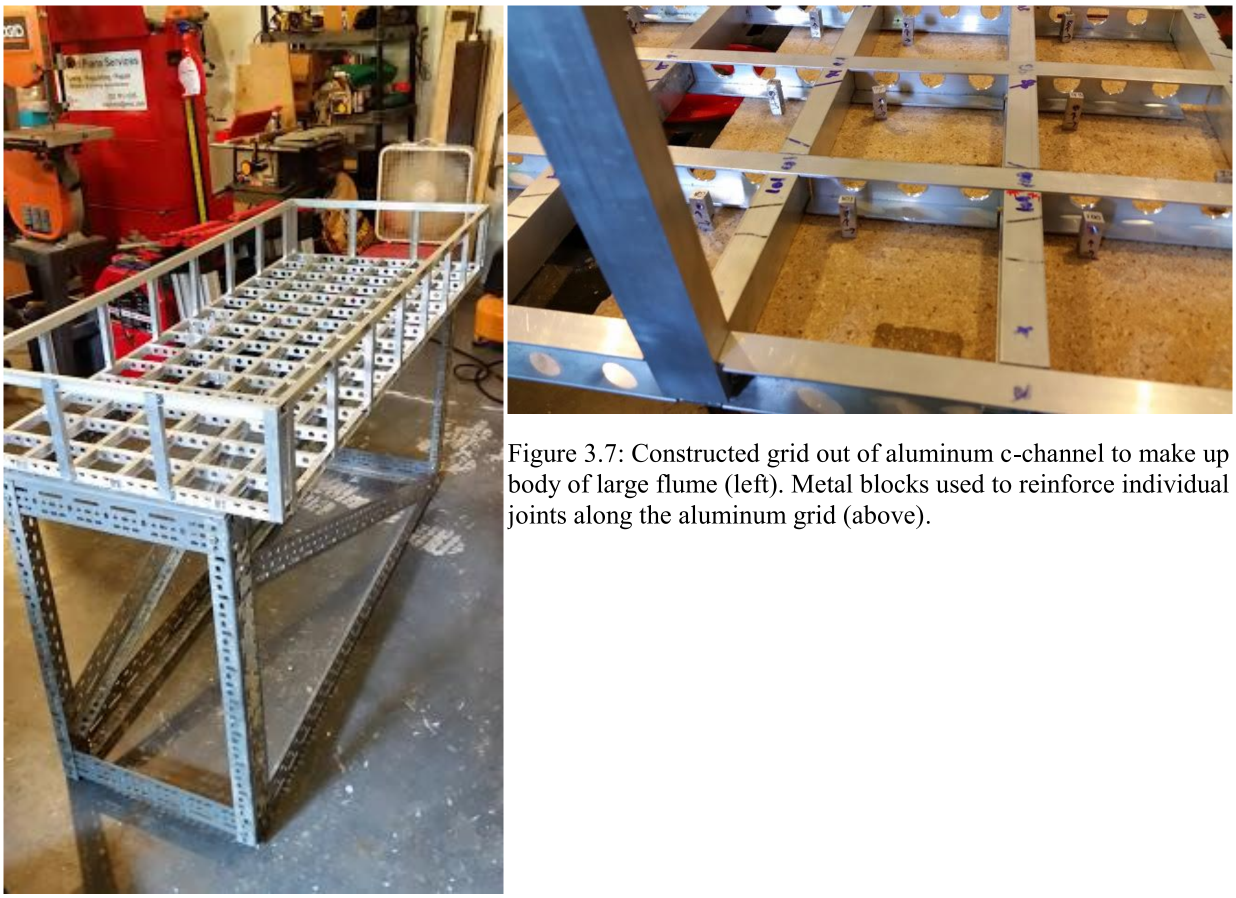


Figure 3.7: Constructed grid out of aluminum c-channel to make up body of large flume (left). Metal blocks used to reinforce individual joints along the aluminum grid (above).

Chapter 4
Observations and Results

Photography was the most important form of documentation of results throughout each experiment conducted in this study. Throughout the various thawing processes, images were taken of the system and of specific thawing patterns and features formed, which were then used for comparison among experiments. During the thawing cycles, darkening of the dry layer of regolith on top of the permafrost was taken to indicate wetting of that area due to thawing of the underlying layer. The results from Experimental Sets 1, 2, 3, and 4 are summarized in Tables A1-A4, respectively, found on pages I-IV of the appendix.

Section 4.1: Topographic Distribution Variations with Thawing at Ambient Temperature

The four topographic distribution experiments conducted at the Arkansas Center for Space and Planetary Sciences each thawed in a slightly different pattern. Based on the thawing trends of the previous experiments, the next setup was designed to thaw in a pattern more closely related to the linear features of RSL. Linear-like features only appeared in Experiments 1.3 and 1.4, and so these experiments used additional cycles of freezing and thawing.

Experiment 1.1

The initial topography experiments conducted at the Arkansas Center for Space and Planetary Sciences each yielded results that influenced the distribution of the dry overburden layer for subsequent experiments. The first experiment, 1.1, contained an even layer of dry sand on top of the permafrost. Upon removing the frozen layer of sand and water from the freezer, there was a patch of ice on the upper left-hand side of the permafrost due to excess water in the system before freezing. The ice patch can be seen in the image in Figure 4.1a. When the 1-cm deep dry overburden of sand was added on top of the permafrost, the ice patch was left uncovered. After 60 minutes of thawing at ambient temperature, there were no notable changes to the appearance system except for slight melting of the open ice patch. There was no indication of movement of meltwater in the system in the form of darkening of the dry layer, from either the melting ice patch or the melting underlying permafrost layer. After an additional 60 minutes of thawing, the size of the ice patch had shrunk and the surrounding sand was slightly darker and wetter than previously. There was also darkening of the overburden sand at the bottom of the 12^{o} slope that the box was sitting on, which can be seen at the bottom of the box in Figure 4.1b. The dark section of sand extending across the bottom of the slope continued to get darker as the remaining overburden became uniformly dark and wet until the entire system, except for the very top of the slope, showed signs of wetting approximately 3 hours into the thaw. At this point, the ice patch had completely melted leaving a small depression in the system where it had been, and the box appeared as seen in Figure 4.1c.

Figure 4.1a: Appearance of system at the beginning of the first thaw. Ice patch appears in top left of box.

Figure 4.1b: Appearance after two hours of thawing with melting ice patch and darkening at bottom of slope.

Figure 4.1c: Following three total hours of thawing, a small depression remains in place of the ice patch and additional darkening at bottom of the box.

Experiment 1.2

Upon removing the box from the freezer for Experiment 1.2, the permafrost layer did not appear to be overly saturated as in the first experiment. Some loose sediment sat on top of the frozen material, indicating that there was not excess water this time around. Following the observations made in Experiment 1.1, the topographic distribution of the overlying sand was not placed evenly deep throughout the box in Experiment 1.2. Observations were taken at similar time intervals to those in Experiment 1.1 and showed darkening of surface sand occurred earlier where the overburden was thinnest. After one hour of thawing, the overlying sand was wet across the width of the bottom of the slope, as shown in Figure 4.2a. This wetting increased moving further up the slope as the thawing process continued. After an additional hour of thawing, the darkening of the top layer of sand extended up and covered approximately a third of the total length of the slope, as shown in the Figure 4.2b. After a total of three hours of thawing, the top of the slope still did not indicate any wetting of the top layer of sand and the experiment was stopped to prepare a new permafrost layer to thaw with a different topographic distribution.

Figure 4.2a (left): Darkening of regolith beginning at the bottom of the slope after 60 minutes of thawing.

Figure 4.2b (right): Wetting of surface regolith extending slightly further upslope after an additional 60 minutes.

Experiment 1.3

Experiment 1.3 started with a newly generated permafrost as a bottom layer with the same 2.5-cm thickness as the previous two experiments. The overburden in this experiment, however, was sloped perpendicular to the 12^{o} slope that the whole box sat on. Figure 4.3a shows sloped topography of the dry sand, with the highest point on the left hand side when looking at the box and the lowest elevation on the right. The bottom right corner of the box showed the first signs of darkening, after only 20 minutes of being removed from the freezer (Figure 4.3b). The bottom right section of the box continued to darken and wetting extended upslope along the right side of the box as thawing continued. After three hours of thawing, the right side of the box was wet in a nearly linear form, in addition to a section of wetness across the slope of the box at the very bottom. The right side wetness extended partly up the slope of the sand. The appearance of the box after three hours can be seen in Figure 4.3c.

Figure 4.3a: Overburden regolith distributed in slope with deepest region on left side of box and low-lying region along right side

Figure 4.3b: Darkening of regolith observed in bottom right corner of box and slightly across width after 20 minutes of thawing

Figure 4.3c: After three hours of thawing, darkening of surface both across the width of the bottom of the box and extending in a linear trend along the right side of the box

Because Experiment 1.3 was the first to create a feature with a slightly linear appearance, along the right side of the slope, it was placed back into the freezer after three and a half hours of thawing to simulate a refreezing of the system. The box was then removed to ambient temperature for a second thawing cycle three hours later. At the beginning of this thaw, the box appeared the same as it did at the beginning of the experiment. After 45 minutes of thawing, the sand appeared to be wetting at the bottom of the sloped box and the surface eventually became uniformly wet. The wetting did not occur in the linear trend along the right side of the box as it did in the first thaw. Upon removing the overburden of sand from the system following thawing, the underlying permafrost layer did not appear to be evenly spread, as it was when it was made at the beginning of the experiment. Figure 4.4 shows the appearance of the system after removing the top layer of thawed sand. The left side, where the overburden was thicker, contained higher, uneven frozen sand and water at the end of the experiment.

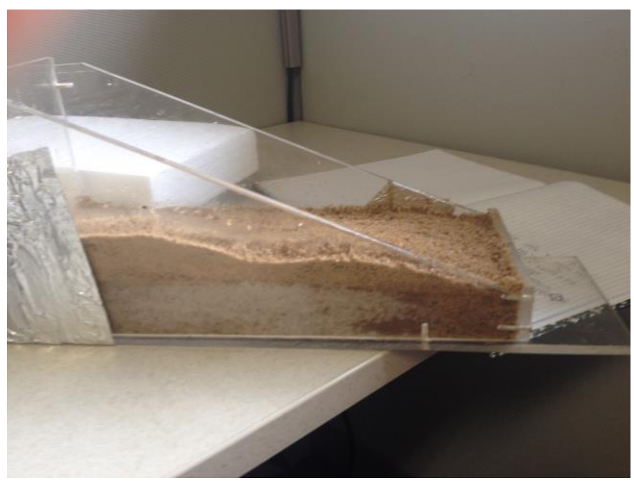


Figure 4.4: Appearance of underlying permafrost after second thawing cycle. Images were taken after loose overburden sediment was removed, showing frozen regolith at a high elevation on left side of the box compared to the right.

Experiment 1.4

The dry sand overburden in Experiment 1.4 was distributed to contain a valley down the center of the box along the 12^{o} slope, with higher sand on both the left and right sides. While spreading the overburden on top of the frozen layer after it was removed from the freezer, larger particles in the poorly sorted sand had a tendency to fall from the sides and end up in the central depression formed in the sand. After placing the overburden on top, the dry layer showed signs of wetting within 45 minutes. Initial darkening of the overburden occurred in a line within the central valley (Figure 4.5a). The small section across the bottom of the sloped box also darkened. Once the linear feature along the center appeared after just 45 minutes of thawing, the box was replaced into the freezer and removed the following morning.

When the box was removed from the freezer to re-thaw, darkening of the surface began after only 20 minutes and was initiated both in the central valley and at the top of the left and right sides of the box where the overburden was the highest (seen in Figure 4.5b). From these locations, the wetting began to extend down the left and right slopes of the sand in the direction of the central valley, while the center continued to darken. After 60 minutes of thawing, the entire surface of the sand was uniformly wet (Figure 4.5c).

Figure 4.5a: Darkening of surface regolith after 45 minutes occurring down the length of the central linear depression and across the width at the bottom of the box.

Figure 4.5b: Darkening of surface along the central channel, bottom of slope, and sides of box after 20 minutes of second thawing cycle.

Figure 4.5c: Dark appearance of entire surface regolith after 60 minutes of second thaw.

Section 4.2: Cold Room Cycles at the Arkansas Center for Space and Planetary Sciences

Experiment Set 2 yielded results based on both topographic distribution and model boulder effects on the thawing systems. Experiment 2.1 occurred over a very long time period in the cold rooms at the Arkansas Center for Space and Planetary Sciences, while Experiments 2.2-2.5 tested the effects of large metal particles, and occurred on a much shorter time scale because of the rapid thawing of the system during use of the heat lamp in the cold room.

Section 4.2.1 Topographic Distribution Experiment

Because the linear depression in the last experiment of Set 1 was the most useful in developing a linear feature during the thawing process, this topographic distribution was investigated in the -20^{o} C and 4^{o} C cold rooms. Figure 4.6a shows the beginning of the thawing process in the 4^{o} C cold room with the same depression of overlying dry sand down the center of the box as was used in Experiment 1.4. After 24 hours of thawing in the 4^{o} C cold room, observations of darkening or wetting of the surface were minimal. The image in Figure 4.6b was taken after approximately 30 hours of thawing. This image, when compared to that taken at the beginning of the thawing process, shows that after 30 hours of thawing there was a slight darkening of the central valley in addition to some wetting at the edges of the box, which were not insulated in this particular experiment. The darkening of the central depression in Experiment 2.1, however, is extremely subtle compared to the start of the thawing process, unlike in the experiments from Set 1.

Figure 4.6a (left): Appearance of overburden and central valley in 4° C cold room at start of thawing.

Figure 4.6b (right): Slight darkening down center of box only slightly apparent after 30 hours of thawing.

When the box was removed from the six-day-long freeze in the -20° C cold room, thawing observations were similar to those during the first thaw. As in the first thaw, the central valley appeared slightly wet only upon extremely close observation. Overall, a large difference in the appearance of the system was not observed 24 hours into the second thawing process. After an additional 24 hours, there still was no major change in the appearance of the regolith. After a total of three days of thawing, the box appeared to only have extremely subtle wetting down the central valley, similar in appearance to the second image in Figure 4.6b. Comparisons between the images at the start of thawing and the end in both thawing cycles show the difficulties in detecting the changes in appearance of the system because the wetting of depression was so slight and was mostly only noticed upon extremely close observations. It was not distinctly picked up by the camera used in the cold room. When the 150-W heat lamp was applied to the system in the 4° C cold room, a uniformly dark surface was observed after 60 minutes of thawing.

Section 4.2.2 Simulated Boulder Experiments

Experiment 2.2 used the heat lamp to thaw the system with the embedded larger particles in the permafrost representing boulders on the rocky Martian terrain in which RSL form. The heat lamp, representing direct solar insolation, thawed the system very rapidly in the 4^{o} C cold room. After the first 15 minutes of thawing, no observable change was seen in the surface of the regolith. An additional 15 minutes later, Figure 4.7 shows patches of wetness throughout the box, especially at the bottom of the slope, with no direct correlation to the location of the larger metal hardware particles. The depth of overlying sand in this experiment was approximately one centimeter.

Figure 4.7: Patchy wetness throughout the surface regolith observed as darker areas after 30 minutes of thawing in experiment 2.2.

Experiment 2.3 used the same metal hardware representing larger particles, but contained a thinner layer of overlying regolith. This overburden was sprinkled extremely lightly, creating only a coating on top of the permafrost layer with embedded model boulders. Thawing again occurred rapidly with the heat lamp applied to the surface compared to Experiment 2.1 without the use of the heat lamp. After 60 minutes of thawing, Figure 4.8 shows the change in appearance of the surface due to differential wetting, which again was difficult to correlate with the placement of any of the larger particles. Wetting of the surface was only observed in patches throughout the box rather than in direct contact with specific particles.

Figure 4.8a (left): Experiment 2.3 set on 12^{o} slope just before application of the heat lamp.

Figure 4.8b (right): 60 minutes after thawing with heat lamp, which shows dark patches that indicate wet areas on the surface.

Experiment 2.4 used one steel sphere with a diameter of 5 cm in place of the metal hardware at the top of the slope to act as a large model boulder in the regolith. During thawing with the heat lamp, mostly uniform wetting appeared on the surface of the very thin overlying sand. Again, thawing was very rapid. The surface of the coating of overlying sand appeared uniformly wet after approximately 30 minutes of thawing under the heat lamp, with no specific pattern of thawing throughout the system. When a slightly deeper overburden was used in Experiment 2.5 so that uniform thawing didn't occur as quickly, some wetting of the sand in direct contact with the sphere was observed approximately fifteen minutes into thawing, but was difficult to capture with camera equipment in the cold room. The thawing at the bottom of the slope in Experiment 2.2 can be seen in Figure 4.9, but the image does not distinctly show the darker sand in

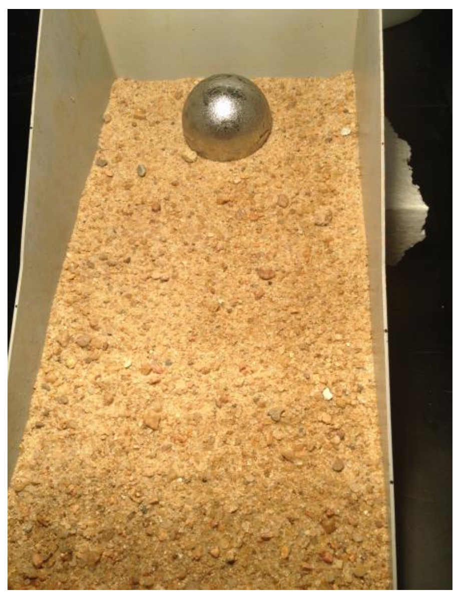


Figure 4.9: Thawing with the heat lamp in Experiment 2.5. Darkening can be seen in image at bottom of slope, and also was observed after 15 minutes of thawing in immediate contact with steel sphere at top of slope

direct contact surrounding the model boulder. This thawing was followed by uniform wetting across the bottom of the slope after an hour of thawing with the heat lamp.

Section 4.3 Topography Experiments Continued at Connecticut College

The continued topographic distribution experiments thawed at ambient temperature like in Experimental Set 1. Results showed signs of thawing in linear trends in the system through the implementation of distinct channels and slight swales down the center of the sloped box.

Experiment 3.1

The first topographic distribution for the experiments conducted at Connecticut College mimicked that of Experiment 1.4 with a central depression down the slope of the new Styrofoam box. This experiment, however, used the loess regolith defined in the methods section comprised of 60% sand, 30% silt and 10% clay. The results from the thawing of this setup were similar to those in Experiment 1.4. The overlying loess on top of the permafrost layer in this experiment was slightly deeper than that in Experiment 1.4 because of the larger size of the box. After four hours of thawing on a 30^{o} slope, the central channel began to show small spots of wetting throughout. An additional 90 minutes later, the spots in the channel began to form a linear feature of darkened loess and after a total of nine hours of thawing a full linear feature of wet loess extended down the depression as shown in Figure 4.10.

Figure 4.10: Dark linear feature extending down the central depression after nine hours of thawing on the 30^{o} slope in the lab.

Experiment 3.2

In Experiment 3.2, a much gentler variation in topography of the overlying loess regolith was used. Upon removing the box for Experiment 3.2 from the freezer to add the overlying dry regolith, the over-saturated permafrost layer appeared to contain approximately one centimeter of pure ice on top of the frozen regolith. Observations of thawing occurred on a shorter time scale than in Experiment 3.1, with the first appearance of wetting of the surface occurring after about 90 minutes of thawing. Figure 4.11a shows the initial thawing, with darkening of the regolith at the top of the box and along some of the sides as well as down the top of the central swale in the overlying regolith. Figure 4.11b shows the appearance of the box after an additional 30 minutes of thawing in which the wetting has moved both further downslope as well as becoming more uniform across the width of the box. After a total of three hours of thawing, the entire surface was uniformly wet including some excess water at the bottom of the slope.

Figure 4.11a (left): Initial thawing began along the top of the slope and extended down both the sides and central swale.

Figure 4.11b (right): Uniform wetting across the width continuing in the downslope direction.

Experiment 3.3

Experiment 3.3 used a fine-grained sand regolith with another slight variation in the thin overburden depth of dry regolith. With a gentle swale down the center of the box, thawing was observed in this experiment to occur throughout the center of the box extending towards the edges. Thawing occurred relatively quickly compared to previous experiments. Figure 4.12a shows the box after approximately 30 minutes of thawing. Wet regolith was observed at this time along the top of the box and slightly extending down the center. After two hours of thawing, the majority of wetting was down the central swale extending outwards, as seen in Figure 4.12b. The wetting of the surface continued to spread throughout the box until it was mostly uniform across the width of the box as in previous experiments.


Figure 4.12a (left): Darkening initiated at top of slope in Experiment 3.3 and extended slightly down central swale after 30 minutes of thawing.

Figure 4.12b (right): Wetting across the center of the box.

Section 4.4 Simulated Boulder Experiments Continued at Connecticut College

Experimental Set 4 tested additional effects of large particles on the thawing of the system, at ambient temperature without a heat lamp rather than in the cold room with the heat lamp in Set 2. The largest marbles acting as model boulders with 2.5-cm diameters and the thinnest distribution of regolith yielded some indication of differential thawing of the permafrost in contact with the boulders.

Experiment 4.1

The first of the continued model boulder experiments that took place at Connecticut College, Experiment 4.1, yielded results that showed some possible differential melting of the permafrost with connections to the placement of the marbles in the sand. Upon removing the frozen permafrost with four glass marbles embedded in the layer from the freezer, along with the four additional small metal spheres for the even distribution of the overburden layer, it was apparent that there were some small patches of ice on top of the permafrost as a result of excess water in the saturated layer of sand before freezing. The dry layer was spread as thin and evenly as possible on top of the frozen sand and water in order to easily spot areas where the ice was melting first. The box then remained in the freezer for an additional two hours before removing the box for thawing in the lab. Areas where water had formed ice patches appeared mostly near the line of four glass marbles that were at the top of the 30^{o} slope during the thawing process. These ice patches were also covered with the thin overburden layer.

The overburden layer in Experiment 4.1 was less than 1-cm deep, and by 30 minutes into the thawing process darkening of the dry sand was observed as a result of the melting permafrost and ice. The areas of the system that showed the first signs of darkening were around all of the edges of the box and around the 2.5-cm diameter yellow marble, which was embedded slightly deeper into the permafrost than the darker brown marble of the same size. Figure 4.13a shows the overall appearance of the darkening overburden in the box 30 minutes into the thawing and Figure 4.13b shows a closer image of the wetting of the sand around the 2.5-cm yellow marble at this time. As thawing of the permafrost continued, the sand immediately surrounding the yellow marble continued to darken and spread further from the marble while wetting of the sand around the brown marble also began approximately 45 minutes following removal of the box from the freezer.

Figure 4.13a (left): After 30 minutes of thawing, edges of box appear darker

Figure 4.13b (right): Sand directly surrounding 2.5-cm yellow marble also appears darker after 30 minutes of thawing

Figure 4.14a shows an image taken 15 minutes after those in Figure 4.13. There was spreading of the wet sand around the yellow marble and the beginning of wetting around the slightly shallower embedded brown marble observed by this time. In addition to these areas of wetting, darkening of the sand also continued to spread further towards the center of the box from the edges as well as around the smaller marbles (Figure 4.14b). The locations of the two smaller marbles, however, correspond to the locations of ice patches that occurred after the freezing of the over-saturated sand layer. The wet sand around these marbles was also observed not to initially appear in the sand immediately in contact with the marbles and spread from there, but rather appeared all at once in a larger area surrounding the marbles. Additional patches of wetness continued to appear throughout the box as thawing continued, including large spots further downslope of the marbles.

Figure 4.14a: Darkening of regolith extending from 2.5-cm marbles and surrounding regions of smaller marbles during continued thawing

Figure 4.14b: Thawing around marbles in addition to patchy wetness throughout the box

Experiment 4.2

The next model boulder experiment, which included an increased number of marbles embedded in the permafrost, did not yield all of the same results as Experiment 4.1. Upon removing the permafrost layer used in Experiment 4.2 from the freezer to add the overburden layer to the system, the frozen layer did not appear to contain as much excess water as Experiment 4.1, so there were no notable ice patches within the system. The box, including permafrost and overburden layers, was removed from the freezer four hours after the placement of the dry sand layer on top of the permafrost. The dry layer in this experiment was designed to be even and under 1-cm deep throughout the entirety of the box. However, after placing the box on the 30^{o} slope and measuring the depth of the dry sand in various locations around the box, it was observed that this was not the case for the whole layer. The layer was thinnest around the edges of the box, as it was in Experiment 4.1, but the top right corner of the box appeared to contain an overburden layer that was thicker than the other areas of the box; the dry layer here was a little over 1-cm deep.

After approximately 30 minutes of thawing, there were no significant changes to the appearance of the system. The first observations of some darkening of the dry layer of sand were made approximately 90 minutes into the thawing cycle, and this darkening included mostly the areas in contact with the edges of the box, as in previous experiments. Figure 4.15a shows the box 15 minutes after the initial observations of wetting near the edges began (45 minutes total of thawing), and includes additional wet spots especially near one 2.5-cm brown marble on the left side of the box. The next observations made two hours after the box was brought to ambient temperature for thawing revealed more distinct wetting around the sand in contact with the first marble that showed wetting in Figure 4.15b. Additionally, while not as obvious, the 2.5-cm yellow marble in the top left also showed slight signs of darkening immediately surrounding the marble. The bottom left brown marble in the box showed the most wetting, with some slight wetting around the left marbles in the top row. The final appearance of the system, 24 hours after thawing began, is shown in Figure 4.15c. Only the first 2.5-cm marble that was observed to be in contact with wet sand went on to show distinct wetting in the immediately surrounding area.

Figure 4.15a: After 45 minutes of thawing, surface indicates patchy wetness with slight association with 2.5-cm brown marble on far left side of box.

Figure 4.15b: Closer image of 2.5-cm marble after additional thawing in which dark regolith was both in contact with marble (bottom left side) and in surrounding area.

Figure 4.15c: After 24 hours of thawing, most significant association between wetting of surface regolith and marble placement is in the same location as in 4.15a and 4.15b.

Experiment 4.3

Figure 4.16a shows the appearances of the frozen layer after remaining in the freezer for four days before the dry layer was added on top for Experiment 4.3. The permafrost layer for this experiment was over-saturated and ice patches remained on top of the frozen sand after freezing. The image shows a distinct ice patch that formed in the area on the right side of the box, especially surrounding the yellow marble on this side. A very thin distribution of overburden was spread on top of the permafrost and the combination was replaced into the freezer for nineteen hours. Upon removing the box to thaw at ambient temperature, the extremely thin overburden was spread as evenly as could be attained without disturbing the system. Because less sand was added in this experiment to create a thinner overburden, the layer was especially thin around the edges of the box. Figure 4.16b shows the beginning of the thawing process and the appearance of the thin dry overburden, which was only 3-4 mm in this experiment.

After 60 minutes of thawing, only slight darkening was observed around the edges of the box, where there was little overburden. Fifteen minutes later, the darkening around the edges, especially at the top of the slope, could be seen as in Figure 4.16c, spreading towards the marbles and center of the box. This darkening was not associated with the locations of marbles in the box. However, after 90 minutes of letting the system thaw, some possible darkening was observed and is seen in Figure 4.16d, immediately in contact with the yellow marble on the right side of the box, where the large ice patch appeared after freezing. This darkening only appeared on the downslope side of the yellow marble, where the top sand layer was slightly thinner than that which was in contact on the upslope side of the marble.

Figure 4.16a: Frozen, over-saturated regolith before addition of dry overburden layer.

Figure 4.16b: System after addition of dry overburden layer at the start of the thawing cycle

Figure 4.16c: Wetting of the regolith extending from the sides of the box after 90 minutes of thawing

Figure 4.16d: Additional wetting after 90 minutes of thawing in direct contact with downslope side of 2.5-cm diameter marble

Chapter 5
Discussion

In all of the experiments with open top boxes, darkening of the surface regolith was observed in various locations and patterns during the periods of thawing. This darkening was attributed to the capillary rise, or wicking, of the melt-water forming from the active layer of the permafrost. Capillary action is the movement of liquid through the pores of a material, and acts in all directions including in opposition to gravity (Ritter et al., 2011). Because the regolith below the active layer was already fully saturated and frozen, the melt-water could only move up through the open pore space of the dry overburden of regolith, against the force of gravity. The topographic distribution of the dry layer in which melt-water could rise affected the appearance of the surface of the system in each experiment during the thawing process. A variation in the depth of porous medium on top of the thawing permafrost directly influenced the magnitude of the melt-water that reached the surface and could darken the overburden compared to the surrounding area. Additionally, the placement of larger particles acting as model boulders affected the surface appearance by varying the rate at which thawing of the active layer occurred, providing different amounts of melt-water to be drawn through the pores of the dry regolith at different locations in the system.

Section 5.1: Experimental Limitations

The scale and size of the boxes used in these experiments placed a limitation on the study. The largest of the boxes used was the Styrofoam box used in Experimental Sets 3 and 4 and still was only 24 cm long. A common observation throughout the experiments was the formation of linear features that could not continue to lengthen or develop, which can potentially be attributed to the small length of the boxes. In order for channel-like features to develop and evolve on Earth, a critical length must be reached (Ritter et al., 2011). According to the definition of RSL as developed by McEwen (2011), these features both darken and lengthen in the downslope direction during the warmer summer months in which they are actively growing. In the experiments performed in which linear features formed in the regolith, they had a tendency to form evenly along the length of the box rather than starting at the top of the slope and lengthening in the downslope direction over time.

The Plexiglas box used in the early experiments at the University of Arkansas displayed its own size limitations in addition to limitations in critical length. Because this box had sloping sides, it was impossible to always build up the height of the regolith at the bottom of the box to the desired depth, as the sides of the box at the bottom of the slope were not as high as those at the top of the slope. Throughout many of the initial topography experiments using this box, wetting of the surface across the width of the bottom of the box was attributed to this limitation of the box. The small Plexiglas box was also not particularly suitable for long-term use in the cold rooms at the University of Arkansas. After continued cycling of freezing and thawing, the Plexiglas box began to crack and break at the joints, requiring a switch to the slightly wider copper box that was used to complete the final experiments of Set 3. This copper box, while slightly larger than the Plexiglas box, had similar restrictions as a result of the sloped slides terminating at a height of 2.5 cm at the bottom of the slope.

In addition to size limitations, the experimental setups used throughout this study also presented insulation limitations. Each setup had a slightly different insulation system in an attempt to prevent thawing from the edges of the system. Although attempts were made to simulate surface thawing and keep the systems fully insulated, there was no way to completely prevent thawing throughout the system. Experiments conducted in Sets 3 and 4 were better insulated than those in Sets 1 and 2 because they were conducted using an insulated Styrofoam container. This higher degree of insulation was taken into account when observing the rates at which features formed in Sets 3 and 4 versus Sets 1 and 2. Thawing occurred much more rapidly at ambient temperature in the Plexiglas box than at ambient temperature in the Styrofoam box.

Section 5.2: Influence of Topographic Distribution

Based on the topography experiments conducted, a linear depression in the overlying regolith was the most effective at developing linear features during thawing of the underlying permafrost. In locations in which the overlying regolith was the deepest, for example along the sides of the box in Experiment 1.4 (Figure 3.2d) and the left side of the box in Experiment 1.3 (Figure 3.2c) the amount of melt-water provided from the thawing of the permafrost was not sufficient to reach and darken the surface through capillary rise during the first thawing cycle. Darkening of the surface appeared in a linear trend along the very low-lying overburden regions. This was generally where overburden regolith depth was one centimeter or less. Essentially, if the low-lying regions of dry regolith atop the permafrost layer are arranged in linear trends, then capillary rise will darken the surface in a linear pattern over time as well. The two possible constraints that were identified in this process, however, are how great the variation in depth of these linear depressions are and how much water is supplied to the region as the result of the thawing layer. These constraints can affect the ability of the system to thaw in a linear trend without approaching uniform wetness before the thawing process is complete.

Experiments 1.4, 2.1 and 3.1 contained very dramatic central depressions compared to the slight swales in the overlying regolith of Experiments 3.2 and 3.3. The height difference in overlying sand in Experiments 1.4, 2.1 and 3.1 was the same, with approximately four centimeters of regolith at the highest point along the sides sloped down to a depth less than one centimeter in the center of the box. Experiments 3.2 and 3.3 investigated the effects of a much slighter swale down the slope of the box, varying in depth from a thin coating down the center to only about 0.5 cm at the highest regions on the sides. Observations showed that this depth variation was not enough to prevent uniform wetting across the width of the box before a linear feature could develop.

In experiments in which linear features formed and were refrozen and re-thawed, the dark lineae did not reappear. This was also attributed to both the amount of water that was provided to the system from the thawing permafrost and the degree of variation in the overlying regolith. During initial thawing, the melt-water was wicked up through the pores of the dry regolith more readily where it was thinnest. During the second freeze session, this water then froze in the regolith at a higher level than the initial permafrost layer, which resulted in a smaller depth of dry, unconsolidated regolith overlying the frozen regolith upon removal from the freezer for the second thaw. Therefore, during the next thawing process, the melt-water forming was able to reach the surface of the regolith in regions where the original depth was too large to show signs of melt-water on the surface for the first thaw cycle. This process was directly observed in Experiment 1.3. The boundary between the permafrost and overburden layers in this experiment was observed through the sides of the Plexiglas box to have risen in between cycles of thawing, as was shown in Figure 4.4. Additionally, during the second round of thawing, the surface of the overlying regolith wet much more uniformly than in the first thawing cycle.

The amount of time that it took for observable thawing in the systems was also dependent on the properties of the regolith used. The regolith in these experiments affected the rate at which the underlying permafrost thawed. The sand used in Experiment 1.4 exhibited lower porosity, or percentage of air space between individual particles, than the loess used in Experiment 3.1 (Ritter et al., 2011). The lower porosity of the sand in Experiment 1.4 allowed for faster heating of the underlying layer, whereas the loess used in Experiment 3.1 with the same overlying topography better insulated the system. This is likely the result of the amount of air within the grains of the regolith in the individual experiments. Because a solid material is better at conducting heat than air space in which there is no convection occurring, the loess with more air space was not as efficient at transferring heat to the subsurface frozen layer (Marshak, 2012). The insulation from the loess kept the system from thawing as rapidly as the sand, resulting in a longer thaw time of about nine hours for a linear feature to form, compared to only three hours for a similar feature to appear in Experiment 1.4. These effects of insulation were also attributed to the box setup limitations described in Section 5.1, which should also be taken into account.

Experiment 2.1 took the longest time to thaw because it was thawed in the 4° C cold room with no additional heat from the heat lamp that was used in subsequent experiments. In this experiment, over the coarse of multiple days, a dramatically darkened linear feature did not form in the linear depression in the sand as it did for the same setup thawed at ambient temperature in Experiment 1.4. This indicates the rate of thawing of the permafrost in a much colder environment did not produce enough melt-water to the system even over this extended period of time to successfully wick to the surface through capillaries and form a linear feature, or that the melt-water was evaporating as quickly as it was being produced through thawing.

The results from the topography experiments indicated that a large variation in depth or a large amount of available water would be necessary for the formation of RSL. These experimental results partly support the modeling conducted by Grimm et al. (2014) on the water budgets of RSL. Their modeling, based on gravity, capillary action and evaporation constrained flows, indicated that the amount of water made available during the active season for RSL still did not meet the amount that would be necessary for groundwater flows to create these features.

According to their study, in order for groundwater flows to form RSL, there would either need to be a greater amount of available water than expected based on the constraints of temperature and evaporation, or the active layer of thawing water would need to be exceptionally close to the surface of overlying regolith. This was further supported by experiments conducted for this study, which did not form linear features in the cold room where the active layer of the permafrost did not provide a large amount of water to the system.

Section 5.3: Influence of Boulders and Particle Size

The main goal of the large-particle size experiments was to determine the effects of these larger particles on how the system thaws. RSL form on relatively rocky slopes on Mars, sometimes originating from bedrock outcrops (McEwen et al., 2011). The placement of larger particles in the regolith in these experiments simulated the occurrence of boulders on Martian slopes. Linear features did not form on the slopes for any of the simulated boulder experiments. In some cases, however, the larger particles were associated with differential darkening of the surface regolith, which can be attributed to properties of the larger particles. Based on the observations made of each model boulder experiment, the scale of the boulder size compared to regolith particle size and the depth of dry regolith to the permafrost layer both can influence how the boulders play a role in the thawing process.

All of the simulated boulder experiments conducted in the cold room, Experiment Set 2, used a heat lamp during the thawing process. Because of the rapid thawing resulting from the application of the heat lamp, it was extremely difficult to identify thawing at different rates throughout the box. However, Experiment 2.1, while not including boulders, showed that even in low lying regions with little cover of regolith on top of the permafrost, it was extremely difficult to observe any signs of thawing in the cold room without the application of an additional source of heat. In order to counteract the strong effect of the heat lamp that was observed in experiments 2.2-2.4, a deeper overlying regolith was used in Experiment 2.5 and some slight thawing was observed in contact with the 5-cm steel sphere acting as a boulder in this experiment before the entire box uniformly wet. In Experiments 2.2 and 2.3, all of the metal pieces embedded in the permafrost were 2.5 cm or smaller, so regardless of the depth of overlying sand, the combination of the smaller size of these boulder-representing particles and the rapid thawing from the heat lamp resulted in uniform thawing of the system.

According to the results of Experiment Set 4, the effects of particle size were only observed in situations with significantly larger particles acting as boulders and very shallow depths of overlying regolith on top of the permafrost layer, which supports the preliminary findings from Set 2 in which only the largest particle (5-cm diameter steel sphere) indicated any signs of more rapid thawing compared to the remainder of the box. The influence of larger particles on the system was observable when wetting of the surface regolith could be seen in direct contact with the larger particles themselves. The experiments in Set 4 used three different marble sizes to act as boulders, and only the largest marbles, with a 2.5-cm diameter, ever indicated signs of direct thawing as a result of the placement of the marble. Additionally, this effect was only observed for conditions in which the depth of overlying regolith was well under one centimeter or the underlying permafrost layer under a particular marble contained a large patch of pure ice from over-saturation of the regolith.

In Experiment Set 4, the marbles that acted as model boulders in the system were all glass, so their composition was not significantly different from the composition of the quartz sand used as a regolith in this experiment. Some direct thawing was observed in contact with these glass marbles, and so this demonstrates the strict effects of the size of the particle rather than different thermal properties of the materials used in the system. Glass, like quartz sand, is essentially made up of silica and oxygen and is not as good of a conductor of heat as metal (Marshak, 2012). Therefore, the sand regolith in these experiments provided a good insulator for the system, but the size of the boulders affects the degree of insulation that the overlying layer can provide. The mostly uniformly sized regolith alone provides a sufficient insulating layer on top of the frozen layer. The large marbles, however, were better conductors of heat because of their large solid structure, which is efficient at conducting heat compared to air space within pores of the smaller grained regolith (Ritter et al., 2011). Because of this, the boulders were able to create regions of more rapid thawing where they were embedded in the permafrost and more efficiently transferring heat from the surface to the frozen layer.

Although linear features did not form during any of the model boulder experiments, differential thawing of the system could play an important role in the initiation of RSL. In the experiments that tested the effects of topography on the thawing of the system, it was concluded that some variation in the regolith distribution was necessary for capillary action to develop a linear feature. Similarly, it may still be necessary to have variations in the regolith depth and distribution for linear features to form after thawing is initiated in contact with larger particles. Throughout the model boulder experiments, there was also spotted or patchy thawing observed throughout the system. Based on the results of the topography experiments, this spotted wetting was attributed to a lack of a perfectly even thickness of the overlying regolith. Although attempts were made to create thin, even distributions of regolith on top of the permafrost in these sets of experiments, there was a slight range in depths. Some wetting was attributed to these variations in the depth when darkening of the surface was observed in areas that were not in direct contact with the model boulders.

Section 5.4: Comparisons to Mars Conditions

The results yielded in this study provided some of the first experimental support for RSL formation hypotheses in which some form of liquid water is supplied to the regolith via the seasonal thawing of a subsurface frozen layer. Based on the interpretations of the topographic distribution results, some form of topographic variation including linear depressions in the regolith would be necessary on the steep slopes of Mars on which RSL form. The melt-water supplied to the system was not sufficient in these experiments to distinctly erode channels into the surface regolith, but according to McEwen et al. (2011), many of these slopes are already associated with small channels extending downslope. These channels are likely evidence of historic water-driven processes on Mars, which left behind a variation in topography that is now conducive to the formation of RSL through this mechanism. The channels associated with these slopes are necessary to provide the variation of overlying regolith depth required to observe darkening of the surface along only the linear low-lying regions from the melt-water provided by the subsurface permafrost.

The various experimental setups also demonstrated the highly important role of insulation in the processes associated with the potential formation of RSL both on Mars and in the lab. Experiments in Sets 3 and 4, which were conducted in a box with two centimeters of Styrofoam insulation on all sides, showed signs of thawing less rapidly than experiments conducted in Set 1 with the Plexiglas box. Given the small size of the boxes used, more insulation to prevent thawing from the surrounding sides likely provides a more accurate representation of thawing rates and should be taken into account in analyzing both these experimental results and those of future experiments.

In addition to the amount of insulation surrounding the small boxes used in this study, the regolith itself provided a certain degree of insulation to the underlying frozen layers. Because solid rock is a better conductor of heat than open air space, the smaller-grained regolith particles and associated pore space provides good insulation for the underlying permafrost. This directly influenced the rate at which the subsurface thawed in experiments in Set 4.

The model boulders used in this study were chosen partly based on availability of materials. Actual boulders on Mars would not exhibit exactly the same heat transfer properties as the ones used in this study. The boulders and outcrops on Mars would not contain the same smooth, glassy texture of the marbles used in Experiment Set 4. The increased roughness could affect the interactions between the larger particles or boulders and surrounding regolith. Additionally, the heat transfer properties of rock on Mars would likely be enhanced compared to those of the marbles used in Set 4 of experiments because iron-rich material is a much better conductor than the quartz material that the marbles were composed of (Marshak, 2012). The metal pieces used in Set 2 differed from Mars conditions because these pieces were not solid metal, but rather contained open, hollow centers, possibly inhibiting some of their heat transfer properties.

RSL are mostly characterized by their seasonal variability, which provides a formation mechanism focused on seasonal thawing and freezing of saturated regolith in the subsurface. However, the time period for freezing and thawing that these experiments simulated was more diurnal in nature than seasonal. The temperatures of the regions on Mars in which RSL form reach peak temperatures during active seasons that could potentially thaw the subsurface for only brief periods of the day (McEwen et al., 2011). Based on our experimental results, it is possible that RSL are formed as a result of diurnal thawing of the permafrost during the peak daily temperatures in the late spring and summer seasons. Because bedrock outcrops in RSL regions have a higher thermal inertia than surrounding regolith, they retain heat more effectively overnight and so warm up more rapidly during the day (McEwen et al., 2011). In some cases, this daily warming of the bedrock outcrops, as well as large boulders, can continue the growth process of RSL each day, with some freezing occurring overnight. With a high enough thermal inertia, however, the larger outcrops could retain enough heat overnight to keep the surrounding region warm enough for liquid to persist until the following day.

The experiments conducted in this study did not contain a recharge mechanism for the subsurface water. Assuming that the actual Martian conditions call for liquid brine, there would need to be some mechanism responsible for resupplying the subsurface layer in order for RSL to be able to reappear. The recent study conducted by Martín-Torres et al. (2015) identified perchlorates as a potential salt on which liquid brines could form through the process of deliquescence in the equatorial regions of Mars. According to their calculations, liquid brine that forms in these regions through deliquescence could seep into the Martian regolith through the pores to a depth of approximately five centimeters. These five centimeters of regolith could potentially provide a significant amount of shielding for the liquid, further decreasing the rate of evaporation; instead, the liquid would eventually freeze when temperatures dropped significantly lower and could remain in the subsurface for future RSL formation and development.

The presence of salts is crucial for the formation mechanism tested in this study and is well supported by the recent detection of perchlorates in the equatorial regions (Martín-Torres et al., 2015). Although the detection of salts in Gale Crater was successfully conducted by the Mars Science Laboratory, direct observations of the slopes on which RSL form have not been conducted. The steepness and rockiness of these slopes prevents landers or rovers from being able to directly explore these regions, making images from the orbiters the only observational evidence. The Mars Reconnaissance Orbiter uses the CRISM instrument (Compact Reconnaissance Imaging Spectrometer for Mars) to identify compounds through spectroscopy, but only has a resolution down to 18 meters (Ojha et al., 2014). Given the narrow width of RSL ranging up to only 5 meters, the resolution of the CRISM instrument is not sufficient enough to identify the composition of these features. Based on the formation mechanism of this study, evaporitic salt deposits would be expected at the locations of RSL after they fade in the winter. Until more direct measurements can be made of these specific regions, the confirmation of salt is mostly supported by the Mars Science Laboratory detection of salts in Gale Crater.

Section 5.5: Implications for Life on Mars

One of the greatest motivators for studying potentially water-driven processes on the surface of Mars is the importance of water for life to develop. The results in this study support a hypothesis in which RSL form as a direct result of the presence of subsurface water with a high concentration of dissolved salts. This has important implications in the search for life on Mars because water with a high salt content means searching for organisms that have adapted to living off of water solutions such as brine. Extremophiles are microbes that thrive in particularly harsh environments on Earth, and are important in broadening the range of conditions in which life can survive on other planets (Bennett and Shostak, 2012).

Extremophiles that are of particular interest to the search for life that can survive on Mars are halophiles and psychrophiles (Bennett and Shostak, 2012). These microbes, discovered in harsh regions on Earth, thrive in environments that are salt rich and that survive at extremely cold temperatures, respectively. Given the abundant detection of salts on Mars and the likelihood that any from of liquid water on the surface would contain dissolved solutions of these salts, any search for past or present life should search for organisms similar to Earth’s halophilic microbes.

Similarly, the cold temperatures on Mars present an environment that is suitable for organisms found in the cold, dry regions of the McMurdo Dry Valleys that thrive only at extremely low temperatures (Bennett and Shostak, 2012).

Although of the known extremophiles halophiles would be the most likely to sustain life on Mars, high amounts of radiation at the surface of Mars would likely still inhibit any present day survival of these microbes in this particular region. With such a thin atmosphere, the shallow layer of overburden in which liquid brine would actually persist based on these experiments would not provide a sufficient amount of shielding for the organisms from the incoming solar radiation that is not deflected by the weak atmosphere of Mars (Bennett and Shostak, 2012). The high amounts of salts now being detected in these equatorial and mid-latitude regions of Mars in combination with identification of geomorphic features that indicate historic water flows on the surface suggest that the ancient existence of water would have also contained a high amount of salt, an environment in favor of the existence of halophile-like microbes if any did exist.

Section 5.6: Future Work

The experiments conducted in this study were the very first of their type. These preliminary experiments successfully set boundary conditions and raised questions for future experiments to take into account in the study of the formation of RSL. Future experiments are necessary to further quantify the constraints that were established in this study and will eventually need to introduce additional factors and variables into the systems to truly simulate the Martian conditions in which these features form.

In future attempts to recreate RSL in the lab, a combination of the preliminary experiments conducted in this study may provide important insights into the development of these features. Through varying the topography of a regolith distributed on top of the permafrost layer and introducing larger particles into the regolith throughout the varying topography, including within linear depressions, it can be experimentally determined if the influence of boulders on the thawing of the system could provide an initiating point for linear features to develop within the topographically lower regions and depressions. It is therefore suggested that further experimental setups include both linear depressions in overlying regolith as well as simulated boulders. This combination may be effective in creating a point from which linear features can begin to form within the channels, as opposed to these experiments in which linear features mostly formed along the length of the slope at the same rate.

Because of the observed limitations of the size and scale of the setup used in these experiments, future work will also need to use a larger box to further develop the necessary length for creating seasonal linear features in the laboratory. The construction of the metal flume described in Chapter 3 took into account the limitations that were observed during the initial experiments of this study. This flume will be used in future RSL formation experiments in order to more greatly vary the topographic distribution and to observe how the features that form continue to develop along the length of the slope. Additionally, the effects of direct solar insolation can be further addressed, especially in determining the various heat transfer properties of different boulder types. This can be done through the use of a larger-scale experiment in which the heat lamp used in Experiment Set 2 will not cause immediate rapid thawing as it did for a much smaller system.

Additional factors that should be investigated in future experiments are the regolith type and water composition. Because the hypothesis for the formation mechanism used in this study calls for briny water on Mars rather than pure water, future experiments should use water with varying salt content in the simulation of RSL. Additionally, experiments should utilize the Mars regolith simulants, JSC-1 and MMS, to investigate more accurately the specific regolith type of Martian slopes and its role in the development of these features. Boulder types should also be tested, considering the different heat transfer properties of different materials.

This study gave insight into the affects of large particle size in which many of the large particles were similar in composition to the regolith in which they were embedded. Future experiments should use different materials to simulate boulders, such as large particles of basalt in the system. Another factor that should be addressed is the amount of evaporation taking place in these regions during the active RSL seasons and how this can constrain the system. Evaporation rate experiments should also study the degree of shielding that can be provided to the subsurface layers by different depths of overlying regolith.

Chapter 6
Conclusions

This study made important strides in the efforts to develop a laboratory setup in which seasonal RSL features could be recreated. Through the experiments we conducted, the initial constraints of topography and particle size on the formation of RSL were identified and can now be further quantified in future studies. The topography experiments conducted in this study concluded that the most probable topographic distribution of regolith to produce features similar to RSL is a linear depression in which there is a large variation in depths of regolith and/or only a small amount of liquid water produced from the thawing permafrost. Experiments additionally concluded that thawing could occur at different rates as a result of regolith type and particle size. In particular, boulders can act as a source for faster rates of thawing on Martian slopes on which RSL form, but only in regions in which overlying regolith is not too deep to prevent the amount of melt-water produced to darken to the surface.

Although these experiments focused on the seasonal thawing of subsurface ice as the formation mechanism for RSL, other hypotheses cannot be ruled out. The aim of this study was to reproduce RSL features in the lab consistent with the subsurface briny water hypothesis. Experiments demonstrated that a subsurface permafrost layer could be a source for the production of liquid water during active season for RSL formation. Literature review shows that this liquid can potentially persist in these regions of Mars if it contains a high concentration of salt, so the hypothesis is further supported by the recent detection of salts in the equatorial and mid-latitude regions of Mars.

Future work will need to be conducted in order to account for limitations in the experimental set up, especially the size and degree of insulation of the systems and critical length of the swale. Future work will also take additional constraints into account such as evaporation and regolith and water composition in the formation of these features on Mars. Further quantifying of the constraints in this study, especially regolith overburden depth and boulder size, can potentially be used to determine further necessary conditions for the formation of RSL on Mars.

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Appendix

Table A1: Summary of results for Experimental Set 1.

Experiment	Regolith Distribution and Overburden Conditions	Results
1.1	Flat layer, approximately 1-cm deep	Thawed uniformly across the width of the box. Ice patch melted and left round depression in surface. No linear feature appeared.
1.2	Sloped along slope of box, 8-cm deep at the top.	Thawed uniformly across the width of the box. Thawing began at bottom of slope and extended upslope over three hours of thawing. No linear feature appeared.
1.3	Sloped across width of the box	Thawed across width of slope at the bottom. Thawed in a slightly linear trend along right side of the box where overburden was the least deep. Linear feature did not reappear on second thaw.
1.4	Linear depression down center of the box	Thawed in a linear trend along the central depression. Linear feature did not reappear on second thaw.

Table A2: Summary of results for Experimental Set 2.

Experiment	Regolith Distribution and Overburden Conditions	Results
2.1	Linear depression down center of box.	Extremely subtle darkening of linear depression observed after 30 hours of thawing in 4^{o} C cold room. Same subtle darkening after three days of second thaw. Very rapid, uniform thawing when 150-W heat lamp applied to the surface for 60 minutes.
2.2	1.5-cm metal nuts and 2.5-cm metal cap embedded in permafrost. Overlying dry layer approximately 1-cm deep.	Patchy wetness observed on the surface after 30 minutes of thawing with 150-W heat lamp. No distinct correlation between areas of wet regolith and placement of larger particles.
2.3	1.5-cm metal nuts, 2.5-cm metal cap, and <1-cm metal spheres embedded in permafrost. Slight coating of dry regolith overburden.	Differential wetness observed on the surface for 60 minutes of thawing with 150-W heat lamp. No distinct correlation between areas of wet regolith and placement of larger particles.
2.4	5-cm diameter steel sphere embedded in permafrost. Slight coating of dry regolith overburden.	No distinct pattern in thawing after 60 minutes of thawing with 150-W heat lamp. Patchy wetness turned to uniform wetting across the system.
2.5	5-cm diameter steel sphere embedded in permafrost Dry overburden layer approximately 0.5-cm deep.	In addition to some patchy wetness throughout the surface, some subtle darkening of the sand in direct contact with steel sphere was observed after 15 minutes of thawing with 150-W heat lamp.

Table A3: Summary of results for Experimental Set 3.

Experiment	Regolith Distribution and Overburden Conditions	Results
3.1	Distinct linear depression down center of box (loess)	Spotted wetting along the central channel appeared after four hours of thawing at ambient temperature. Spotting turned into dark, linear feature along the central channel after 9 hours of thawing at ambient temperature.
3.2	Slight central swale (loess)	Wetting along top edges and top of central swale after 90 minutes of thawing at ambient temperature. Wetting extended downslope and became uniform across the width at approximately halfway. Surface appeared uniformly wet after three total hours of thawing.
3.3	Slight central swale (sand)	Wetting of surface along edges and top of swale after 30 minutes of thawing. Center section of surface wet across after two hours of thawing.

Table A4: Summary of results for Experimental Set 4.

Experiment	Regolith Distribution and Overburden Conditions	Results
4.1	Marbles embedded in permafrost with 1.0-cm, 1.5-cm, and 2.5-cm diameters Overlying dry layer between 3-6 mm deep	After 30 minutes of thawing at ambient temperature, edges darkened in addition to some wetting around 2.5-cm marble. Wetting continued in patchy spots around edges of box and darkened and extended around 2.5-cm marble.
4.2	Marbles embedded in permafrost with 1.0-cm, 1.5-cm, and 2.5-cm diameters Overlying dry layer between 6-10 mm deep	Wetting around edges of the box began 90 minutes into thawing at ambient temperature. After 2 hours, some wet sand observed in direct contact with 2.5-cm marble. After 24 hours of thawing, patchy wetting throughout the surface included sand in contact with only one 2.5-cm marble.
4.3	Marbles embedded in permafrost with 1.0-cm, 1.5-cm, and 2.5-cm diameters Overlying thin coating, under 0.5-cm deep throughout	Wetting observed around edges of box starting after 60 minutes of thawing at ambient temperature. Continued patchy wetting was observed. Only marble to show wetness in direct contact was 2.5-cm marble embedded in ice patch area of box after 90 minutes of thawing.