Identifying Long-Runout Landslides on the Surface of Mars

by

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To my family, who are my constant support through this journey, and to the special people in my life who never let me doubt this was possible.

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Abbreviations

GIS	Geographic information system
GISci	Geographic information science
SSI	Spatial Sciences Institute
USC	University of Southern California
THEMIS	Thermal Emission Imaging System
HRSC	High-Resolution Stereo Camera

Abstract

Geologists have studied Earth's long-runout landslides for many decades due to their unpredictability and massiveness. Long-runout landslides on Earth largely depend on initial mass position, friction, slope, topographic relief, gravity, and sediment composition. Landslides on Mars exhibit a high degree of preservation, offering insights into the planet's history, including the occurrence of water in past eras. This study examined long-runout landslides in the Valles Marineris canyon system of Mars and compared them to similar landslides on Earth. The methodology developed in this study utilized GIS tools and High-Resolution Stereo Camera (HRSC) imagery to visually interpret and measure the mass movement of long-runout landslides of affected terrain. Landslide visualizations and cross-sections were manually created to facilitate estimating changes in the length and height of the Mars long-runout landslides. These measurements were used to calculate Heim's ratio, an approximation of the friction coefficient of Mars surface regolith comprising the landslide masses, and to compare these values to those of similar long-runout landslides on Earth. The goal was to test the assumption that friction, specifically, plays a significant role in long-runout landslides on Mars. In the future, an improved understanding of long-runout landslides on Mars may assist scientific communities in interpreting Mars's geological processes and climatology and illustrate important knowledge gaps in Mars history.

Chapter 1 Introduction

When earthen material on a slope gives way, the result may be due to forces acting down the slope that exceeds the earthen material strength resulting in a landslide (USGS, 2022; Varnes, 1978). Landslides on Earth are unpredictable, critical geohazards, and pose dangerous risks to human settlements because of potential slope failure (Barnett, 2016). One hazardous type of Earth landslide that is challenging to predict is the long-runout landslide due to mass sediment movement that can unexpectedly travel a long horizontal distance over a short vertical fall. The mechanisms for the mass volume of long-runout deposits moved over extremely short vertical displacements have puzzled scientists for years (Wheeling, 2016). The unpredictability of Earth's long-runout landslides makes them very interesting to study. In the 1990s, researchers such as Straub (1997) stated that we first need to understand mass sediment movement flow mechanisms to understand a landslide's motion. Earth's long-runout landslides depend heavily on the initial mass location, geologic properties of the sediments, and topographic relief (Crosta, 2018).

Landslides on Mars exhibit a high degree of preservation, offering insights into the planet's history, including the occurrence of water in past eras. The main goal of this study is to investigate long-runout landslides on Valles Marineris, Mars, and compare the findings to similar long-runout landslides on Earth. In addition, this research may assist in understanding if friction plays a significant role in making long-runout landslides more massive on Mars than those on Earth. Long-runout landslides on Earth exhibit runout that violates the frictional behavior of other types of landslides, meaning that they exceed the expected runout distance (Parez, 2015). The friction coefficient is calculated using the ratio between the friction force and normal force to determine the amount of friction between two surfaces. The friction coefficient is dependent on the surface material and the surface roughness (Zhang, 2016). The remainder of this chapter introduces how these properties or forces contributing to long-runout landslide earth materials were investigated. This thesis project proposes that the investigation of similar, comparable landslides on Mars can help many scientific communities discover more about the geological and climatological history of Mars (Figure 1).

1.1. Motivation

Long-runout landslides are a rare phenomenon on Earth but common features within Valles Marineris on Mars (Watkins, 2015). Compared to the thousands of minor landslides documented on Earth, only five long-runout landslides with volumes exceeding $10^9 m^3$occurred in the twentieth century (Korup, 2013). According to Korup (2013), the rarity and rapid erosion of long-runout landslides on Earth pose substantial challenges to performing related hazard assessments.

Long-runout landslides are unpredictable natural hazards that can cause mass destruction, capable of obliterating everything in their path. For example, in 1903, the deadliest landslide in Canadian history, known as the Frank Slide, was a long-runout landslide (Bonikowsky, 2013**).** This landslide occurred when the side of Turtle Mountain gave way, ninety million tons of rock sliding down the side of the mountain. The landslide obliterated a local power plant, a bridge, farmhouses, and approximately 121 people were entombed under the rubble (Peters, 2021).
The leading forces contributing to landslide events on Earth include friction and gravity, but the triggers for these long-runout landslides are different from gravity. The role gravity plays in Earth landslide occurrences focuses on the internal strength of the earth material, the degree to which the material can retain its position or stability before a slope fails, and how much friction is applied to the material. On Earth, a landslide occurs when the force of gravity surpasses

friction and the material's internal strength, causing a slope to fail (Washington Geological Survey, 2017).

Primary triggers that can induce landslides include increased pore water pressure, soil type, weathering, loading, changes in vegetation, and earthquakes. Water can reduce friction between underlying bedrock and the overlying soil mass. For example, triggers may include rainfall or a change in the groundwater table level. According to Watkins (2011), one prominent theory attributes the greater spreading and distance, or runout, traveled by Earth's landslides to hydrated minerals, also known as clays. The question of whether or not water is, or was, present on Mars has been the subject of much research**.** Lubrication by some liquid or water in the Mars terrain may have come from ice, which would have made the terrain susceptible to sliding (Lucchitta, 1978). If clays are present within a given Mars slope relief, this will support the hypothesis that water was once present on Mars during mass slope movements. As stated above, soil types are also a significant factor contributing to where a landslide may occur on Earth. Sediments derived from rock types such as shale, clay, and sediment deposits consisting of silt-sized grains are strongly associated with landslides (Watkins, 2020).

This research project aims to contribute to Mars geology and environmental studies and Earth landslide research communities by investigating the mechanisms that drive long-runout landslides on Mars. Since Mars has cooled, the landslides on this world with no active erosion, vegetation, or plate tectonics are believed to be remnants of earlier environments, which did once include water, erosion, and crustal plate movement (Magnarini, 2019). These remnants are massive compared to long-runout landslides on Earth, providing important clues or evidence of past geologic history since they are undisturbed. In addition, determining the causes and triggers of long-runout landslides on Mars may help scientists better understand the occurrences of the same types of landslides on Earth. However, since Earth is very active with tectonics, erosion, and weathering, remnants or evidence related to the causes of the events are often destroyed shortly after the occurrences, making these natural hazards, particularly ancient landslides, extremely difficult to study on Earth.

In summary, the main goals of this thesis include the following:

- To understand the drivers of long-runout landslide occurrences on Mars, compare long-runout landslides on Mars to those on Earth, and determine if analytical methods of explaining observed rock and sediment flow on Earth can be applied to Mars landslides;
- To investigate if soil material strength and friction along the slope of a given relief may play a significant role in long-runout landslides on Mars, as they do on Earth; and
- To learn about the triggers of long-runout landslides on Mars and if their behavior can help improve our understanding of the same landslides on Earth.

1.2. Study Area

As mentioned above, Mars possesses a system of canyons named Valles Marineris, the focus of this research. This system runs across the surface of Mars and resembles a scar (Figure 1) (Tillman, 2017). Valles Marineris is composed of steep-walled canyons and extends over 4000 km in length, approximately the size of the United States measured from East to West (Tillman, 2017). Landslides on Mars have been observed since 1971, starting with images obtained by Mariner 9 and the Viking missions (Magnarini, 2021). In this project, many landslides within the Valles Marineris feature area were compared to long-runout landslides found on Earth to determine their similarities and understand the causes of the Mars landslides.

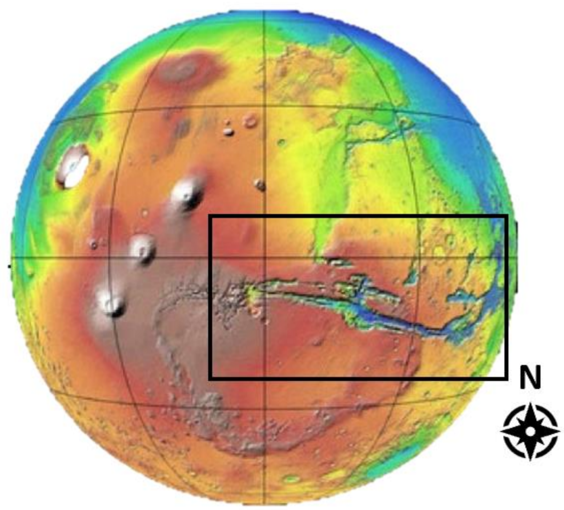


Figure 1: Image of Mars (Mason, 2014). The Canyon seen on the planet is Valles Marineris.

1.2.1. Comparing Landslides

To narrow down the driving mechanisms of the Valles Marineris landslides on Mars and compare them to similar Earth landslides, this study began with a review of six different long-runout landslides on Earth to develop analysis criteria. The first Earth landslide compared was the Blackhawk landslide in 2019 in Lucerne Valley, California. The Blackhawk landslide consisted of about 300 million cubic meters of earth material (Petley, 2019). The second, the Frank Slide, located in Alberta, Canada, comprised an estimated 82 million tonnes of limestone that sheared off the east side of Turtle Mountain (Bonikowsky, 2013). The third, the St. Helens landslide, was connected to the 1980 volcanic eruption in the state of Washington. The St. Helens landslide had an estimated volume of 2.8 cubic kilometers (USGS, 2022). The fourth, the Val Pola, Italy landslide, occurred in 1987 and consisted of approximately 34 million cubic meters of rock. (Petley, 2019). The fifth, the Montserrat, West Indies landslide, resulted from a volcanic eruption and estimated a volume deposit of 1 to 20 cubic kilometers. The sixth Earth landslide used in this study for comparison was the Mount Steller, Alaska, long-runout landslide, was triggered by meltwater and had a runout volume of approximately 50 million cubic meters (Molnia, 2012). This historic Earth event information represents a wide variety of long-runout landslides that occurred around our world. Because of their different geographical locations, an assumption can be made that the causes and triggers for these long-runout landslides may all be different, or at least exhibit some variation, even though their massive runout volumes are all similar.

Chapter 2 Related Work

This chapter reviews previous studies focused on identifying and understanding the main mechanisms driving long-run landslides on Mars and Earth.

2.1. Landslide Morphology

The investigation of Mars landslides found in the Valles Marineris system started when their nearly complete preservation was observed in images that Marine 9 and Viking transmitted to Earth (Watkins, 2020). The well-preserved Mars landslides provide a window into the geologic past, perhaps clues to historical climate, and may allow scientists to piece together if there was, indeed, water on Mars.

Studying landslides requires knowledge of basic geomorphology to explain the evolution of landslides and landscapes (Cordova, 2016). Landslides found within the Valles Marineris system have previously been studied to learn about their morphology, geological structures, similarities to landslides on Earth, and how sediment is transported a significant distance (Watkins, 2020). Many of the observable landslides on Mars appear to be similar in age, which may help scientists determine when Mars was tectonically active in the past. Some landslides studied on Mars have been dated to have occurred when the Tharsis volcanoes erupted approximately 3.7 billion years ago, which is assumed to have caused the sediments in the area to give way to the formation of multiple long-runout landslides (Figure 2) (Phillips, 2001).

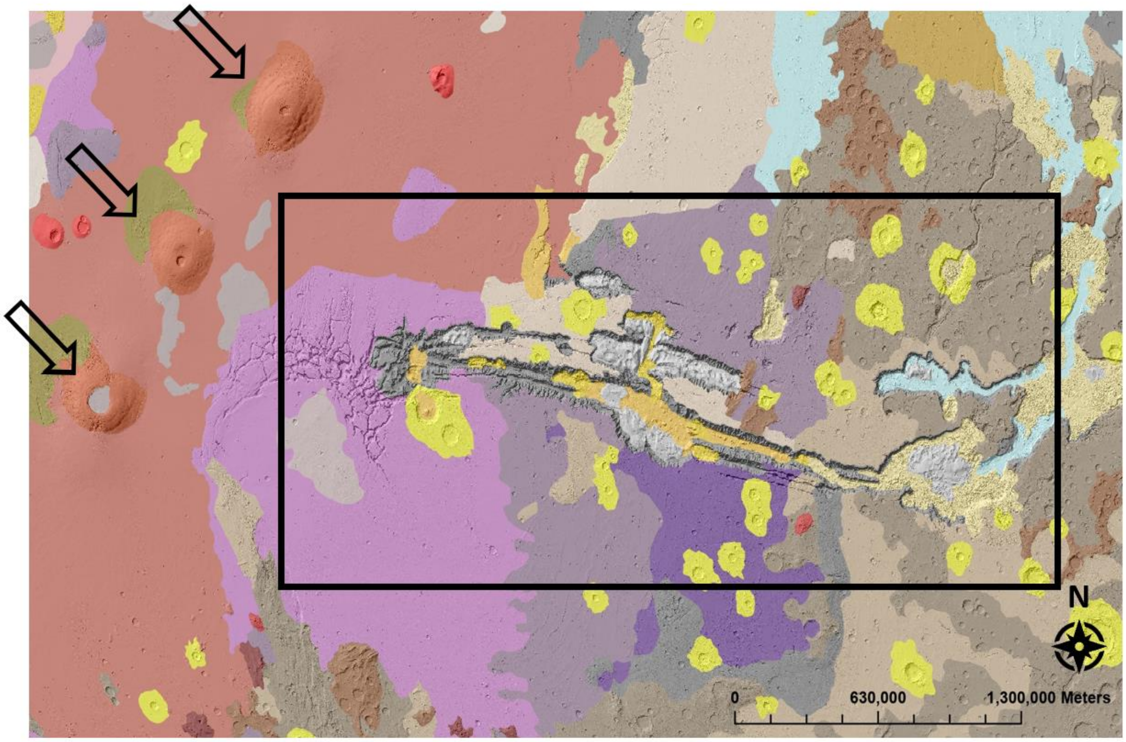


Figure 2: Image of Mars (Wright, 2021). Tharsis volcanoes (shown by arrows) in relation to Valles Marineris (inside the rectangle).

According to Magnarini (2021), the Mars long-runout landslides may have originated as gigantic mudflows triggered by excessive water that once existed in a Martian subsurface aquifer. Based on images gathered from Mariner 9, scientists classified long-runout landslides into four categories within Valles Marineris: unconfined, confined, composite, and superposed (Figure 3). Unconfined, the first type of landslide was dispersed over surrounding open plains. The second type was confined, which occurred in narrow spaces. The third type was composite, an intermediate between confined and unconfined. Finally, the fourth type was superposed, a landslide that had overridden an older landslide in a different source area. (Lucchitta, 1979). Also, some of the most prominent long-runout landslides found on Mars have occurred along fault scarps.

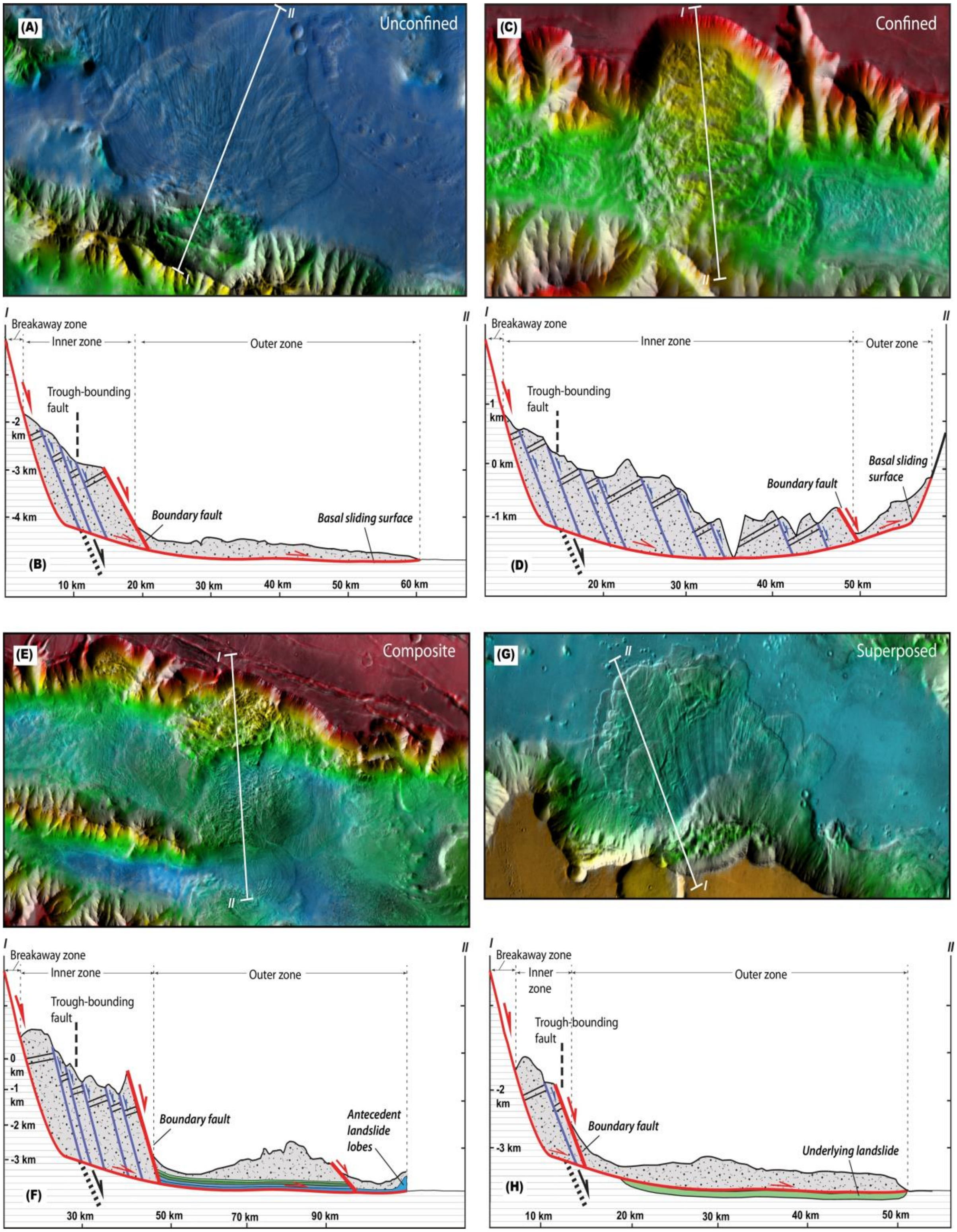


Figure 3: Valles Marineris long-runout landslide classifications. (A and B) unconfined, (C and D) confined, (E and F) composite, and (G and H) superposed landslide examples (Watkins, 2020).

Using Watkin’s (2020) classification and the characteristics shown in Figure 3, the long-runout landslides studied in this thesis were classified in Figure 4. Images 1-4 within Figure 4 display s confined landslides. Image 5 displays landslides 5 and 6, which were classified as unconfined landslides. The geomorphological features identified in the images shown in Figure 5 were obtained using a High-Resolution Stereo Camera (HRSC). The features identified include the toe and scarp that the long-runout landslides left behind.

Five classifications used to describe mass movements on Earth include rockslides and deep-seated slides, complex/compound slides, rock avalanches, debris flows, and rock glacier features (Brunetti, 2014). This study uses these Earth classifications to help describe the different types of landslides that can be identified on Mars. Long-runout landslides can also be triggered by erosion that undermines canyon walls making them unstable, contributing to the Earth’s materials such as sediment or rocks moving down the slope. Long-runout landslides can also be triggered by even a small amount of water, wind, or seismic activity.

In addition, a Thermal Emission Imaging System (THEMIS) recorded infrared images of the rocks on Mars (Smith, 2003). The images record heat emitted from the rocks and sediment on the surface (Figure 6). As on Earth, the colors are decoded the same way: reds represent warm material, and blues represent colder material. The images reveal the age of the landslides by studying visible craters, assumed to have been caused by meteor strikes. At present, in-situ impact craters provide the best mechanism for dating Mars surface features, for example, using radiometric techniques (Williams, 2017). In most cases, craters appear to postdate many of the landslide features on Mars, which allow scientists to date the landslides (Mar Odyssey THEMIS, 2021).

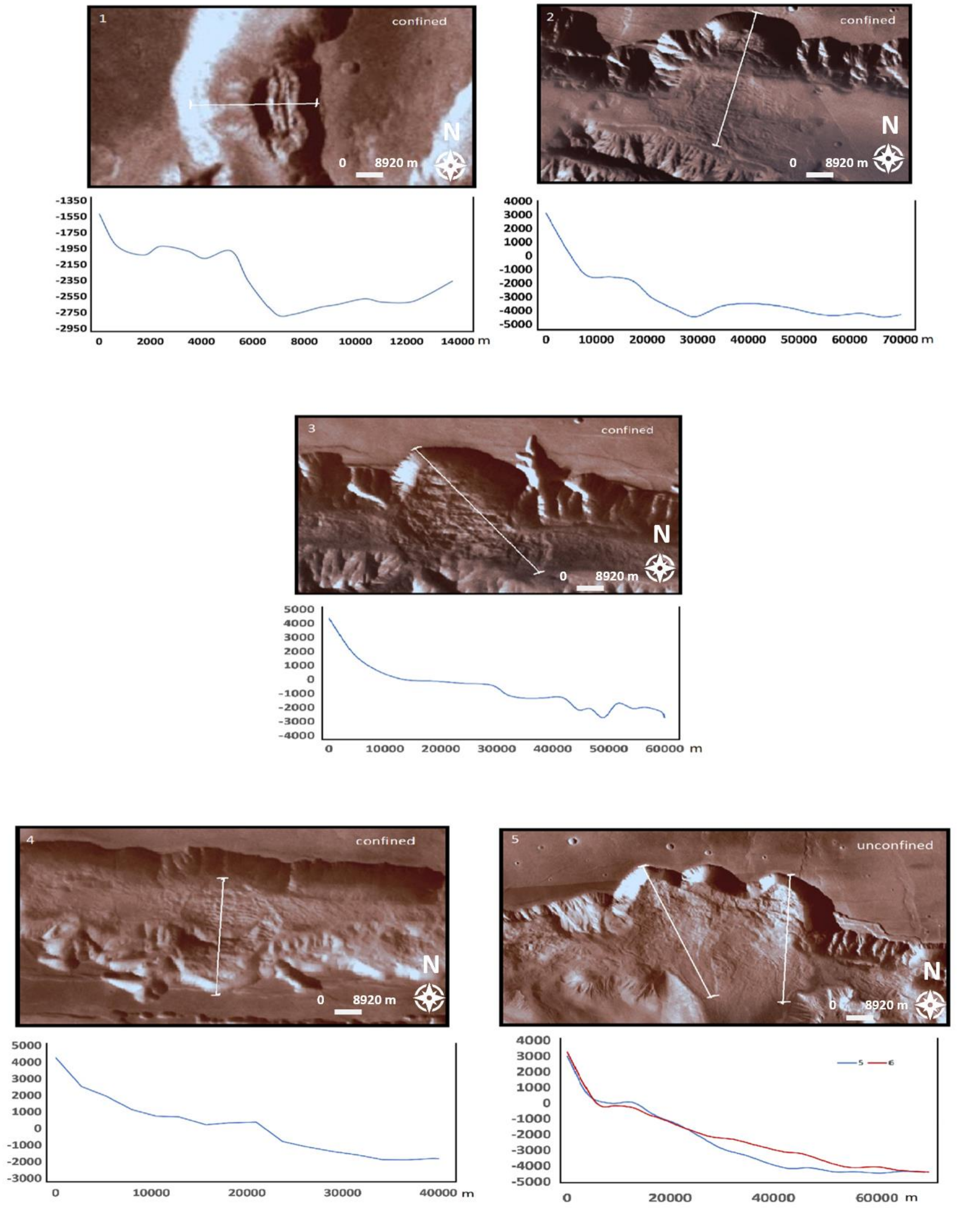


Figure 4: Long-runout landslide classifications of the study area. (1) confined, (2) confined, (3) confined, (4) confined, and (5) unconfined

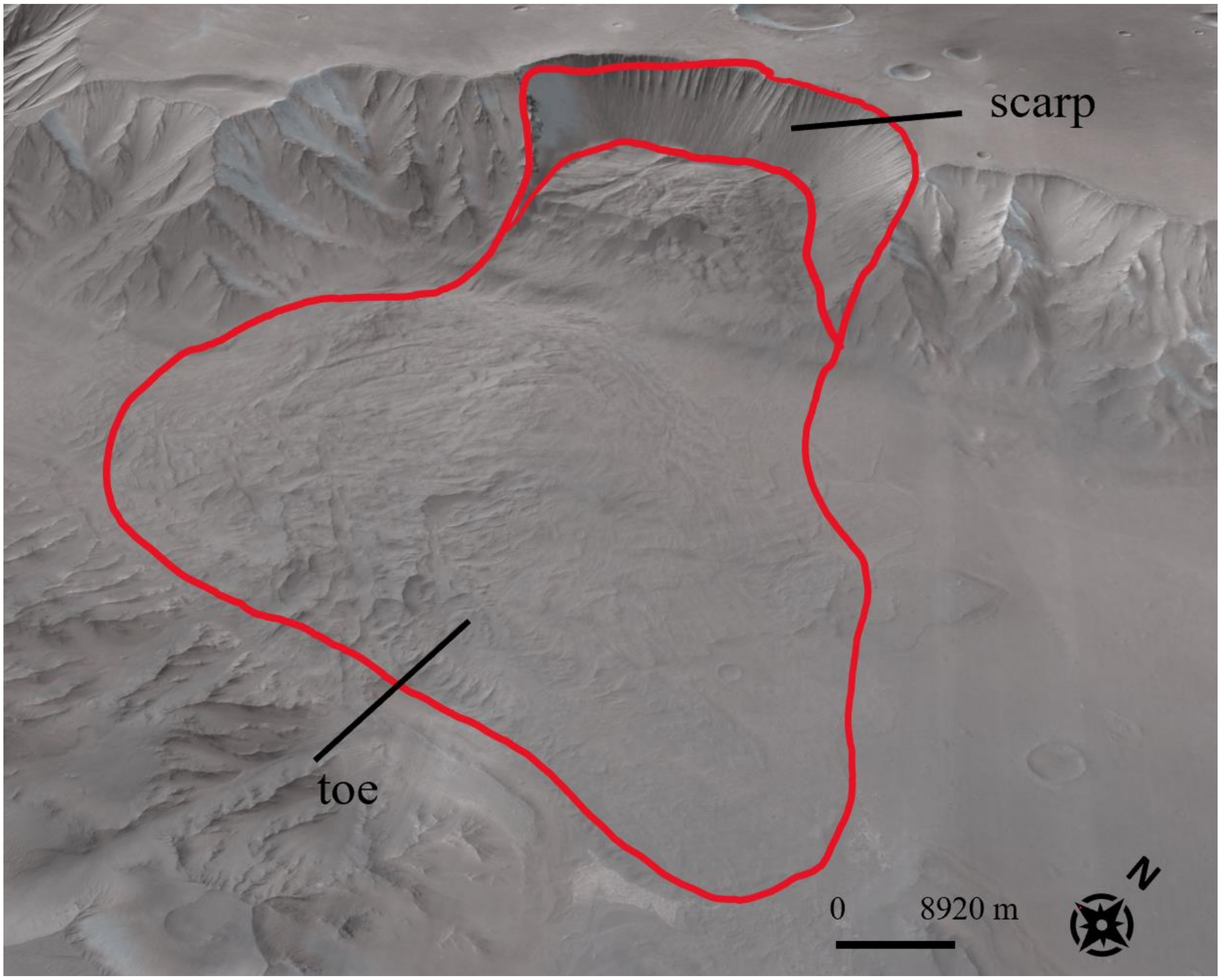


Figure 5: Depiction of the scarp and toe left behind the from a long-runout landslide

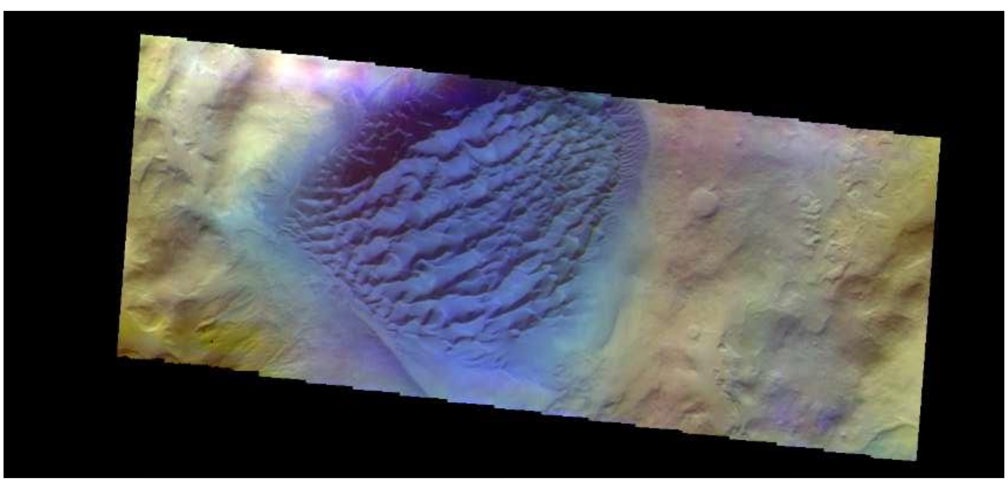


Figure 6: THEMIS image showing a false-color image of the large sand sheet on the floor of the Matara Crater (Mar Odyssey THEMIS, 2021)

2.2. Landslide causes

One leading theory regarding the mechanism of landslides found on Mars is that they were triggered by water and ice events previously occurring on the planet (Magnarini, 2019). However, other contrasting research has indicated that materials that comprise landslides on both Earth and Mars are dry in some cases. This means that the trigger mechanisms may be other factors, such as the types and degree of consolidation of sediments, slope steepness, drop height, and the sediment volumes comprising the landslides (Johnson, 2017).

The study of long-runout landslides has interested many scientists because the sediments and can exceed the maximum mobility volume $10^5 m^3$ associated with long-runout landslides on Earth. Mobility is generally defined using the ratio of the landslide fall height to the travel length (Bessette-Kirton, 2020). As previously noted, the large spreading magnitude of the regolith on Mars has not been observed on Earth (Tillman, 2018).

2.2.1. Slope Angle

Slope angles play an essential role in landslide formation, development, and susceptibility (Çellek, 2020). Slope angle measures the surface steepness and determines when the soil becomes unstable. The slope angle is measured by determining the height displacement (H) in various sections of a landslide and calculating the distance (L) the landslide travels (Figure 7).

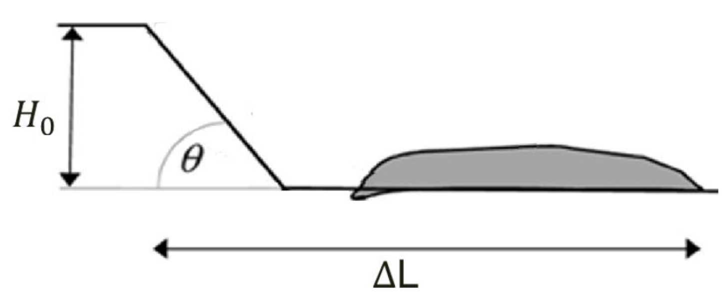


Figure 7: Cross-section of terrain showing slope angles (Parez, 2015).

Steep slopes do not always produce massive landslides, such as in the case of long-runout landslides. However, previous research done by Donnarumma (2013) included comparing landslides to stable land areas (Figure 8). The data gathered from Donnarumma (2013) was obtained from sites rich in clays. Bell curve graphs were constructed to determine at what angles slopes became unstable, which varies based on the geology or the type of clay in Donnarumma's (2013) case study. Donnarumma's (2013) bell curves indicate that a significant occurrence of Earth landslides comprised of clayey materials falls within a slope range of 9 to 14 degrees. These slope angles on Earth are highly relevant compared to those of similar landslides on Mars, because their range of angle values are significantly different.

2.2.2. Geological material

Compared to Earth's numerous soil classifications, Mars only has one category, regolith; since there is no known organic material on Mars, there is technically no soil. In contrast, since the Earth has organic matter, multiple stratified soil types exist. Regolith is a broad term used for loose material covering some planets, such as Earth, Mercury, and Mars. Mars regolith consists primarily of silicon dioxide and ferric oxide, with small amounts of sulfuric oxide, calcium oxide, and aluminum oxide (Savage, 2017).

Landslides studied in Capri Chasma, part of Valles Marineris, possess a low friction coefficient, defined as the ratio between the vertical fall and the runout length (Table 1) (Mahler, 2003; Blasio, 2011). In this study, the Mars regolith was named based on the friction coefficient obtained when calculating the slope. Each friction coefficient is associated with a similar, corresponding soil type on Earth, even though the regolith on Mars does not follow the strict definition of soil.

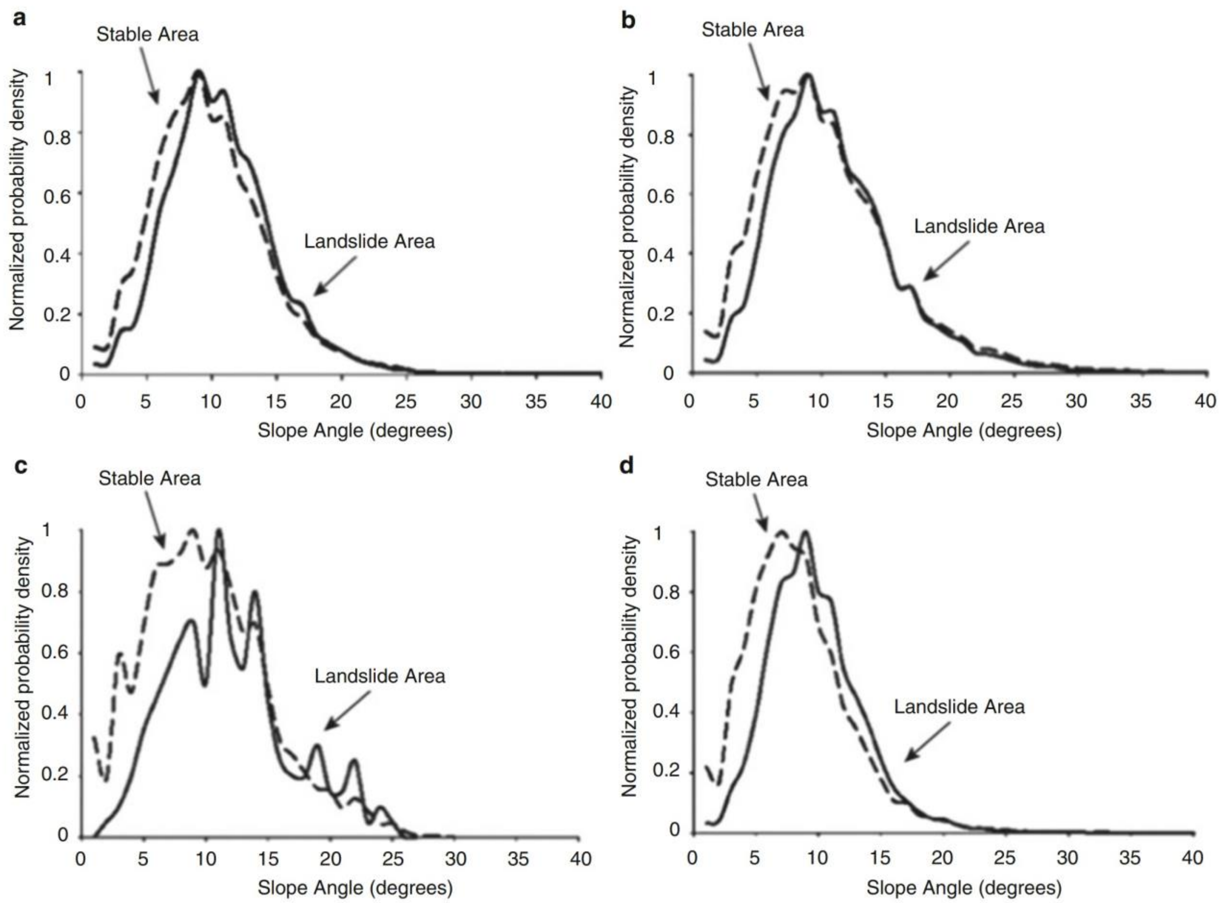


Figure 8: Donnarumma's area probability density distribution. The bell curves graphs indicate the slope angle at which the sediment detached and a landslide occurred. Each graph represents a different clay composition. (a) clayey sequence (b) arenaceous clayey conglomeratic sequence; (c) clayey, silty sequence; (d) clayey marly sequence (Donnarumma, 2013)

Table 1: Friction Coefficient of Mars landslides compared to soil material on Earth (Mahler 2003).

Landslides	Friction Coefficient	Material
1	0.090	Clay/silt
2	0.027	Clay/silt
3	0.058	Clay/silt
4	0.060	Clay/silt
5	0.037	Clay/silt
6	0.042	Clay/silt

2.2.3. Gravity and shear stress

When it comes to landslides on both Mars and Earth, gravity plays a significant role. The gravitational pull of Mars is much smaller than on Earth. Mars has a gravity of 3.721 m/s^2, while Earth's gravity is 9.807 m/s^2. The shear strength of a material such as soil or regolith is determined by the frictional resistance and cohesion of the sediment or rock material. When a tectonic event occurs, shear stress becomes more significant than the shear strength holding an object or deposit in place on a slope. Then sediment or rock mass will move downward due to the force of gravity, and a landslide will occur, as illustrated in Figure 9 (Nelson, 2015). It is important to note that the gravity values for Earth and Mars were not utilized in this study's calculations of high mobility and Heim's ratio. The future work section of this thesis discusses the role of gravity in long-runout landslides on Mars.

2.3. Existing Methodology for Explaining Long-Runout Landslides

Long-runout landslides are interesting to scientists because they travel long distances with a small vertical displacement. In the future, understanding the mechanism that causes these landslides to flow a lengthy distance on Mars may allow us to apply the findings to better understand long-runout landslides found on Earth. Furthermore, in turn, better understand how the tectonic history of Mars differs from that of Earth.

Understanding the role that friction plays in landslides is crucial. The amount of friction present within these Mars long-runout landslides is minimal, making them highly destructive (Johnson, 2017). According to Lucas (2016), the effective friction coefficient of landslides on other planets in our Solar System seems to decrease as sediment volume decreases.

After the first images were sent back from the Viking Orbiter, the landslides along the Valles Marineris canyon caused much controversy (Watkins, 2020). The landslides found within the canyon contain evidence that water was once present on Mars. Today, many of the landslides that have been photographed have been studied (Magnarini, 2019). Some studies generated 3D geometric models of the landslide deposits using the topographic images acquired by the Mars Orbiter Laser Altimeter and remote sensing images obtained by the Mars Obiter camera (Lajeunesse, 2006). The volume of the landslide deposits was obtained in these past studies by analyzing the landslides' aprons, meaning the regolith deposits. The apron of the landslide hints at the hazard magnitude and indicates that lubrication with a liquid or water was involved.

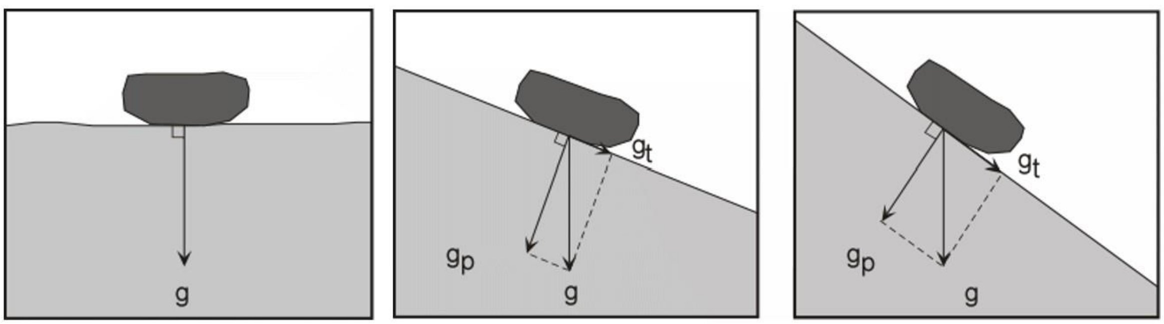


Figure 9: The left-hand image shows gravity (g) pushing down on the object. The middle and right-hand images illustrate that when an object is on a gentle or steep slope, there is a perpendicular component of gravity (gp), the acting gravity holding the object in place, and the tangential component gravity (gt) is the shear stress. Thus, shear stress is always parallel to the slope (Nelson, 2015).

Understanding all of the factors that drive the long distances that Mars landslides travel is still a mystery. Borykov (2019) created a discrete model to help understand what drives landslides on Earth, which can also be applied to Mars. While conducting simulations, some observations demonstrated that the friction of geological materials weakens with increasing velocity of movement, which is also observed in earthquake mechanics. If earthquakes can increase the velocity in a simulation, the question that needs to be answered is if these types of triggers can reduce friction enough to cause long-runout landslides on Mars as happens on Earth. Borykov (2019) conducted a simulation using 3D digital elevation models (DEMs) that reproduced general behaviors of unsteady Earth structure collapses. The model can simulate a number of scenarios after being properly calibrated to reflect the terrain being studied.

The analysis method includes slope change, interpretation of topography as steep versus not steep, estimation of the sediment volume deposited by the landslide, and calculation of the friction coefficient. Producing a digital simulation facilitated the testing of different scenarios to assist in the identification of causes for long-runout landslides.

Friction Coefficient (μ) is defined as the ratio of the frictional force (F) and normal force (N) acting against each other, where the normal force is much more significant because it prevents other objects from moving (Eqn. (1)) Borykov (2019). Low friction can be due to the material losing traction and experiencing no resistance to the motion (Mangnarini, 2019).

$$\mu = \frac{F}{N} \quad \text{(Equation 1)}$$

As shown in Equation 2, Heim's ratio uses the vertical drop of the sediment or block as the height (H) and the runout distance (L) of the landslide to calculate landslide "mobility." Incorporating the Coulomb friction law, a relationship is established between the effective friction coefficient μ_{eff}, the initial thickness of height (H_0), change in length (ΔL), and tanθ (Eqn. (3)) (Lucas, 2014). Using the cross-sections created for each landslide, tanθ, which represents the slope, was acquired using this simple slope equation (Eqn. (4)).

$$\text{High Mobility} = H/L \quad \text{(Equation 2)}$$

$$\mu_{eff} = tan\theta + \frac{H_0}{\Delta L} \quad \text{(Equation 3)}$$

$$\theta = tan^{-1}(m) \quad \text{(Equation 4)}$$

Each of the equations presented above contributed to finding the correlation between the Earth's sediment and the regolith on Mars. The next chapter focuses on using friction to better understand and explain the behavior of the Mars long-runout landslides investigated in this study.

Chapter 3 Methods

As previously stated, one of the main goals of this project is to deduce what drives long-runout landslides on Mars. Analytical methods applied to observed rock and sediment flow on Earth were used on Mars landslides to see if soil material strength and friction along the slope of a given relief can help explain the existence of long-runout landslides on Mars. Furthermore, understanding the triggers of long-runout landslides on Mars might improve our understanding of the same type of landslides on Earth in the future.

3.1. Data

The Mars long-runout landslide data for this project consists of images acquired from Google Earth Pro and Esri's Explore Mars application. To the author's best knowledge at the time this study was conducted, these images had not been used in any other similar research published about Mars landslides. Google Earth has recently developed a tool to facilitate digital exploration of Mars, which can facilitate the collection of elevation of surface features such as landslides across the planet and includes a DEM of Mars (Google earth V. 7.3.4.8248, 2021). Therefore, in this study, Google Earth was used to identify long-runout landslides on Earth as well as on Mars. In addition, Esri's Explore Mars application was used to discover and explore the landslides (Figure 10 - Figure 19) examined in this study (Esri Explore Mars, 2021).

3.2. Methodology

For this study, the preceding work on long-runout landslides studied on Mars described in Chapter 2 provided a starting point for the project in identifying the basics of what makes up these particular landslides, including information on how large they are compared to their counterparts on Earth. Images of the Mars surface documented in previous years were used to identify landslides within the Mars landscape **(**Esri Explore Mars, 2021, Smith, 2003, Google earth V. 7.3.4.8248, 2021). As previously stated, Mars landslides have remained undisturbed since the first images were collected and facilitated landslide studies for millions of years (Magnarini, 2019).

3.2.1. Landslide Analysis

This analysis utilized 3D images captured by previous rover explorations and obtained through Esri's Explore Mars application (Esri Explore Mars, 2021). The application includes a 3D DEM of Mars (USGS, 2022) and spatial analysis tools that can be used to visualize landslides in 2D and 3D. In addition, the application enables the visual exploration of Mars landforms and provides a measurement tool where elevation, length, width, and area can be obtained.

This study gathered elevation points for the six landslides within Valles Marineris. First, the Esri Explore Mars application tool was used to obtain the height and length of the six landslides of interest at specific points on either end of each landslide needed to create one cross-section or vertical profile per landslide. Then, using the landslide's cross-section, the total length (ΔL) and height of the landslide sediment mass (H) were calculated using the values obtained. Second, each landslide's slope angle was calculated using the same cross-sections. These calculations are explained in detail in the next section of this chapter.

3.2.2. Mobility Calculations

Using Heim's ratio, the friction coefficient was calculated for each landslide. Heim's ratio is dependent on the volume of the landslide. According to Parez (2015), the approximate friction coefficient value observed for large landslides on Mars is lower than a coefficient value of 0.1, which is significant because this value is much lower than the friction coefficient of standard rock or soil on Earth. This indicates that landslides on Mars have a much more substantial mass volume. On Earth, Heim's ratio is approximately 0.4 to 0.7 for landslides that exhibit a volume smaller than $10^6 m^3$. For volumes much greater than $10^9 m^3$, Heim's ratio is less than 0.1, which corresponds to a decrease in the friction coefficient as the volume increases (Lucas, 2014). This means that, as expected, based on using Heim's ratio, the much more massive landslides on Mars are probably due to at least in part to low friction.

Figures 10 – 19 show both the images used to create the cross-sections and the latter for each of the Mars landslides studied. For each landslide, a cross-section was created using the elevation points of the landslides obtained using the Esri's Mars Explorer application. In Figure 15, orange dots begin at the scarp of the landslide extending to the toe. Each point provided an elevation unit and a distance (length) of the landslide. Using these measurements, Equations 2- 4 were used to calculate the frictions coefficient, mobility (H/ΔL), and slope. The volume for each landslide was calculated using Esri's Explore Mars application tool, where the area can be calculated by the tool and by multiplying the using the length, the volume for each landslide was calculated (Figure 12). Table Table 2 summarizes the six studied landslides' coefficient, angle, volume, height, length, and slope, according to the data gathered from each Figure 10 - Figure 19.

Calculation Example for Landslide 1:

H= 1141.3 m

L = 14400 m

High Mobility = $\frac{H}{L} = \frac{1141.3}{14400} = 0.079$

$\mu_{eff} = tan\theta + \frac{H_0}{\Delta L}$ = 0.0106 + $\frac{1141.3}{14400} = 0.090$ (indicative of silt/clay on Earth)

Volume = l x w x h = $8.41\text{x}10^{11} m^3$

Table 2: values calculated for each landslide

Landslide	Height (m)	Length (m)	H/L	tanθ	μ_eff	Volume (m^3)
Mars Landslide						
1	1141.3	14400	0.0793	0.0106	0.090	8.41x10^{11}
2	1924.8	70942.6	0.0271	0.00028	0.027	1.46 x10^{11}
3	3317	62441.1	0.0531	0.00485	0.058	7.63x10^{10}
4	2516.9	42409.3	0.0593	0.00101	0.060	2.70 x10^{10}
5	2536.5	68418.5	0.0371	0.00035	0.037	2.41x10^{13}
6	3106.3	73656.5	0.0422	0.00029	0.042	4.89x10^{13}
Earth Landslide						
Blackhawk	800	9000	0.09	0.08	0.15	3.0 x10^{10}
Frank Slide, Canada	350	3800	0.20	0.18	0.24	3.60x10^{7}
St Helens	2070	23000	0.09	0.18	0.15	2.8x10^{9}
Val Pola, Italy	500	2035	0.45	0.23	0.4	3.80x10^{7}
Montserrat, West Indies	180	3500	0.25	0.18	0.23	4.00x10^{7}
Mount Steller, Alaska	135	9120	0.24	0.11	0.22	6.00x10^{7}

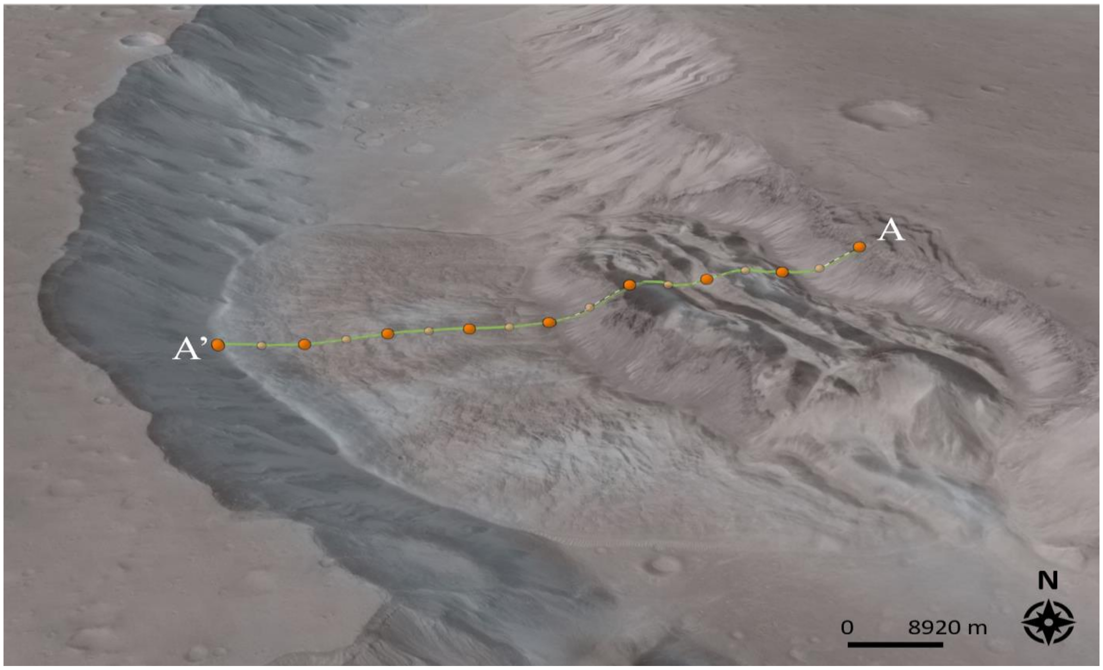


Figure 10: Landslide 1: Long runout landslide within Valles Marineris

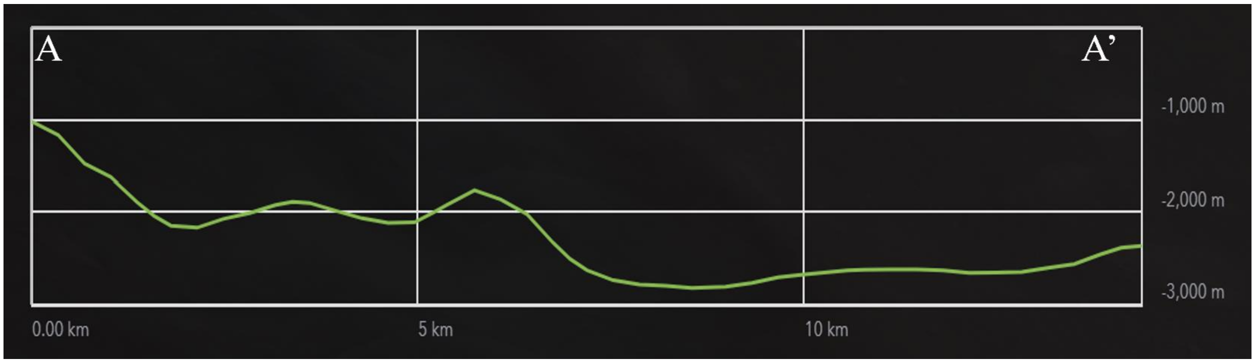


Figure 11: Elevation cross-section for Landslide 1

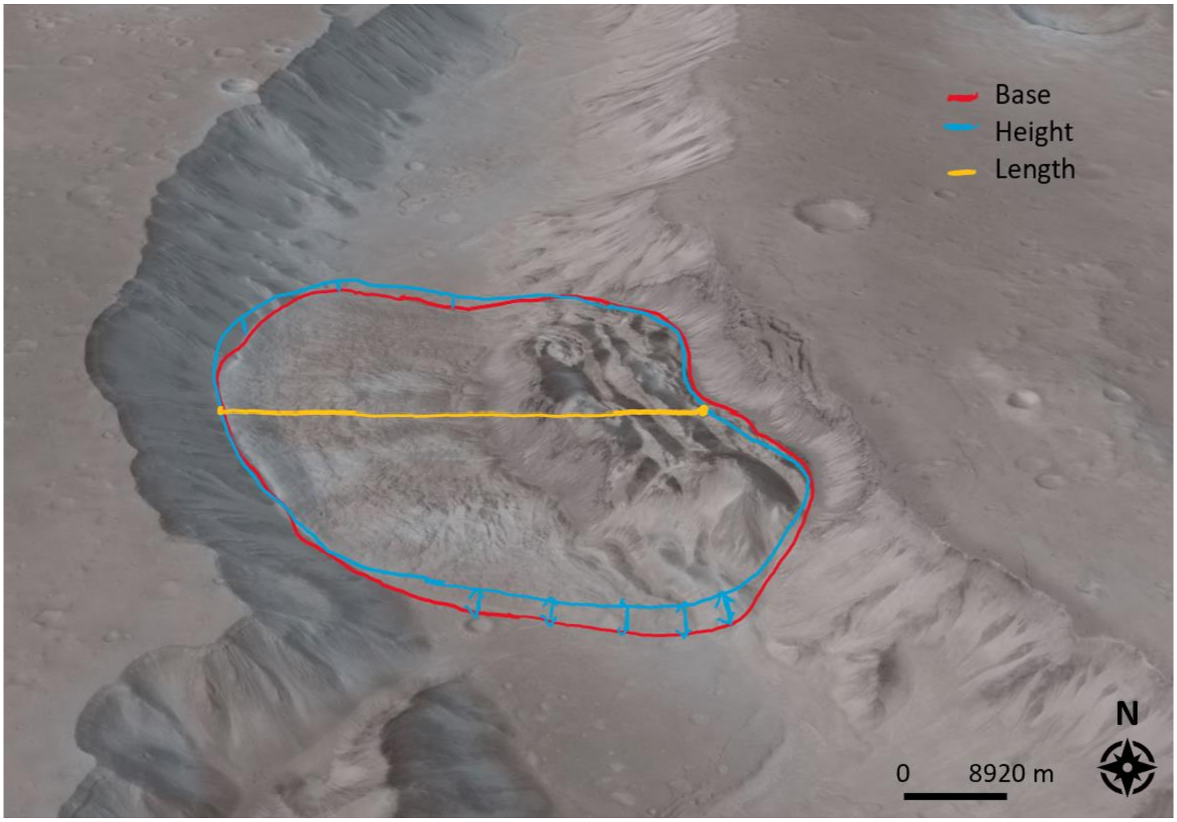


Figure 12: Landslide 1: Volume calculation of Landslide

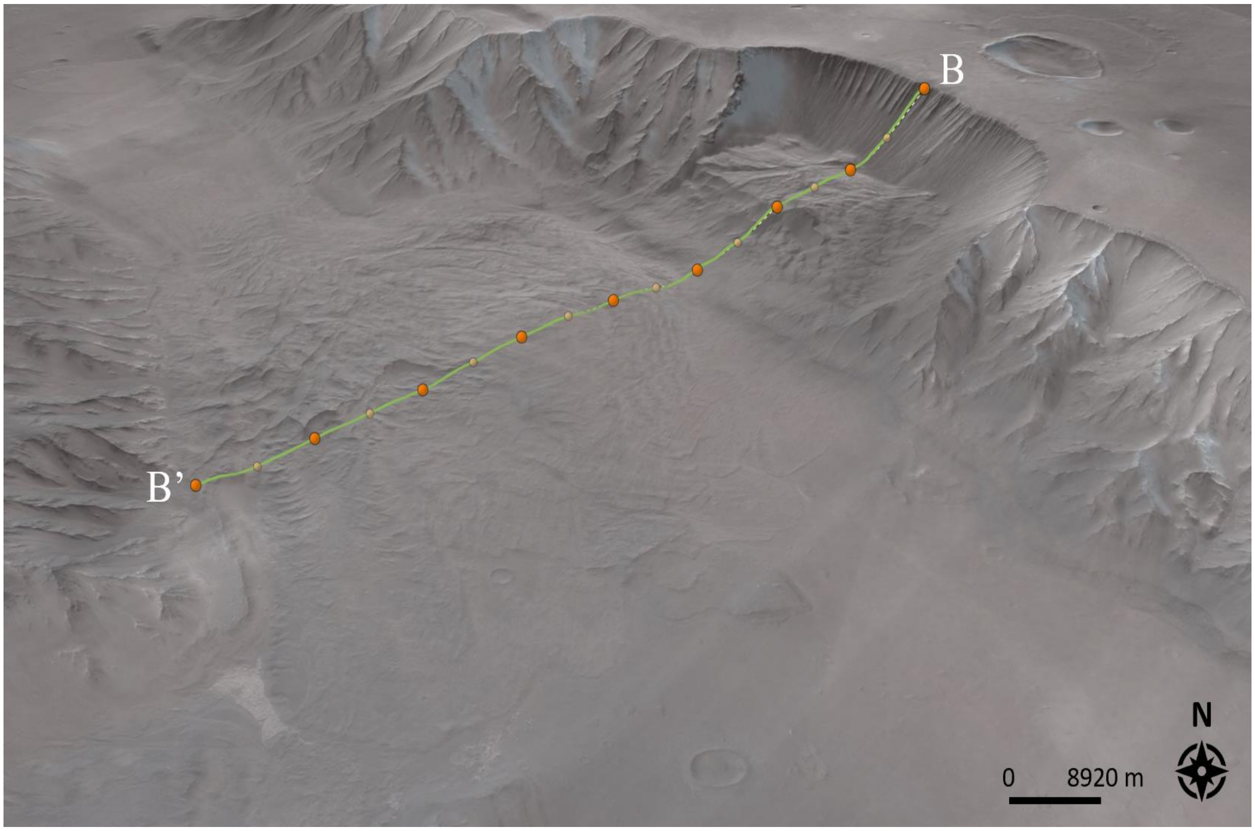


Figure 13: Shows Landslide 2 within Valles Marineris and its elevation cross-section

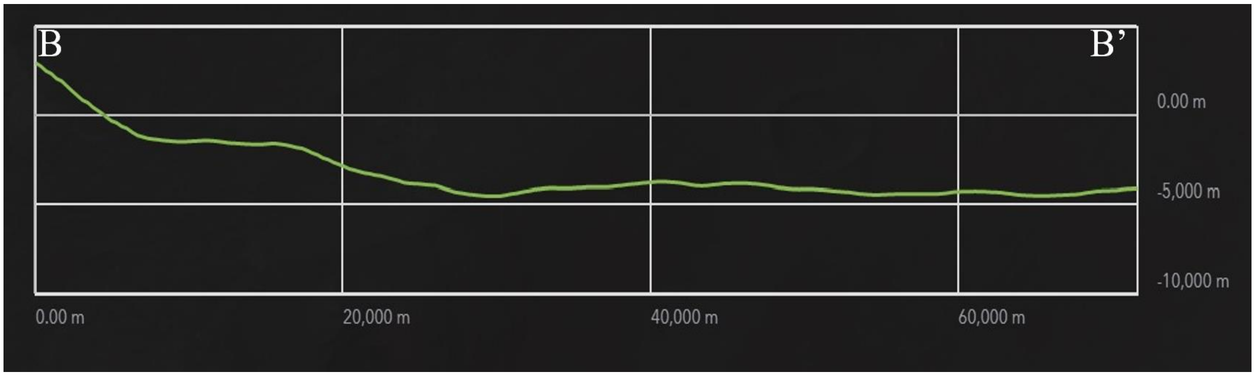


Figure 14: Elevation cross-section for Landslide 2

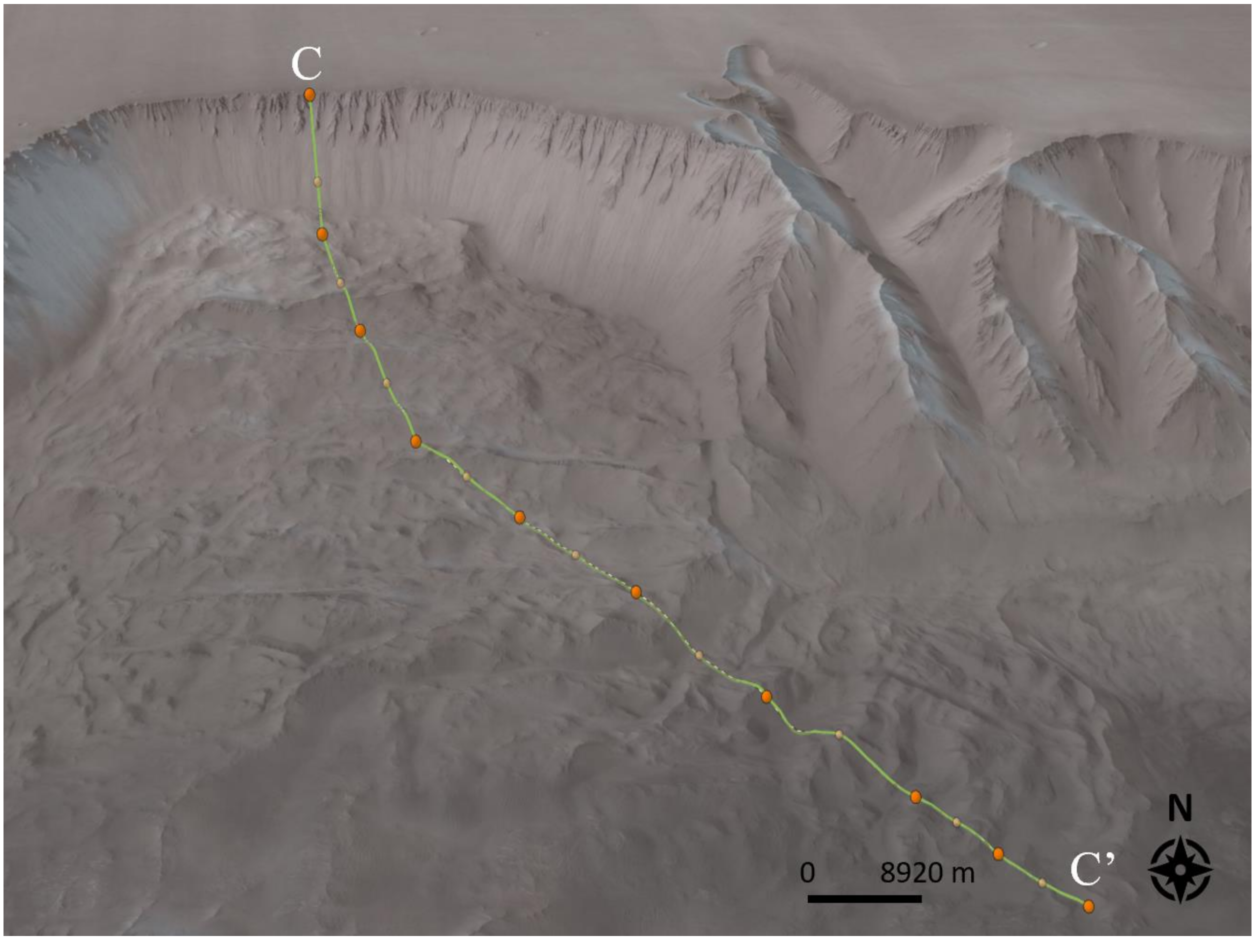


Figure 15: Landslide 3 within Valles Marineris

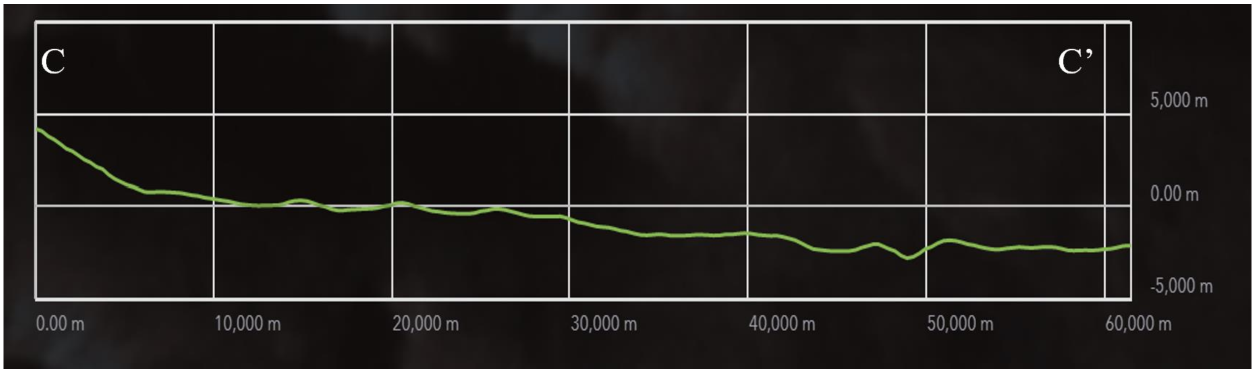


Figure 16: Elevation cross-section for Landslide 3

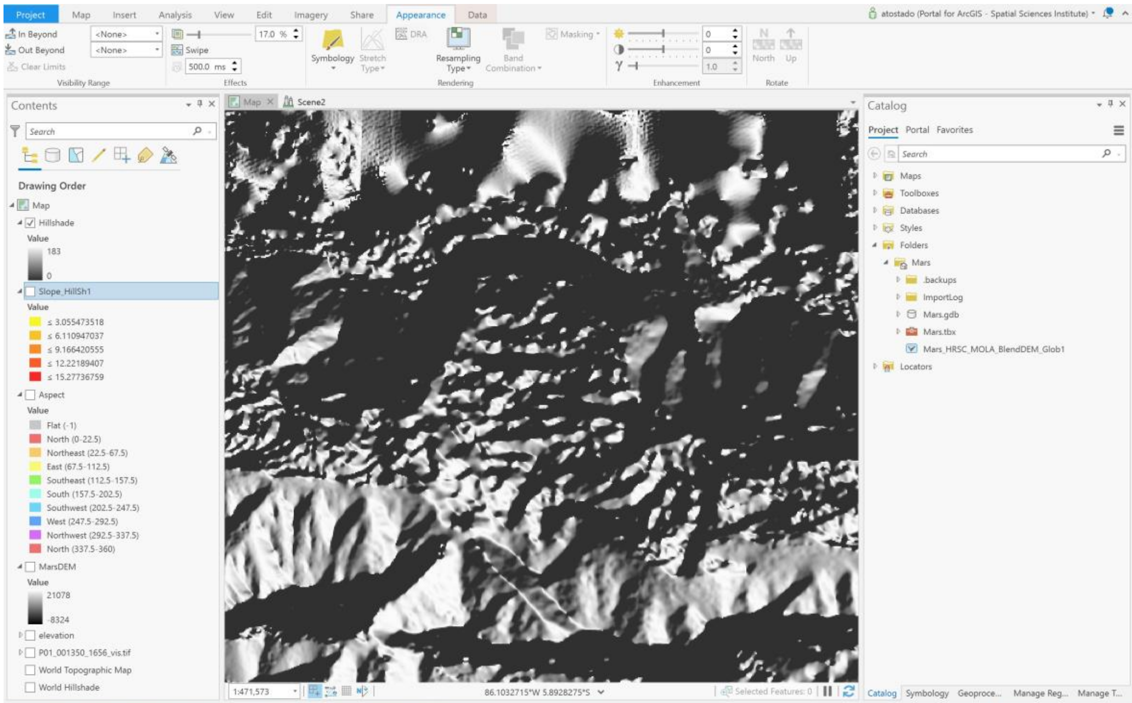


Figure 17. Hillshade of Landslide 1 processed using ArcGIS Pro

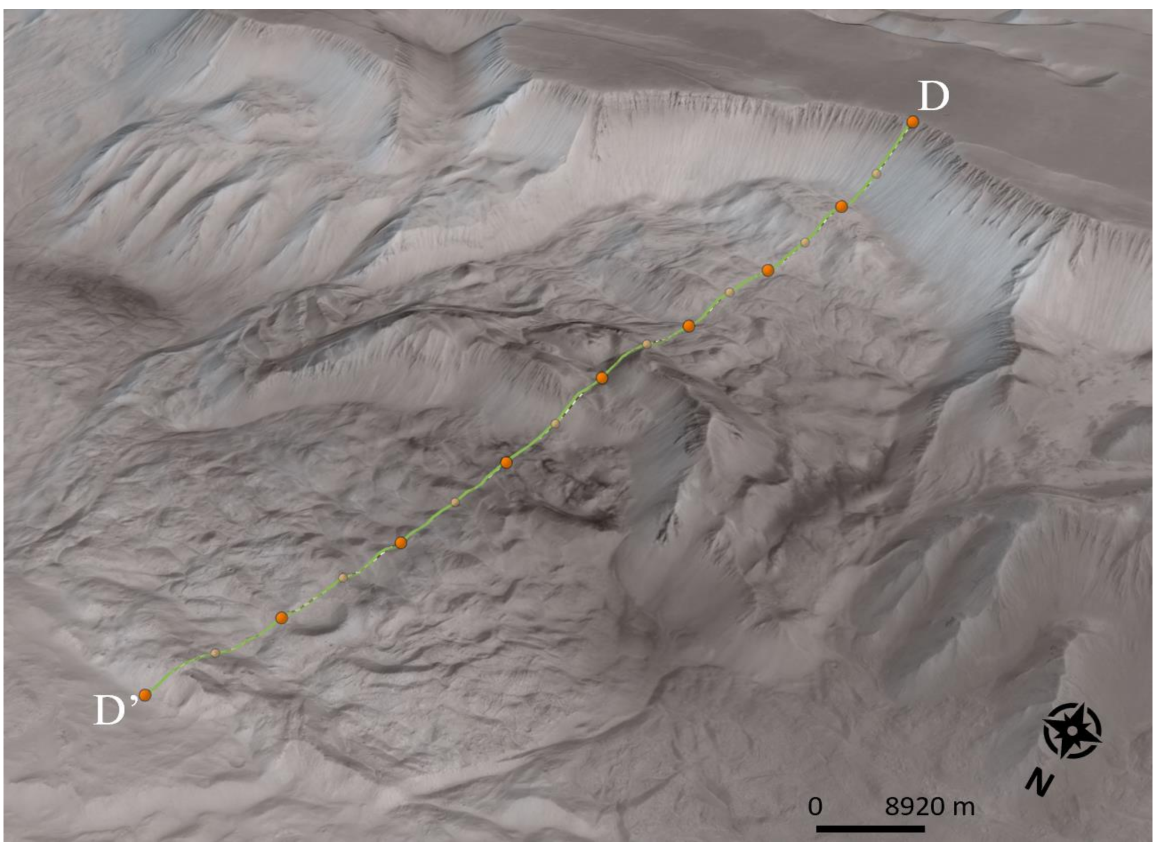


Figure 18: Landslide 4 within Valles Marineris

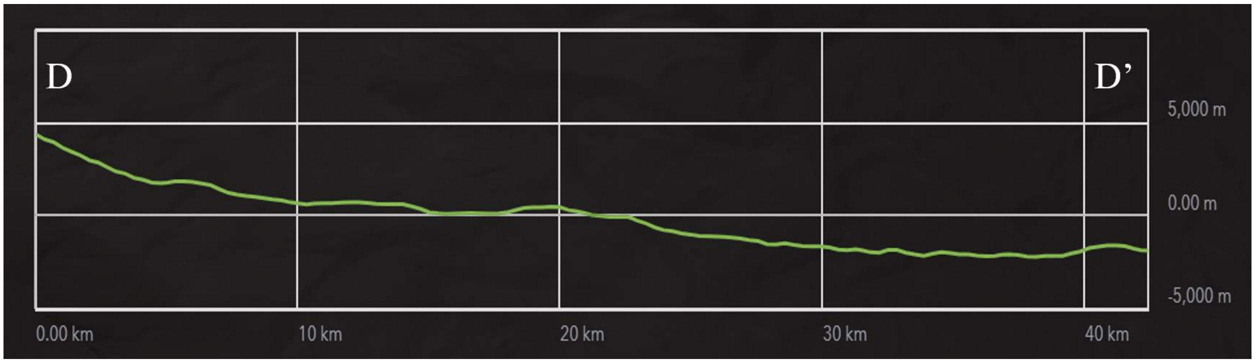


Figure 19: Elevation cross-section for Landslide 4

Some recent studies show that the massiveness of long-runout landslides might not only be due to the friction coefficient of the geological materials but may also be controlled by the height drop of the landslide (Johnson, 2017). According to Johnson (2017), it is believed that the lower gravity on Mars may lead to a greater fall height. If the force of gravity becomes greater than the internal strength of the soil, a lower gravity present may account for a much larger fall height if the coefficient of that material is low.

The results from Figure 20 show that the friction coefficient of the Mars long-runoff landslides falls within 0.01 – 0.09, making them small enough that it can be speculated that the fall height of the landslide is of great significance. Furthermore, the equation shown on the graph can be used to predict the coefficient for other landslides, which is biased since we are using Earth equations.

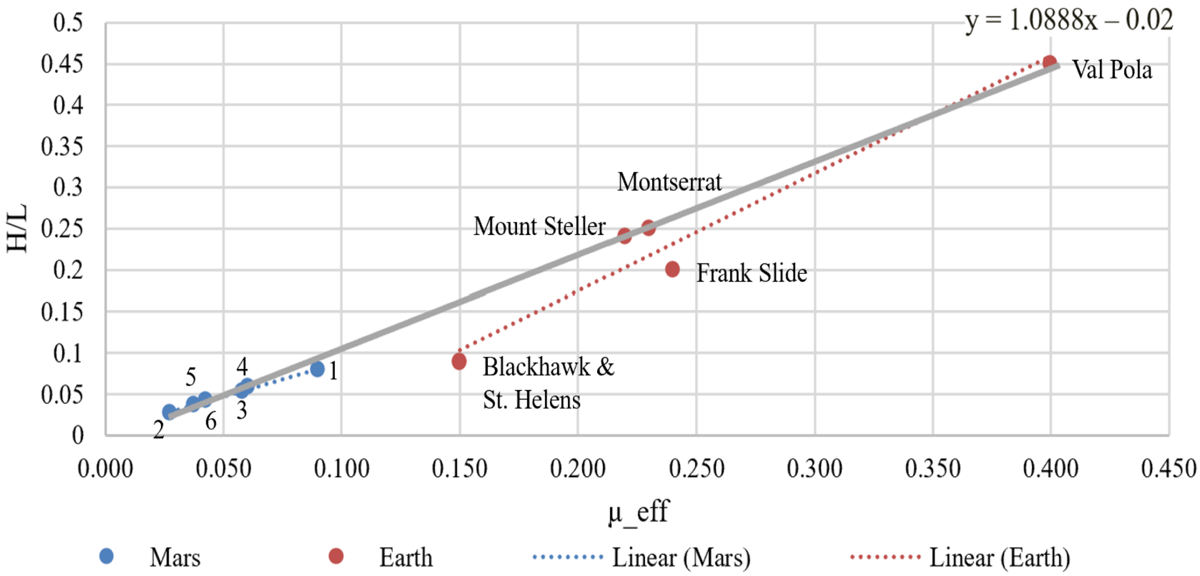


Figure 20: Graph depicting Heim's ratio over the friction coefficient for the six landslides

Table 3: Friction Coefficient values calculated using Heim's equation and Coulomb's equation

H/L	μ_eff
0.0793	0.090
0.0271	0.027
0.0531	0.058
0.0593	0.060
0.0371	0.037
0.0422	0.042

Figure 21 shows that the displaced regolith comprising each landslide reaches volumes of $10^{10} - 10^{13}$ m^3. These results support Lucas's (2014) assumption that landslides with volumes more significant than those of 10^9 m^3 have a friction coefficient value less than 0.1. This agrees with the expectation that as the friction coefficient decreases, the volumes of the landslides should increase. Figure 22 illustrates the differences between the Earth and Mars long-runout landslide volumes and the similarity in the shape of the trends of slide volume vs. falling height, which will be discussed in Chapter 4.

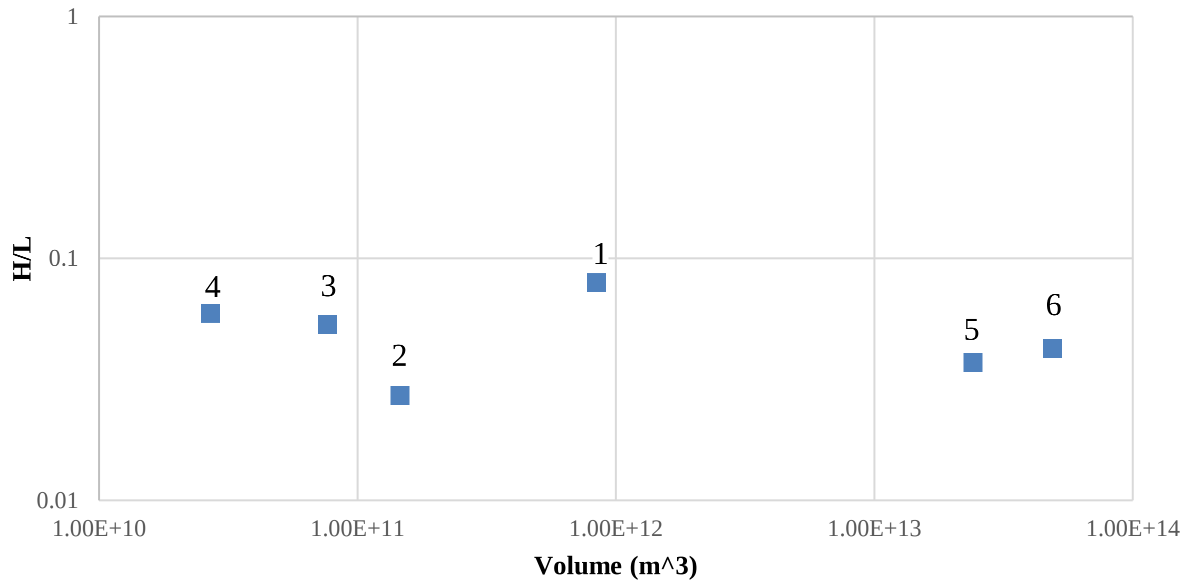


Figure 21: The volume of each landslide on Mars vs. Heim's ratio

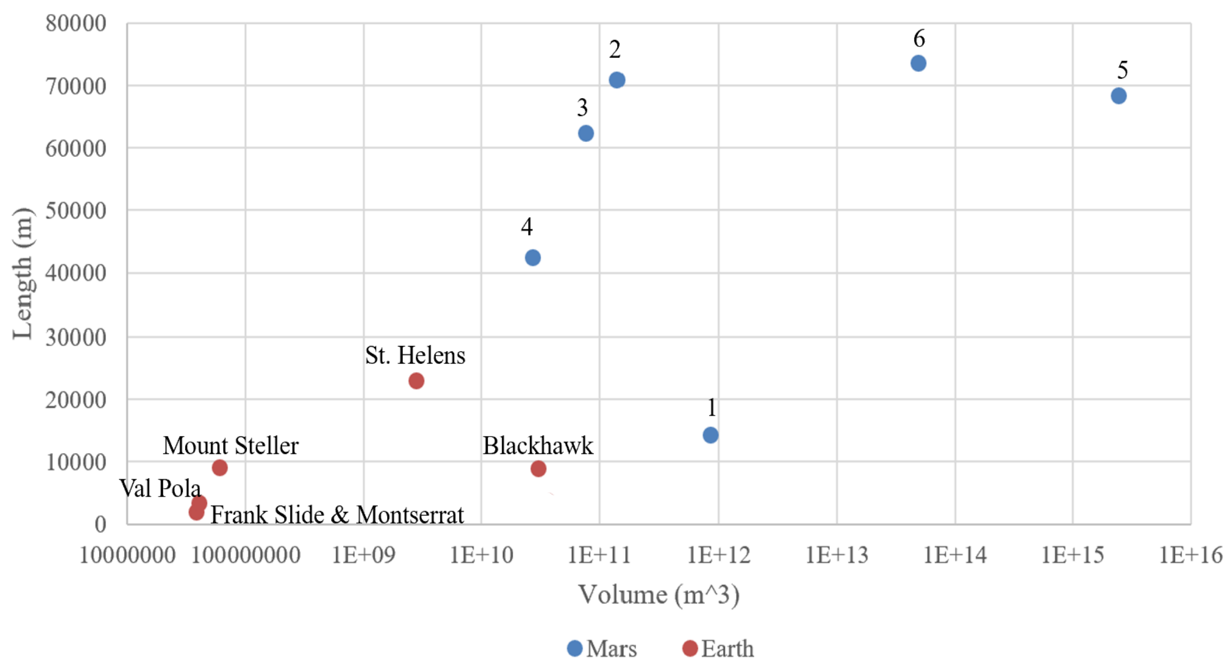


Figure 22: Runout as a function of landslide volume versus the length of the landslide runout.

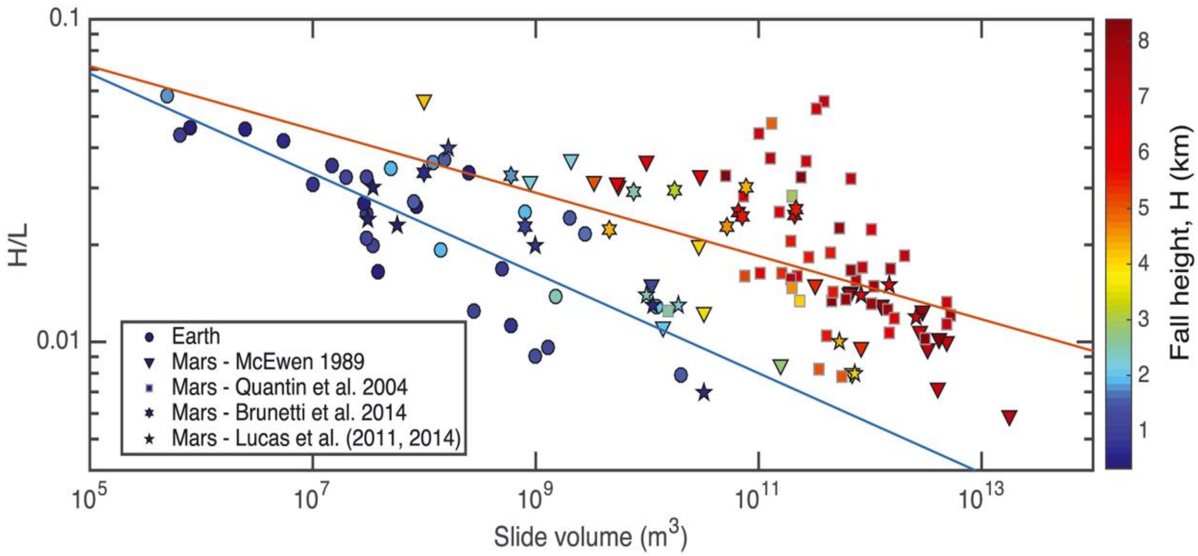


Figure 23: Johnson and Campbell's (2017) graph depicting the landslides between Earth and Mars.

Figure 23 shows Johnson and Campbell's (2017) graph for *H*/*L* versus slide volume of both Earth and Mars landslides. The graph depicts a negative trend in the points that indicate that as Heim's ratio decreases, the sediment volume of the landslide increases, which means that as friction decreases, the volume increases, as would be expected. The negative trendlines within the graph are based on Earth (blue) and Mars (red) landslides, drawn according to the fall height of the landslides. It is assumed by the author that the trendlines were drawn manually. The reasoning for this assumption is that since the Y-axis is logarithmic, the trendline would be expected to be curved rather than straight. This can be seen in the Heim's ratio versus volume graph created as part of this study (Figure 24).

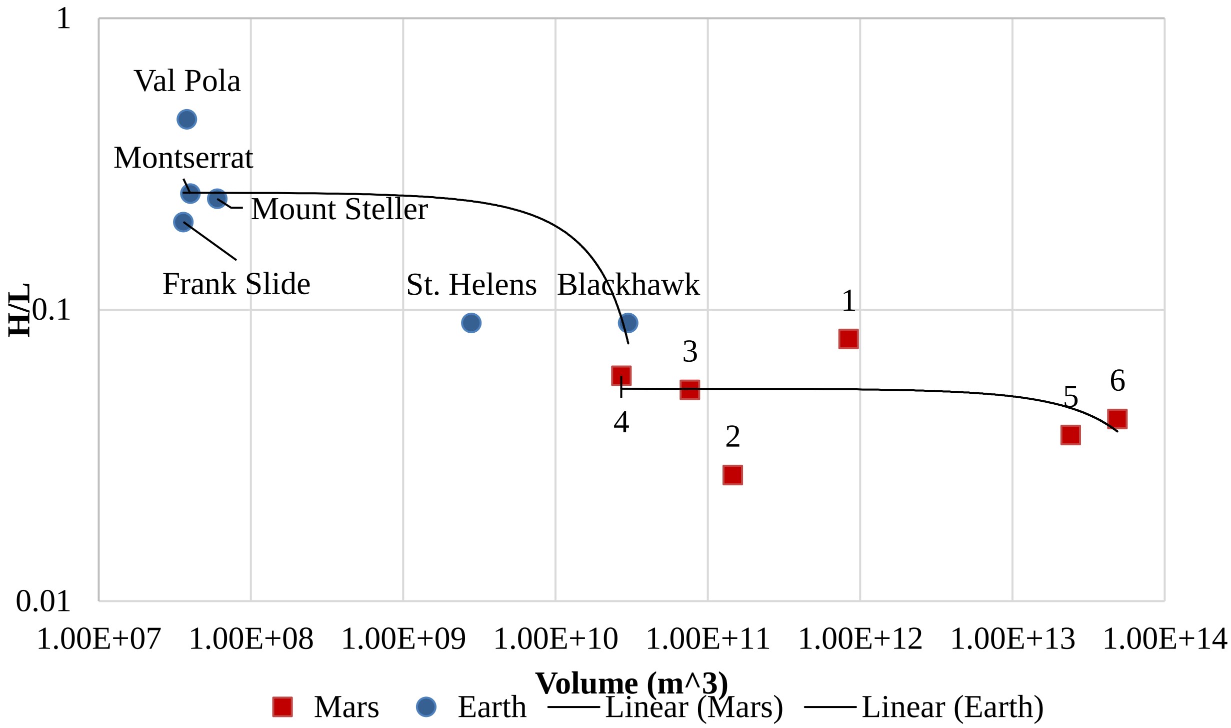


Figure 24: Volume of long-runout-landslides versus Heim's Ratio for the same events

Chapter 4

The results of this project were generated utilizing HRSC images obtained from the USGS Annex program and Esri's Mars exploration webpage (USGC Astrogeology Science Center, 2018). This chapter explains the results of calculations of Heim's ratio for each Mars long-runout landslide, the high mobility (H/L) results, and the use of cross-sections in these interpretations for each landslide. A comparison of these results and those of similar log-runout landslides on Earth is also provided.

4.1. Friction coefficient

As stated previously, the friction coefficient is the force acting between two objects divided by the force pushing them together (Kurtus, 2002). Different materials such as rock and sediments on Earth have assigned coefficient values that range from 0 to 1. In

, the friction coefficient for each Mars long-runout landslide analyzed was provided along with the corresponding mobility (H/L) value. Previous studies and articles about the phenomenon of long-runout landslides speculate that a low coefficient is a contributing factor to massive landslides on Earth (Lucas, 2014).

As explained in Chapter 3, the mobility of each Mars long-runout landslide is less than 1. Therefore, the friction coefficient for these landslides was determined by calculating Heim's ratio, where the height, length, and slope angle of the landslide are needed to determine the value. As noted above, the results provided in Table 3 show that the friction coefficient of the Mars landslides falls within 0.01 – 0.09, where those of Earth long-runout landslides vary from 0.1-0.25. Figure 24 shows that the volumes of the displaced regolith of each landslide reach volumes of $10^{10} - 10^{13} \mathrm{m}^3$ compared to sediments comprising long-runout landslides found on Earth. These results concur with Lucas's (2014) statement that Earth landslides with volumes more significant than those of $10^9 m^3$ have a coefficient value smaller than 0.1, which is considerably lower than the coefficient of rock or soil (Parez, 2015). This finding may assume that the volumes of the Mars long-runout landslides increase at least in part due to the decrease of friction. Compared to Johnson and Campbell's (2017) results, Earth's long-runout landslides partially overlap $10^8 - 10^{11}$ m^3 in volume with this study's findings of volumes ranging between $10^{10} - 10^{11} \mathrm{m}^3$. This similarity indicates that the mass volumes calculated for Mars's long-runout landslides correlate with those obtained in previous studies of landslides on Earth.

4.2. Cross Section

Using Esri's Explore Mars and the DEM provided by the USGS, points within the landslides were gathered to create a cross-section for each long-runout landslide investigated in this study. The general geology of Mars is based on observations only, as shown in Figure 25. The unit acronyms are provided only, as the exact composition of each of these geologic units is unknown to date. It is anticipated that the latest planetary rovers currently exploring Mars may bring back more geological samples so that the units on this map may be classified according to how geologic units on Earth are identified; Appendix A provides a detailed list of all the known geological units. The maps shown in Figure 26 – Figure 30, each having a selected cross-section depicted by the letters A-E and A'-E', illustrate each landslide location at the global scale (1), regional canyon scale (2), and local scale within the canyon (3). Using the cross-sections, both the height and length of the landslides were measured and calculated. The cross-sections show elevation on the y-axis for each of the landslides. The elevations collected show a range of numbers from negative to positive numbers.

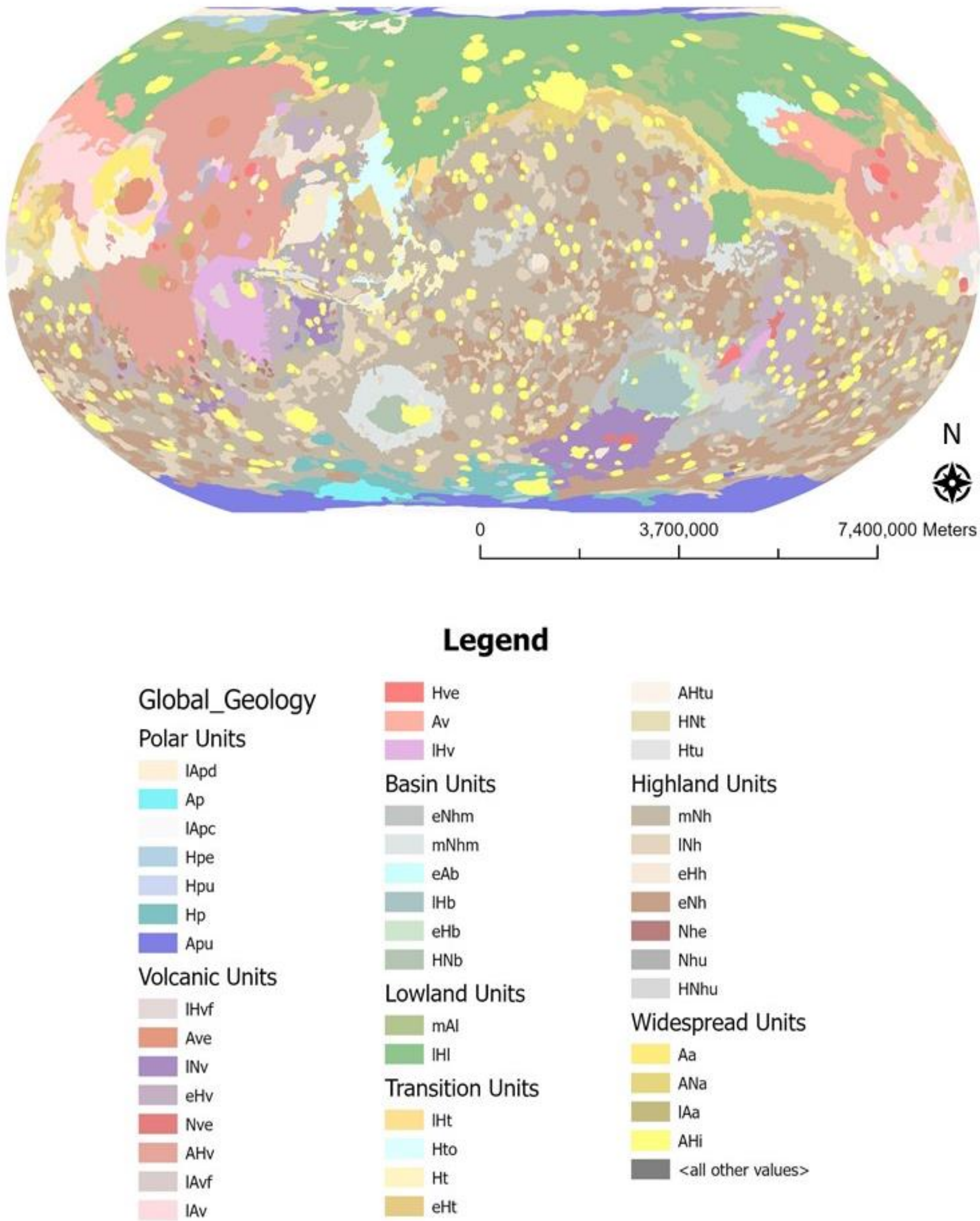


Figure 25: Map of the geology of Mars

Figure 26: Map depicting landslide with corresponding cross-section (A-A[1]) of

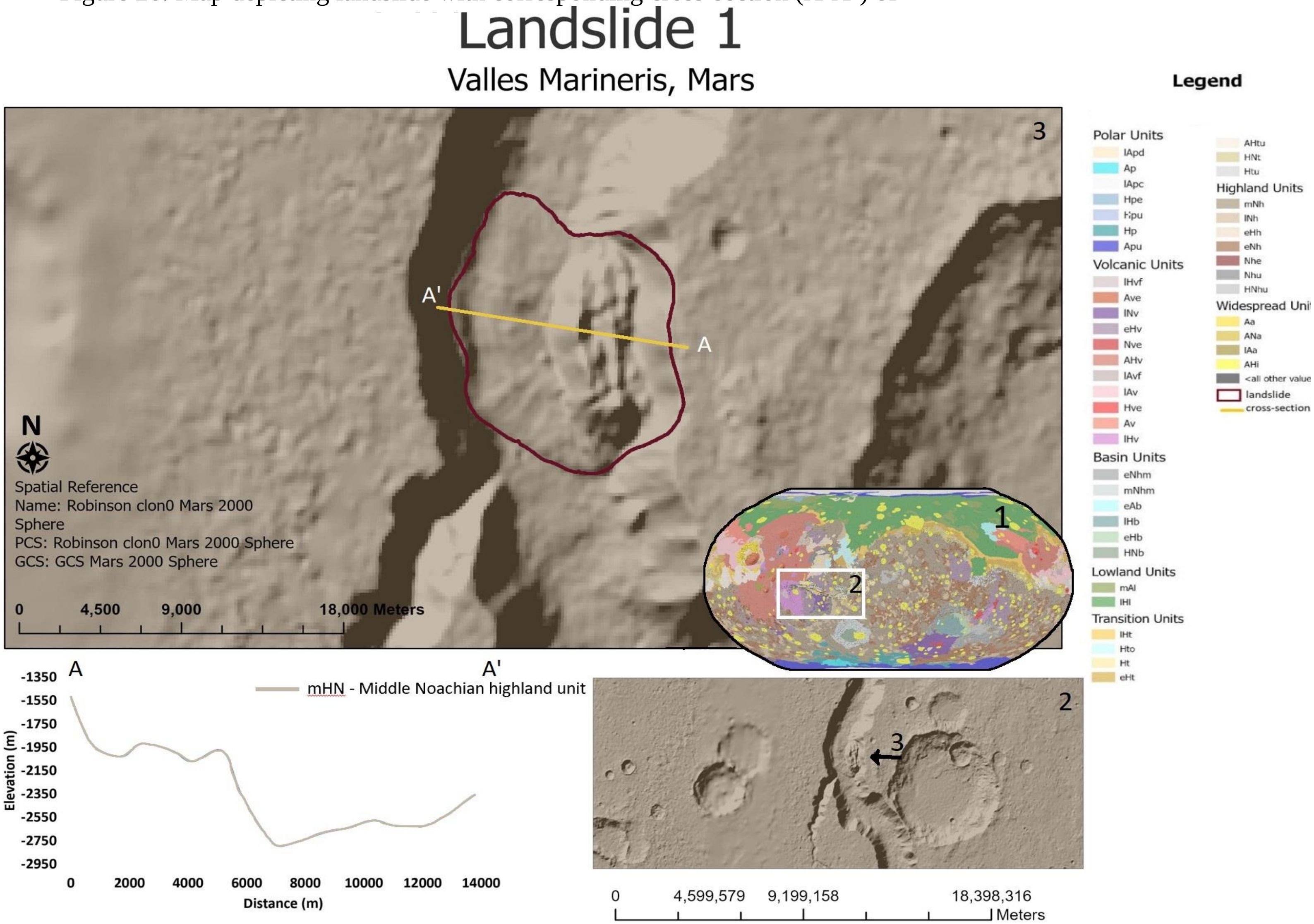


Figure 27 : Map depicting landslide with corresponding cross-section (B-B[1]) of landslide.

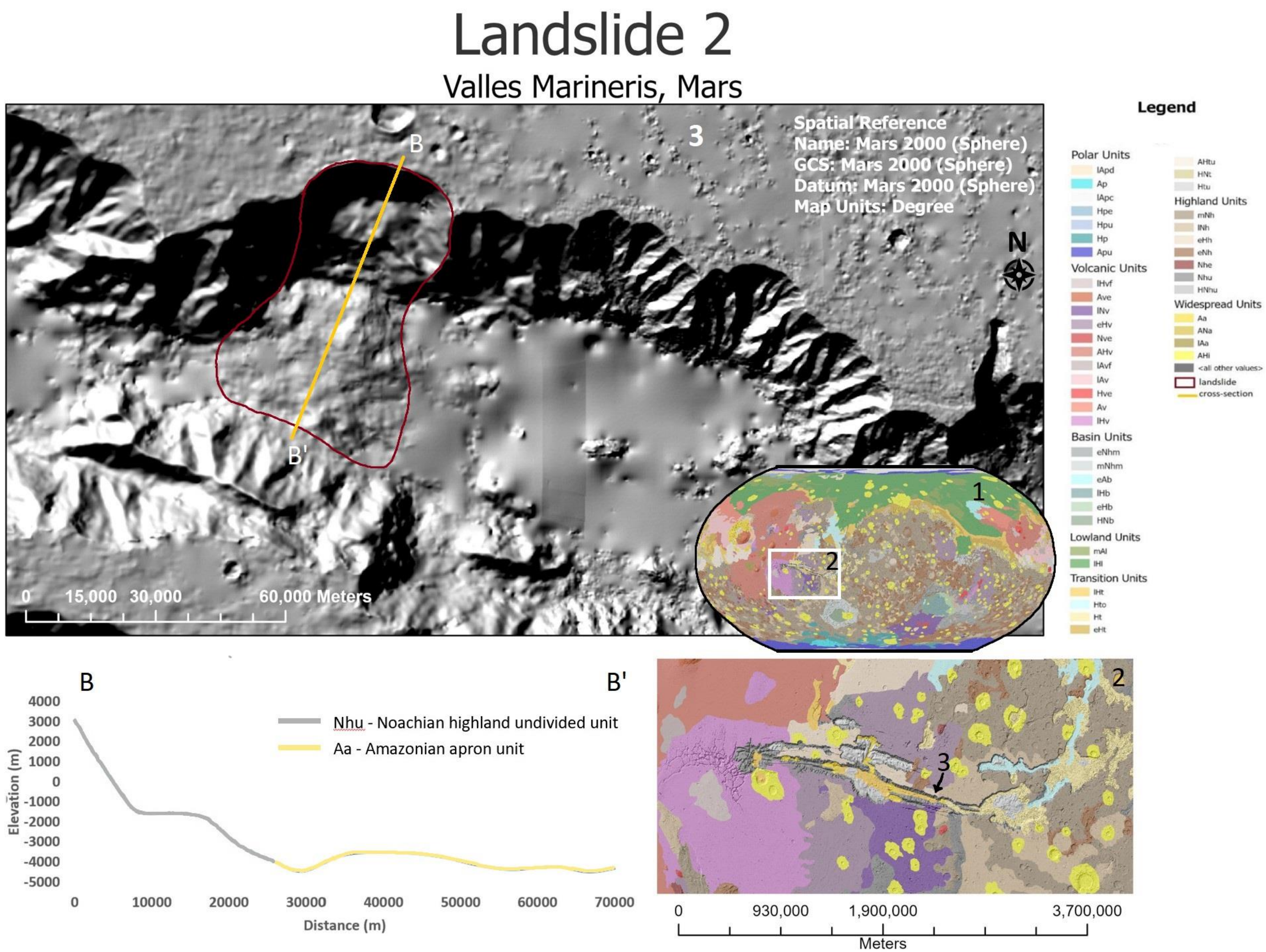


Figure 28: Map depicting landslide with corresponding cross-section (C-C[1]) of landslide.

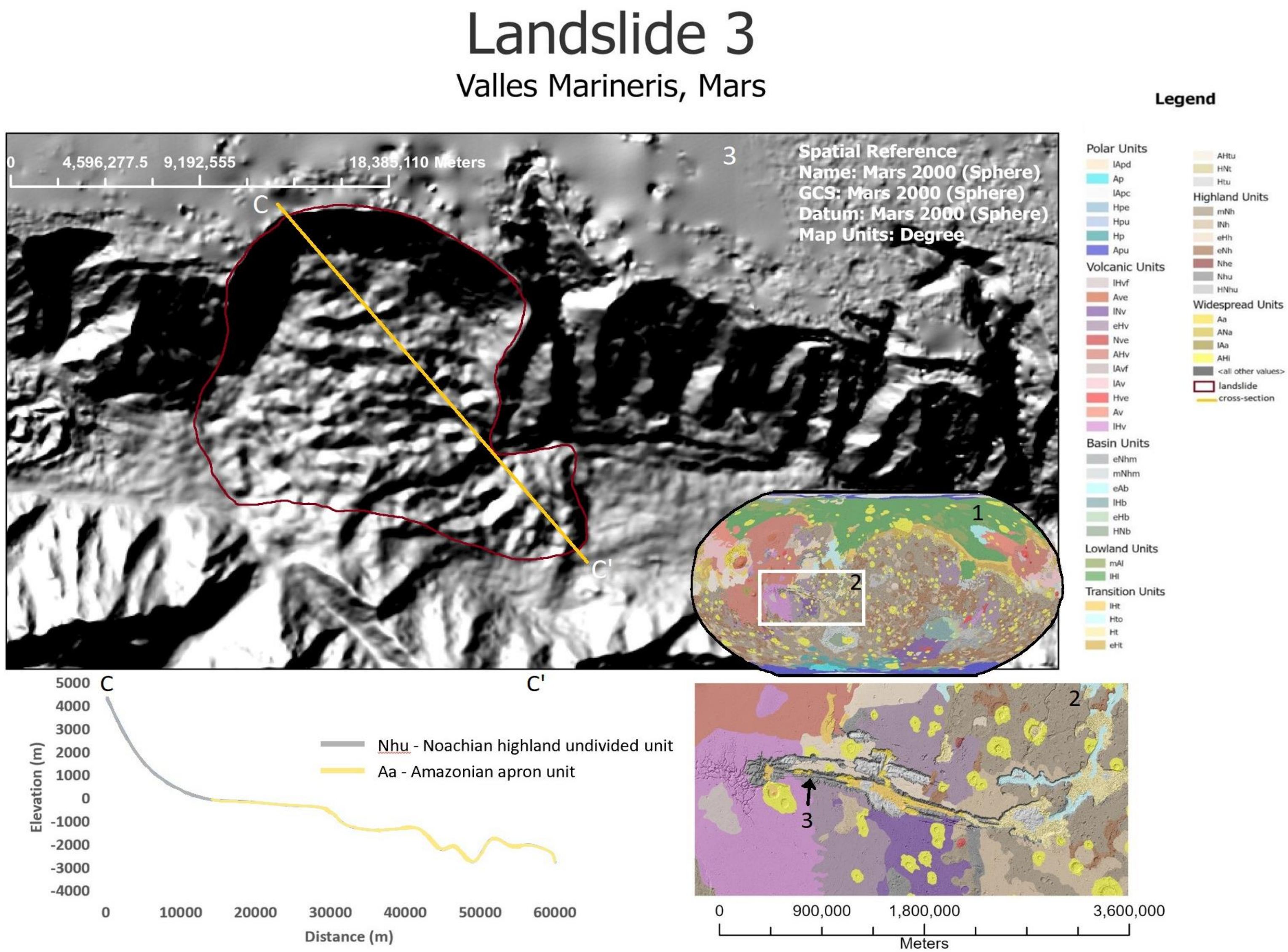


Figure 29: Map depicting landslide with corresponding cross-section (D-D[1]) of landslide.

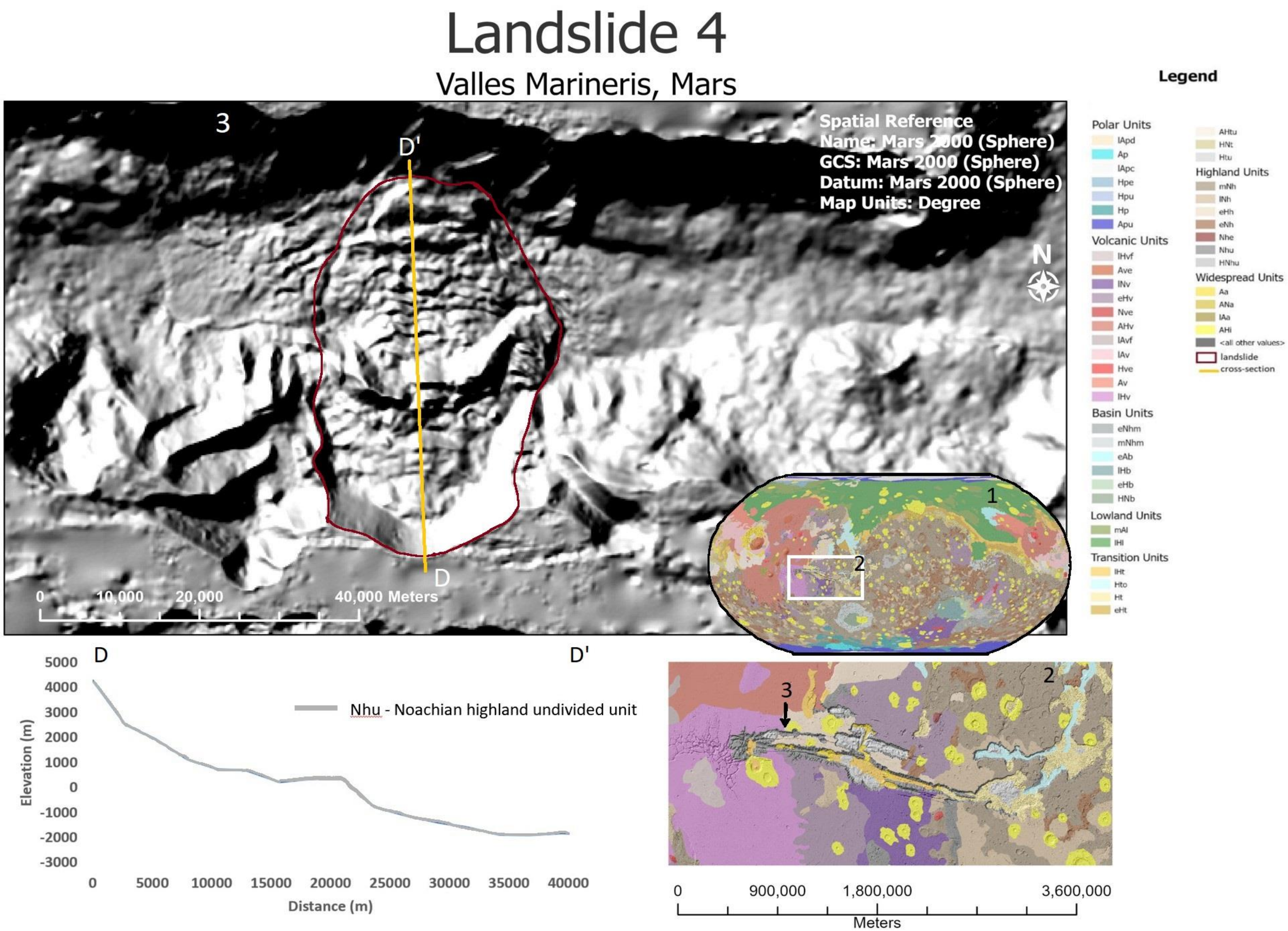
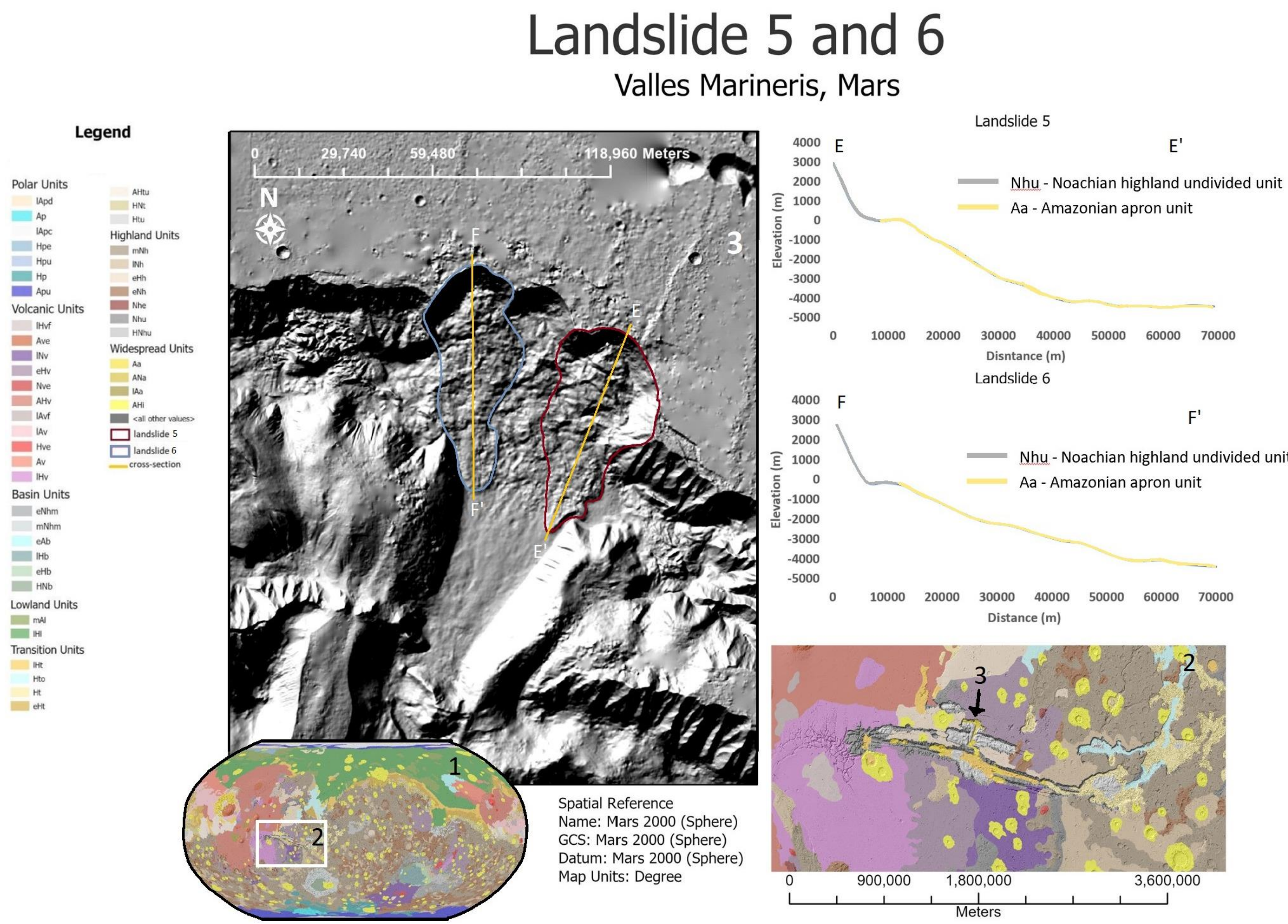


Figure 30: Map depicting landslide with corresponding cross-section (E-E[1] and F-F[1]) of landslide.



A sea level elevation has not yet been established on Mars, thus it is not shown in the cross-sections. The friction coefficient and slopes of the landslides were then calculated using this information. Slope is the measurement of the steepness of the surface, which is measured in degrees (Cellek, 2020). The slope measurements conducted on the Mars satellite imagery provided the slope values for each of Mars's landslides investigated in this project. For example, the values shown in Table 4 for landslides 1 through 6, have slope angles lower than the average angle of 22.2 °. Landslides with low slope angles contain sediment that of clay layers (Kansas Geological Survey, 2020). These findings correlate with the sediment relationship found through the calculations of the friction coefficient shown in Table 1.

The slope measurements conducted on the Mars satellite imagery (Figure 26 – Figure 30) demonstrate that height drop plays a significant role in landslides on Earth but not for Martian landslides. These findings suggest that slope steepness does not contribute significantly to the occurrence of long-runout landslides.

Table 4: Values represent the slopes and volume of landslides on Valles Marineris, Mars

	Landslide	**Slope**	**Volume (m^3)**
Mars	1	18.21	8.41E+11
	2	6.107	1.46E+11
	3	5.82	7.63E+10
	4	8.47	2.70E+10
	5	13.06	2.41E+13
	6	18	4.89E+13

4.3. High Mobility

The High Mobility (H/L) calculations determined that the height drop of the Martian landslides are more significant than those found on Earth. Mars long-runout landslide height drops may also contribute to the length of the landslide and the distribution of the regolith. Mars gravity (g = 3.73 ms^{-2}) is much less than that of the Earth (g = 9.81 ms^{-2}), which may be another contributing factor to the drop height of the landslides. As stated in Chapter 3, the differences in length versus volume of the long-runout landslides on Mars and Earth analyzed in this study are illustrated in Figure 22.

The length of the long-runout landslides was obtained from the cross-sections created for each Mars landslide, which can be seen in Figure 26 – Figure 30 for comparison in this study. The results obtained by constructing the cross-sections are illustrated and explained in detail in Section 4.2. The length information for the selection of long-runout landslides on Earth was obtained from Parez (2015).

4.4. Final Results

From the results obtained from this study and the accessible satellite imagery, also supported by previous research on Mars long-runout landslides, it can be speculated that low friction and height drop are the main factors contributing to the massiveness of these long-runout landslides. Similar to long-runout landslides on Earth, the results of the calculations show that as the friction decreases, the volume of sediment displaced increases. Although these results are expected, research is still being conducted to determine if there are other triggers for these long-runout landslides (Watkins, 2020). Both on Earth and Mars, the magnitude of long-runout landslides may be better understood by calculating the volume of the mass movement of each landslide. Mars landslides have a much more significant height drop than Earth's, but the coefficients for each landslide are similar in that they are both less than 0.1.

Chapter 5 Conclusions and Future Work

This thesis work was performed to obtain a better understanding of what some of the mechanisms that drive long-runout landslides might be and how they might work, assuming that the behavior of long-runout landslides on Mars can be analyzed using the same mass movement equations as those used to explain or characterize Earth long-runout landslides. First, several Mars long-runout landslides were identified and visually interpreted based on newly available high-resolution satellite imagery. With the data obtained from the DEMs provided by the USGS and the information gathered using Esri's Explore, each long-runout landslide was visually inspected, then calculations of friction coefficient, height, length, volume, and slope were performed. The measurements conducted on each Mars long-runout landslide selected for this thesis project indicate that a low friction coefficient plays a significant role in the massiveness of these landslides.

5.1. Conclusions

Initially, research on long-runout landslides on Earth allowed speculation of possible causes of long-runout landslides on Mars. It was then determined that an understanding of the massiveness of Mars landslides might be found using publicly available high-resolution satellite imagery of Mars created by the USGS and provided by Esri. Previous research speculated that friction, soil composition, water, or earthquake (also called marsquakes) could have contributed to various types of landslides on Mars.

While the research conducted in this study did not incorporate analysis of analog or physical field data from Mars, the satellite imagery gathered delivered the information needed to develop a reasonable explanation of one driver of long-runout landslides on Mars. The results showed that landslides with a friction coefficient of 1or smaller are associated with mass volumes more significant than $10^{11}m^3$, which corresponds to the definition of a long-runout landslide on Earth. These results correlate with previous research findings on long-runout landslides on Mars. When comparing long-runout landslides on Mars with those on Earth, the mass volume values calculated for those on Mars exceed those for long-runout landslides on Earth. Furthermore, the results suggest that long-runout landslides on Mars and Earth are both associated with low friction coefficients, meaning that lower friction allows the landslide mass to flow more easily. These findings may provide some insights for future researchers interested in Mars landslides.

5.2. Future Work

Future research could include comparisons of long-runout landslides on different planets, such as Pluto's moon Charon. After the 2015 Pluto flyby, New Horizons sent multiple images back to Earth (NASA, 2016). In all these images, long-runout landslides were captured and identified by geologists. Figure 31 shows five long-round landslides within Serenity Chasma (NASA, 2016). Calculating Heim's ratio, friction coefficient, and landslide volumes on landslides on Charon might determine if the values obtained are similar to those on Earth and Mars. It may be possible to gather data from long-runout landslides on other planets or moons and plot additional Heim's ratio vs. volume graphs (as seen in Figure 20). If such future findings fall within the trendline, it will support the assumption that Heim's ratio and volume are dependent on each other, which will contribute to understanding what drives long-runout landslides. As stated before, it is anticipated that the equation found for the trend line shown in Figure 20 could be used to determine a landslide's friction coefficient even though the equation is biased since it is based on Earth equations.

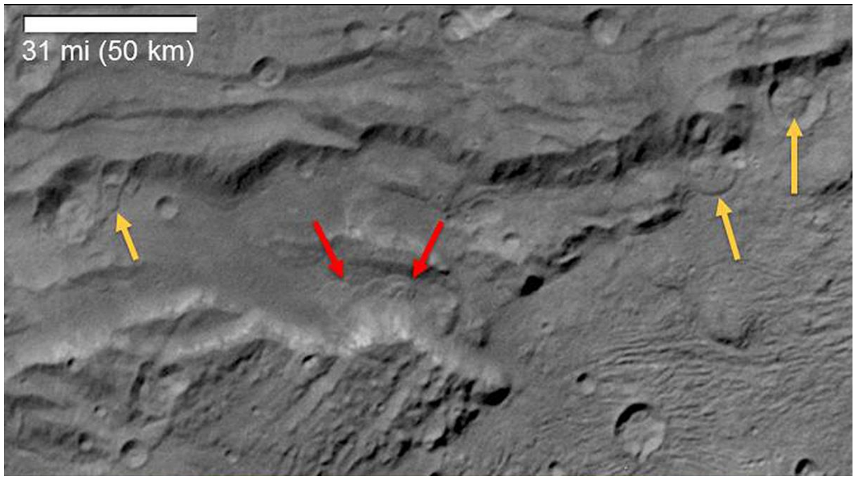


Figure 31: Long-runout landslides on Pluto's Moon Charon (shown by arrows) (JPL, 2016)

Future experiments may determine if gravity plays a critical role in long-runout landslides. Flumes, analog hydraulic equipment used to study sediment movement (Southard, 2021), could also be used if different gravity values were simulated in a given experiment (Figure 32). When using computational flumes, the gravity may be changed within the experiment helping to determine if it plays a critical role in driving long-runout landslides. A computational flume also allows for a change in height and sediment flow to determine if these factors also contribute to driving long-runout landslides on other planets.

Future work might also determine if triggers such as marsquakes, volcanic eruptions, and windstorms contributed to the low friction coefficient values or the corresponding runout landslide volumes on Mars and other planets. Lastly, determining the causes of long-runout landslides could contribute to the body of knowledge about Earth landslides and thus help lessen the impact of these disasters on human populations and man-made infrastructure. At the moment NASA's InSight Mars lander has been detecting quakes on Mars (NASA, 2022). InSight has a highly sensitive seismometer that is able to detect quakes within the planet and sent back the findings to Earth. Different sediment material react different to quakes, not only can an quake be a contribution to a low friction coefficient but it can also give an insight to the regolith by comparing to Earth sediment and the reaction it has to earthquakes.

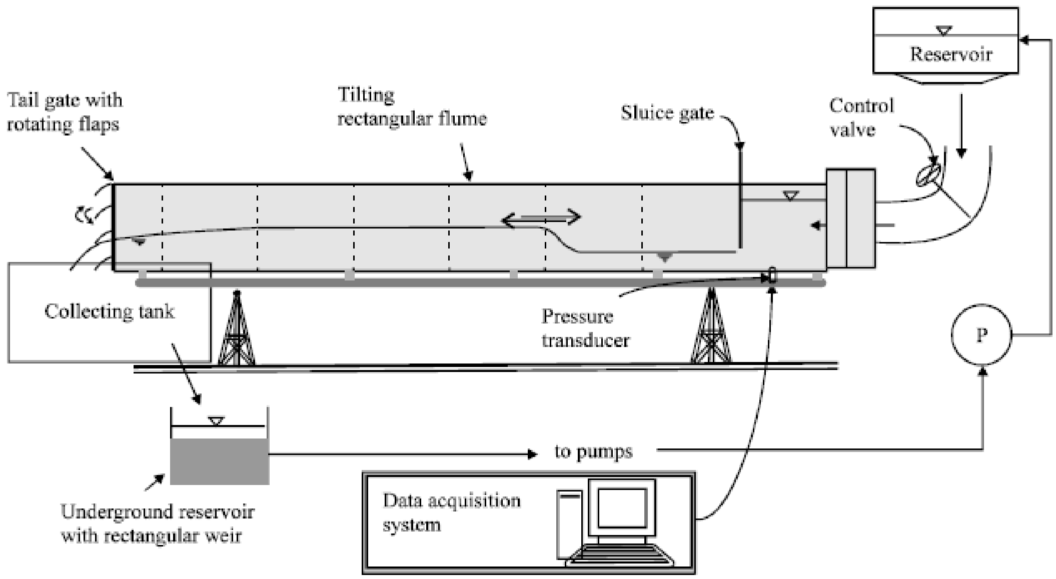


Figure 32: Flume representation (Rizi, 2006)

Other future work will require looking outside the region of this study, Valles Marineris, at other work currently being done on Mars. Some of the most recent research includes investigation of Jezero Crater, which was believed to be once flooded with water (NASA, 2020). What interests' scientists most is that the regolith found in this crater resembles that of clays. Knowing that clays might be present within this area and the assumption made that the material found in the six landslides studied in this thesis is most likely also clay/silt may indicate a connection that these long-runout landslides could have been driven by, or triggered by, environmental conditions of catastrophic events involving water. As NASA's Mars 2020 rover, continues to collect sample of Mars, NASA and the European Space Agency will be launching the Mars Sample Return Campaign in 2026, which will bring back rock and soil samples to Earth (NASA, 2021). Having a physical sample will allow for a better identification of Mars’ regolith and will determine if the findings of this thesis where correct, that some of the regolith that makes up Mars is similar to Earth’s clays and silt sediments.

If a correlation is found between these landslides on Mars, Earth, and another planet, this research may be presented to NASA or Arizona State University (ASU) in the future by the author. Presenting these findings could lead to various scientific communities’ understanding about whether or not water was once present on Mars. This research will also be shared with other interested researchers, including all of the data (e.g., imagery and resulting map) and results of measurements and calculations (e.g., values, cross-sections), who then may build upon the author’s findings documented in this thesis as well as the additional related work the author plans to work on in the future.

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Appendix A Geological Units

	Unit	Name
	Aa	Amazonian apron unit
	AHi	Amazonian and Hesperian impact unit
	AHtu	Amazonian and Hesperian transition undivided unit
	AHv	Amazonian and Hesperian volcanic
	ANa	Amazonian and Noachian apron unit
	Ap	Amazonian polar unit
	Apu	Amazonian polar undivided unit
	Av	Amazonian volcanic unit
	Ave	Amazonian volcanic edifice
	eAb	Early Amazonian basin unit
	eHb	Early Hesperian basin unit
	eHh	Early Hesperian highland unit
	eHt	Early Hesperian transition unit
	eHv	Early Hesperian volcanic unit
	eNh	Early Noachian highland unit
	eNhm	Early Noachian highland massif unit
	HNb	Hesperian and Noachian basin unit
	HNhu	Hesperian and Noachian highland undivided unit
	HNt	Hesperian and Noachian transition unit
	Hp	Hesperian polar unit
	Hpe	Hesperian polar edifice unit
	Hpu	Hesperian polar undivided unit
	Ht	Hesperian transition unit
	Hto	Hesperian transition outflow unit
	Htu	Hesperian transition undivided unit
	Hve	Hesperian volcanic edifice unit
	lAa	Late Amazonian apron unit
	lApc	Late Amazonian polar cap unit
	lAv	Late Amazonian volcanic unit
	lAvf	Late Amazonian volcanic field unit
	lHb	Late Hesperian basin unit
	lHl	Late Hesperian lowland unit
	lHt	Late Hesperian transition unit
	lHv	Late Hesperian volcanic unit
	lHvf	Late Hesperian volcanic field unit
	lNh	Late Noachian highland unit
	lNv	Late Noachian volcanic unit
	mAl	Middle Amazonian lowland unit
	mNh	Middle Noachian highland unit
	mNhm	Middle Noachian highland massif unit
	Nhe	Noachian highland edifice unit
	Nhu	Noachian highland undivided unit
	Nve	Noachian volcanic edifice unit