Geologic Mapping of Ascraeus Mons, Mars

by

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ABSTRACT

Ascraeus Mons (AM) is the northeastern most large shield volcano residing in the Tharsis province on Mars. AM has a diameter of ~350 km and reaches a height of 16 km above Mars datum, making AM the third largest volcano on Mars. Previous mapping of a limited area of these volcanoes using HRSC images (13-25 m/pixel) revealed a diverse distribution of volcanic landforms within the calderas, along the flanks, rift aprons, and surrounding plains. The general scientific objective for which mapping was based was to show the different lava flow morphologies across AM to better understand the evolution and geologic history.

A 1: 1,000,000 scale geologic map of Ascraeus Mons was produced using ArcGIS and will be submitted to the USGS for review and publication. Mapping revealed 26 units total, broken into three separate categories: Flank units, Apron and Scarp units, and Plains units. Units were defined by geomorphological characteristics such as: surface texture, albedo, size, location, and source. Defining units in this manner allowed for contact relationships to be observed, creating a relative age date for each unit to understand the evolution and history of this large shield volcano.

Ascraeus Mons began with effusive, less viscous style of eruptions and transitioned to less effusive, more viscous eruptions building up the main shield. This was followed by eruptions onto the plains from the two main rift aprons on AM. Apron eruptions continued, while flank eruptions ceased, surrounding and embaying the flanks of AM. Eruptions from the rifts wane and build up the large aprons and low shield fields. Glaciers modified the base of the west flank and deposited the Aureole material.

Followed by localized recent eruptions on the flanks, in the calderas, and small vent fields. Currently AM is modified by aeolian and tectonic processes. While the overall story of Ascraeus Mons does not change significantly, higher resolution imagery allowed for a better understanding of magma evolution and lava characteristics across the main shield. This study helps identify martian magma production rates and how not only Ascraeus Mons evolved, but also the Tharsis province and other volcanic regions of Mars.

This manuscript is dedicated to my wife, Kendal, and my baby girl, Elizabeth. Kendal, thank you for putting up with my long hours and sometimes lack of attention. Elizabeth, let this be a good reminder for you to always follow your dreams and never give up.

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This study would not have been made possible were it not for NASA's Mars Data Analysis Program (MDAP) for which this project is funded. I would like to thank Dave Williams for all the help, support, and giving me the chance to begin my planetary career. I also would like to thank the staff at the Ronald Greeley Center for Planetary Studies for all their help, especially David Nelson for putting up with all my ArcGIS questions.

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1. Introduction

The Tharsis Montes (Arsia Mons, Pavonis Mons, and Ascraeus Mons) are three large shield volcanoes, forming a NE-SW-trending chain across the Tharsis rise of Mars [*Carr* et al., 1977; *Crumpler* and *Aubele*, 1978]. Their location and recent eruptive activity coincide with the youngest major magmatic and tectonic phase of Mars' Tharsis volcanic province [*Plescia* and *Saunders*, 1979, 1982; *Mege* and *Masson*, 1996; *Anderson* et al., 2001; *Wilson* and *Head*, 2002; *Werner*, 2005]. Although the evolution of the martian large shield volcanoes and their relationship to the larger Tharsis province is not well understood, the latest generation of Mars spacecraft is producing high-resolution images that are enabling new insights into the geological evolution of these volcanoes via geologic mapping. Geologic maps are critical tools required to relate spacecraft observations of a region of a planetary surface to its geologic history, the results of which can provide crucial information that can be used to refine models of planetary evolution.

A systematic program of geologic mapping of the large Tharsis volcanoes is underway, beginning with Olympus Mons [*Bleacher* et al., 2007a; in preparation] and Arsia and Pavonis Montes [*Bleacher* et al., 2007b; *Garry* et al., in preparation], including characterization of their surface features and their distribution in time and space, with the goal of identifying any changes in the volcanic and gradational processes working within and on these volcanoes. This work completes this systematic mapping of the Tharsis Montes, in which I generated a 1:1M geologic map of Ascraeus Mons, the only Tharsis Montes volcano for which a prior 1:1M map had not been previously published [cf., *Scott* and *Zimbelman*, 1995; *Scott* et al., 1998]. Figure 1 depicts the Tharsis Montes with the mapping area of Ascraeus Mons noted with a square.

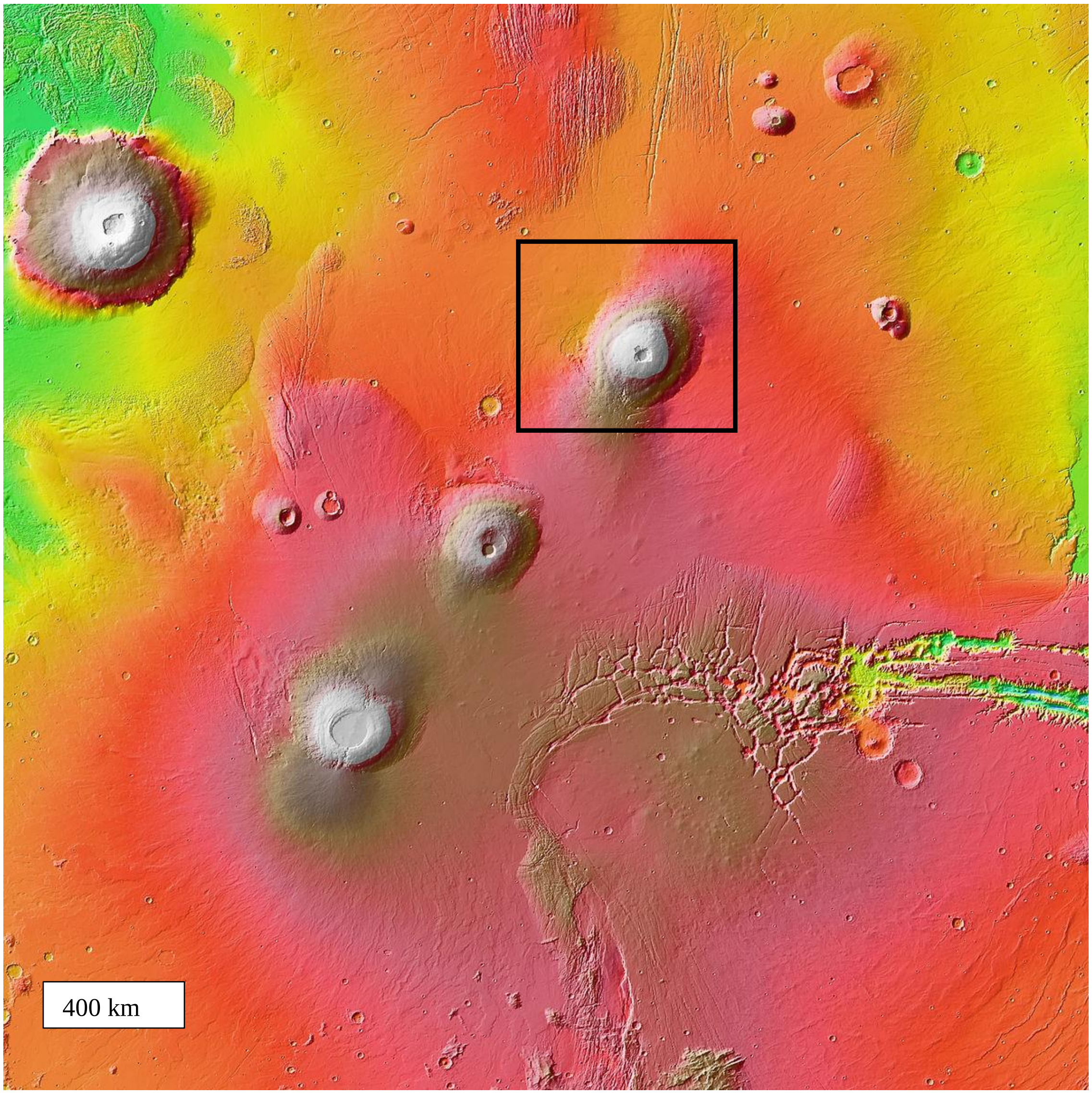


Figure 1. THEMIS Day IR image overlain with MOLA topography. Areas in white are high elevation and green are low elevation. The mapping area of this study is marked with a square and notes the location of Ascraeus Mons.

Ascraeus Mons is the northeastern most large shield volcano found in the Tharsis province. AM has a diameter of ~350 km and a height of ~16 km, making Ascraeus the 3rd largest volcano on Mars. The scientific objective of this work is to investigate the volcanic, gradational, and tectonic processes that have formed Ascraeus Mons and its southerly small vent field, and to identify its geologic history, using established geologic mapping techniques. I used *Mars Reconnaissance Orbiter (MRO)* Context Camera [CTX: *Malin* et al., 2007] and *Mars Express* (MEX) High Resolution Stereo Camera [HRSC: *Neukum* et al., 2004a] data that are geometrically rectified to *Mars Global Surveyor* (MGS) Mars Orbiter Laser Altimeter [MOLA: *Smith* et al., 1999; 2001] data as the primary map base. These data were supplemented by MGS Mars Orbiter Camera [MOC: *Malin* et al., 1992; *Malin* and *Edgett*, 2001], *Mars Odyssey* (MO) Thermal Emission Imaging System [THEMIS: *Christensen* et al., 2004], and MRO High Resolution Imaging Science Experiment [HiRISE: *McEwen* et al., 2007] images. HRSC and CTX have complete coverage of Ascraeus Mons, enabling consistent mapping across the shield. All of these data were available in NASA's Planetary Data System prior to start of the project. I created a digital geologic map using ArcGIS™ software, which will be linked to the maps for both Arsia and Pavonis Montes, all to be published through the US Geological Survey.

1.1 Objectives

The specific scientific objectives of this mapping project include: 1) Determining the areal extent, spatial distribution, and age relationships of different lava flow morphologies on the main flank, rift apron, and associated small-vent field of Ascraeus

Mons to identify and understand changes in effusive style across the volcano, and to provide insight into martian magma production rates. Results, when linked with those of the other Tharsis Montes, will provide insight into the overall volcanic evolution of each structure, enabling comparisons between volcanoes, and the determination of the extent of each shield's contribution to the Tharsis plains; 2) Determining the areal extent and spatial distribution of purported glacial and aeolian deposits on the flanks and their relationship to the lava flows. Results will establish a volcano-wide understanding of the nature of potential lava-ice interactions and the contribution of aeolian cover to the current form of the shield, enabling comparison among the Tharsis Montes potentially in different stages of development; 3) Characterizing erosional and tectonic features, such as rift zone graben, flank terraces, and channel networks, present on the flank, rift apron, and small-vent field, to determine their relationships to volcanic materials and processes. Objectives were accomplished using standard techniques of planetary geologic mapping applied to CTX and HRSC images in an ArcGIS™ image basemap project provided by the USGS. The basemap image data cover the whole volcano at consistent resolution, and when supplemented by HiRISE, MOC and THEMIS images enable improved morphological interpretations. The product of this research is a digital map for Ascraeus Mons, which will be published online by the USGS, at a scale of 1: 1,000,000 (1:1M).

2. Background

Geologic mapping is an investigative process used to understand the evolution of the terrestrial planets and satellites, the importance of which was discussed by *Carr* et al. [1976, 1984], *Greeley & Carr* [1976], *Wilhelms* [1990], *Tanaka* et al. [1994, 2010], and

Hansen [2000]. Geologic mapping is used to put observations of surface features into stratigraphic context to develop geologic timescales for planetary surfaces (see *Carr* et al. [1976]). The Earth and Moon's geologic timescales were developed by extensive field work and absolute ages obtained by radiometric dating, for the Earth; for the Moon, lunar samples from the Apollo missions as well as photometric data returned from spacecraft and telescopic observations. For other planets and satellites, understanding their geologic evolution requires mapping of relative stratigraphy and estimates of ages derived from impact crater populations. Use of crater statistical techniques beyond the Moon has been controversial. In the case of Mars, even with impact crater statistics developed [i.e., *Neukum & Ivanov*, 1994; *Hartmann & Neukum*, 2001], data from orbiters suggests that the usefulness of crater statistics on Mars is problematic. This result is becasue of multiple populations of secondary craters at small (<300-500 m) crater diameters [*McEwen* et al., 2005; *Tornabene* et al., 2006] and repeated burial & exhumation of craters [e.g., *Malin & Edgett*, 2001; *Edgett & Malin*, 2002].

Geologic mapping has advantages over photogeologic analyses because it reduces the complexity of heterogeneous planetary surfaces into discrete material units that are defined and characterized according to specific physical attributes (morphology, texture, albedo, color, etc.). These attributes are related to specific physical geologic processes like those observed on Earth. *Wilhelms* [1987] applied this technique to the Moon, revealing the complex geologic evolution of the Moon's surface, which was later confirmed by the return of Apollo samples. The stratigraphic techniques originally developed for the early lunar studies [*Shoemaker* and *Hackman*, 1962; *McCauley*, 1967] are now the basis for the study of other rocky and icy bodies in the solar system [*Wilhelms*, 1972; 1990].

The interpretation of planetary surfaces is done within the context of geologic processes that resulted in their current state. Two broad classes of geologic processes (exogenic & endogenic) have had various relative roles on different planets and satellites, and can be assessed from stratigraphic studies. In the case of Mars, evidence exists for large-scale volcanism in the Noachian, decreasing through the Hesperian and Amazonian [e.g., *Greeley & Spudis*, 1981; *Carr*, 1981; *Greeley*, 1987a; *Head* et al., 2001; *Neukum* et al., 2004b; *Werner*, 2005; *Williams* et al., 2007, 2008, 2009]. Channels and valley networks, generally found in the southern cratered highlands [e.g., *Sharp & Malin*, 1975; *Carr*, 1981 and references therein], implies there was wide-ranging fluvial activity in the martian past. Glacial activity has been suggested with new imagery and perhaps was widespread, including at mid-latitudes [e.g., *Head* et al., 2005], during a period of high martian obliquity [e.g., *Jakosky & Carr*, 1985; *Mischna* et al., 2003; *Levrard* et al., 2004, *Forget* et al., 2006]. Mars is strongly dominated by aeolian processes today [e.g., *Greeley* et al., 1992, 1993]. By mapping the different types of material units & structures from images, geologically recent features can be differentiated from more ancient features, which is required to have a better understanding of the evolution of Mars's past. For example, mapping of higher resolution Mars images suggests Marte Valles, originally thought to have formed by fluvial processes [*Greeley and Guest*, 1987], has been resurface and modified by younger lava flows [*Keszthelyi* et al., 2000]. Geologic maps are tools that aid in understanding processes that produced morphologically-distinct materials observed on Mars and other planetary surfaces [*Scott* and *Tanaka*, 1986; *Tanaka* and *Scott*, 1987; *Greeley* and *Guest*, 1987], and enables better chemical and physical analyses of a given location on a planetary surface if the geologic setting is known first. A fundamental concept in terrestrial geology, but it is a concept that has found slow acceptance in the exploration of other planets & satellites in the Solar System.

2.1 Previous Mapping of the Tharsis Montes

The three large Tharsis Montes (TM) have a NE-SW trending orientation within the Tharsis province [*Carr* et al., 1977; *Crumpler* and *Aubele*, 1978; *Carr*, 1981]. These shield volcanoes are ~350-500 km in diameter and each has a summit caldera and rise between 8 and 15 km above the surrounding plains [*Plescia*, 2004]. The *Mariner 9* orbiter showed a complex mixture of lava channels and tubes, suggesting the Tharsis Montes are shield volcanoes [*McCauley* et al., 1972]. Ascraeus Mons was originally mapped at a 1:5M scale by *Carr* [1975], and all three TM volcanoes were mapped in the Mariner-9 global geologic map of Mars (1:25M) by *Scott & Carr* [1978]. The *Carr* [1975] map depicts a shield and caldera with embaying flow field units. The *Scott & Carr* [1978] map displays the large Tharsis Montes a single lightly-cratered volcanic material. Crater statistics show ages of ~100-500 million years (Ma) for Ascraeus Mons [*Plescia & Saunders*, 1979; *Crumpler & Aubele*, 1978; *Hartmann* et al., 1981]. Mapping of distinct individual flow units was not possible at the Mariner-9 resolution of 60 m to 2.5 km per pixel.

Data from the 1976 Viking orbiters were used to produce controlled photomosaics of the Tharsis region, which allowed for four 1:2M scale regional geologic maps covering the TM and their surroundings to be created, all published by the USGS [*Scott & Tanaka*, 1981; *Scott* et al., 1981a,b,c]. Different units for the caldera, flank, and embaying plains flow fields were defined using these new regional maps, however, all volcanic materials on the shields themselves were mapped as a single unit, AHvu, Undivided Volcanic Material [*Scott & Tanaka*, 1981; *Scott* et al., 1981a,b,c]. These maps were integrated into the *Viking*-based western regional geologic map of Mars (1:15M) by *Scott & Tanaka* [1986]. The TM shields were mapped as a single unit, AHt3, Member 3 (central shields) of the Tharsis Montes Formation. Each unit consisting of volcanic flows with few lobate flow fronts, pressure ridges, and dark streaks than the embaying plains units. This did lead to new geologic maps of Arsia Mons [*Scott & Zimbelman*, 1995] and Pavonis Mons [*Scott* et al., 1998] at a scale of ~1:1M, using higher resolution Viking imagery. The Viking-based mapping observed six major lava flow units extruded from the TM, ranging from the Hesperian (Ht1-2, AHt3) to the late Amazonian (At4-6), four of which are present at Pavonis [*Scott* et al., 1998], and all six of which are present at Arsia [*Scott & Zimbelman*, 1995]. The Tharsis Montes Formation units are composed of a combination of overlapping lava flows and are differentiated by the degree of degradation, degree of faulting, and clarity & dimensions of flow margins. The youngest lava flows were thought to have formed at the same time or shortly after the formation of the large fan-shaped deposits found on the northwest of each shield. These fan units were suggested to be a mixture of glacial moraines, overlain by ash flow tuffs and lahars.

An important point about the mapping of the TM is that new geologic maps were produced with the acquisition of each improved image data set. Even with the most recent imagery at the time (Viking-based) mapping campaigns [*Scott & Zimbelman*, 1995; *Scott* et al., 1998] were limited to grouping lava flows into generic morphological units and unable to differentiate lava flows by emplacement style (e.g., channel-fed vs. tube-fed) across the shields. Different lava flow structures tend to develop as a result of different eruption and emplacement conditions [*Greeley*, 1977; *Head* et al., 1981; *Whitford-Stark*, 1982], making the emplacement style of lava flows an important characteristic for understanding the evolution of volcanoes. Basaltic lava is dominantly transported to flow fronts either through open, leveed channels or enclosed tubes [*Wentworth & Macdonald*, 1953; *Macdonald*, 1956]. Through observation of actively forming basaltic structures researchers determined that lava tubes tend to form during long-lived, stable eruptions of low viscosity lavas at low to moderate effusion rates, whereas channels tend to develop during shorter-lived, unstable eruptions of higher viscosity lavas at moderate to high effusion rates [*Greeley*, 1987b; *Holcomb*, 1987; *Rowland* and *Walker*, 1990; *Peterson* et al., 1994; *Kauahikaua*, et al., 1998; *Calvari* and *Pinkerton*, 1998, 1999; *Calvari* et al., 2002, *Kauahikaua* et al., 2003]. Lava tubes increase the length of a flow relative to channels [*Malin*, 1980; *Pieri* and *Baloga*, 1986], because tubes are able to thermally insulate the lava [*Swanson*, 1973; *Keszthelyi*, 1995; *Sakimoto* and *Zuber*, 1998], acting as a surface extension of the conduit [*Greeley*, 1987b]. This result allowed researchers to conclude that Kilauea has experienced more stable, longer-lived eruptions than Mauna Loa in the Holocene, based on mapping the relationship between eruptive conditions & resultant lava flow morphologies [*Greeley*, 1987b; *Holcomb*, 1987; *Lockwood & Lipman*, 1987]. Although proving helpful for understanding other terrestrial basaltic systems [e.g., *Rowland*, 1996], this approach had not previously been applied to martian volcanoes because of the lack of image data combining spatial resolution high enough to resolve different lava flow types over areas large enough to conduct regional geologic mapping.

2.2 Stratigraphy and Geologic History

Crumpler & Aubele [1978] created a four-stage evolution for the Tharsis Montes, including: 1) construction of the main shields, 2) outbreak of parasitic eruption centers on the NE & SW flanks, 3) subsidence of the summits becasue of evacuation of a magma chamber, and 4) continued eruption of lavas along the NE and SW rift zones resulting in inundation of the NE and SW flanks. They suggested that Arsia is the oldest, which is supported by crater counts [reviewed by *Hodges & Moore*, 1994] and that Ascraeus was the youngest also becasue of Arsia appearing more advanced and Ascraeus appearing least advanced. A stratigraphic sequence was produced from Viking-based map units for the TM [*Scott* et al., 1981a-c; *Scott & Tanaka*, 1981, 1986; *Scott & Zimbelman*, 1995; *Scott* et al., 1998] including six extruded units of the Tharsis Montes Formation, ranging from the late Hesperian to Amazonian. The Hesperian units are located on the NW flank of the volcanoes near the younger fan deposits, while the oldest Amazonian flows are generally found on the main flanks. The rift apron flows are the youngest surfaces, older flows are located further from the rift zone, which includes the largest flows found on Mars [*Zimbelman*, 1998; *Baloga* et al., 2003; Glaze & *Baloga*, 2006; *Garry* et al., 2007]. The rift zones have a NE trend through the volcanoes [*Crumpler & Aubele*, 1978; *Plescia*, 2004], and are the source for apron flows and channels resembling sinuous rilles found on the Moon [*Wilson & Mouginis-Mark*, 1984] with some channels possibly carved by fluvial processes [*Scott & Wilson*, 1998]. Dikes and sills are likely the source for producing the rift aprons [*Mouginis-Mark*, 2003; *Scott & Wilson*, 1999] potentially producing explosive eruptions [*Edgett*, 1997; *Edgett* et al., 1997; *Mouginis-Mark*, 2002], as well as effusive eruptions found in the aprons of Pavonis and Ascraeus [*Crumpler & Aubele*, 1978; *Mouginis-Mark*, 2003; *Plescia*, 2004]. Fan deposits to the northwest of each large volcano are suggested as possible glacial deposits or lahars and were emplaced concurrently with the Amazonian flows [*Scott* et al., 1981a-c; *Scott & Tanaka*, 1981, 1986; *Scott & Zimbelman,* 1995; *Scott* et al., 1998; *Head & Marchant*, 2003; *Marchant & Head*, 2006; *Shean* et al., 2007]. Preliminary mapping with newer imagery from MGS, MO, and MEX, *Bleacher* et al. [2007b] added to the formation and evolution of Ascraeus as described by *Crumpler & Aubele* [1978]. *Bleacher* et al. [2007b] used mapping techniques applied to late-Amazonian flows and tectonic as seen on shield volcanoes in Hawaii to develop an enhanced formation: 1) eruptions on the main flanks, including: emplacement of channel and tube-fed flows from the main flank summit, which transitioned to channel-fed flows of decreasing length, followed by emplacement of the hummocky unit, and later less extensive channel-fed flows that embay the hummocky unit; 2) eruptions from the rift aprons, including: formation of the collapse terrain concurrently with the emplacement of channel and tube-fed flows, and that lava flows decreased in length with time from each rift zone; and 3) eruptions from a vent field at distances of several hundred kilometers from the main flank, both concurrent and subsequent of the emplacement of lava flow from the rift aprons.

Bleacher et al., [2007a, b] identified several trends of the rift aprons of the TM. The maximum elevation of rift aprons decreases from 12.5, to 9.3, to 8.5 km (Arsia to Pavonis to Ascraeus, respectively), and the estimated apron volume decreases from ~7 x 10^{14} m^3 to ~9 x 10^{13} m^3. Median slope increases slightly from 0.8º at Arsia to 1.0º at Pavonis and Ascraeus. The abundance of the tube-fed flow unit increases from 9%, to 12%, to 16%, while the channel-to-tube-fed flow unit ratios decrease from 4.3, to 3.8, to 2.0 from Arsia to Ascraeus, respectively. Tube-fed flows found in the rift aprons of Arsia are embayed by younger channel-fed flows, while channel-fed flows are not seen embaying tube-fed flows in the rift aprons of Pavonis and Ascraeus [*Bleacher* et al., 2007b]. This is similar to trends seen in the Hawaiian chain of volcanoes, where long lived eruptions produced more tube-fed flows in the shield building phase. A transition to shorter lived eruptions with decreased magma production rates increases the abundance of lava channels which increases the slopes of the shields [*Greeley*, 1987; *Holcomb*, 1987; *Lockwood & Lipman*, 1987; *Moore & Mark*, 1992; *Rowland & Garbeil*, 2000; *Bleacher & Greeley*, 2008]. The decrease in magma production generates isolated bodies of magma which may reach the surface generating parasitic eruption vents [*Wolfe* et al., 1997]. The Hawaiian volcanoes display an age progression with a chain of volcanoes linked to the same magma source. This same idea could be applied to the late Amazonian eruptive sequence of the Tharsis Montes forming from a single body of magma with a decrease in magma production with time [*Bleacher* et al., 2007b].

3. Methods

Mapping of Ascraeus Mons and the surrounding plains was performed by following standard principles established for the geological mapping of planetary surfaces [*Shoemaker and Hackman*, 1962; *Wilhelms*, 1972, 1990; *Tanaka* et al., 2010]. The maps were produced and edited using ArcGIS™ software for manipulation & consistency with USGS standards. I worked with the USGS to define the appropriate map projection and to produce the base materials, as now required by NASA for all NASA-funded geologic maps. The current extent of the map boundary is -112 to -100º E and 7.5-17.5º N with an area of 420,000 km^2. This approach facilitated spatial co-registration & comparison of all geographically referenced data, including MOLA, CTX, HRSC, HiRISE, MOC, and THEMIS. Mapping in GIS aided in spatial comparisons of map unit interpretations between the data sets. The final maps were converted to GIS layers for map review & production, and they will be digitally published as part of the USGS planetary geological map series. For Ascraeus Mons I produced a 1:1M scale geomorphology map. At 1:1M scale, regional characteristics and relationships can be shown, while smaller scale features such as individual lava flows can still be differentiated and displayed. Choice of the 1:1M scale is based on results of our preliminary mapping and consultation with the USGS. Our geologic map focused on identifying discrete material units indicative of volcanic [*McCauley* et al., 1972; *Carr*, 1973; *Greeley*, 1973; *Carr* et al., 1977, *Greeley & Spudis*, 1981; *Mouginis- Mark* et al., 1992; *Morris & Tanaka*, 1994], glacial [*Neukum* et al., 2005; *Head* et al., 2005], aeolian [*Thomas & Veverka*, 1981; *Veverka* et al., 1981; *Arvidson* et al., 1989; *Greeley*, et al., 1992, 1993; *Malin & Edgett*, 2001], fluvial [*Carr*, 1981, 1996; *Baker*, 1982; *Mouginis-Mark*, 1985; 1990; *Squyres* et al., 1987; *Gulick & Baker*, 1990; *Greeley & Crown*, 1990; *Crown & Greeley*, 1993; *Scott & Wilson*, 1999; *Fassett & Head*, 2006], or tectonic/erosional activity [*McCauley* et al., 1972; *Carr*, 1974; *Wise* et al., 1979; *Frey*, 1979; *Thomas* et al., 1990; *Banerdt* et al., 1992; *Mouginis-Mark & Robinson*, 1992; *Zuber & Mouginis-Mark*, 1992; *McGovern & Solomon*, 1993; *McGovern* et al., 2004].

The current data available enabled me to generate a lava flow morphology map to show the distribution of different flow types within each volcanic unit. Determining the amount of the surface emplaced via lava channels, tubes, sheets, or other structures, provides insight into the eruptive dynamics of each volcano as shown by different flow types resulting from different eruption and emplacement styles seen on Earth [*Greeley*, 1987b; *Holcomb*, 1987; *Rowland and Walker*, 1990; *Peterson* et al., 1994; *Hon* et al., 1994; *Kauahikaua*, et al., 1998; *Calvari and Pinkerton*, 1998, 1999; *Calvari* et al., 2002, *Kauahikaua* et al., 2003; *Bailey* et al., 2006]. The results provide a minimum estimate for the abundance of each flow type because unit interpretations are influenced by data resolution. The data also allows for consistent mapping across individual and other volcanoes, enabling trends to be recognized at a scale in which flow features can be identified [discussed by *Zimbelman*, 2001]. A rigorous classification of lava flow structures, their abundance, and distribution across each shield serves as a tool for characterizing eruptive histories and identifying potential long-term evolution [Head et al., 1981], shown for terrestrial basaltic systems [*Greeley*, 1987b; *Holcomb*, 1987; *Lockwood & Lipman*, 1987; *Rowland*, 1996].

4. Results

Geologic units were defined and characterized by looking at flow morphologies across the main shield, rift aprons, and the surrounding plains. A total of 26 units have been mapped on the finished printed version; some of these units have facies changes, but have been lumped together to best fit the 1:1,000,000 mapping scale. Figure 2 shows the 1:1,000,000 scale map of Ascraeus Mons created for this study.

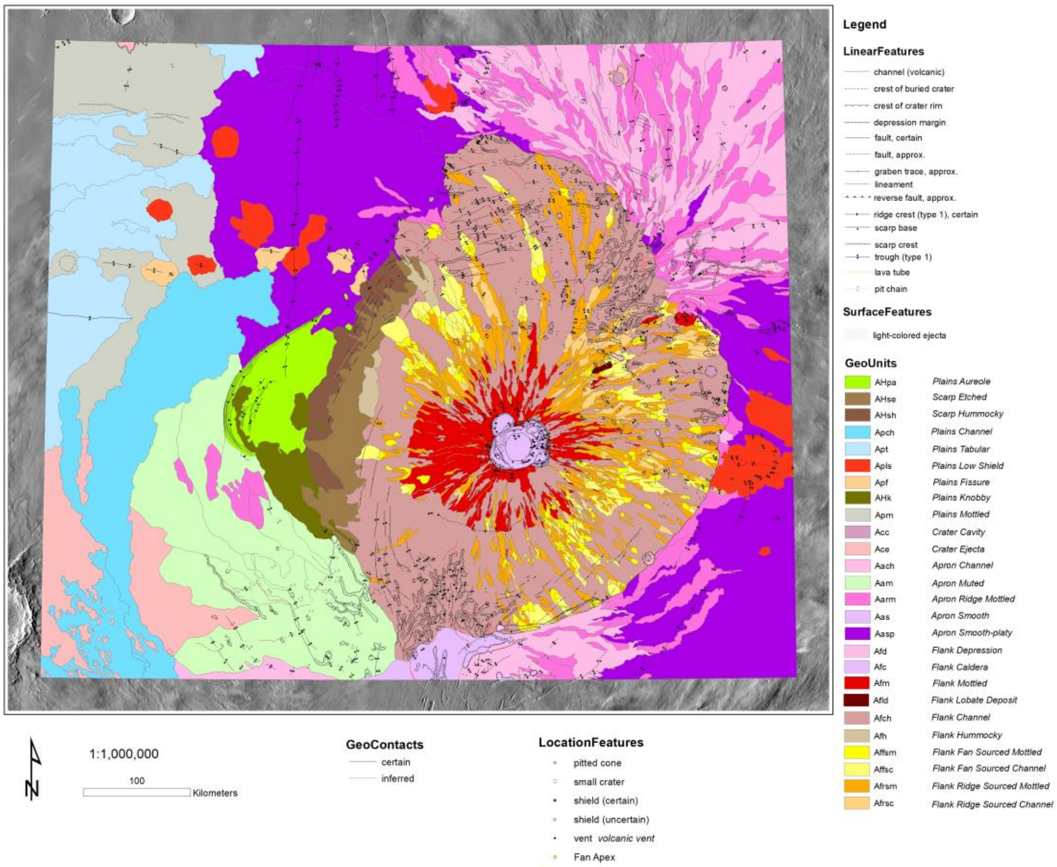


Figure 2. 1:1,000,000 scale map of Ascraeus Mons, Mars generated for this study. The map is colored with the geologic units described below. The colored map overlies a THEMIS Day IR mosaic.

4.1 Unit Descriptions

Mapping of geologic units for AM were based on and modified from the mapping style defined by *Bleacher* et al., [2007a, b]; and *Bleacher* et al., [in preparation] for Olympus Mons and the other Tharsis Montes. While the map scale for the finished project is 1:1M, CTX, HRSC, and HiRISE imagery allows for mapping at a higher resolution. For this reason, several map units have facies changes and can be further subdivided, but were lumped together for the final map product. The following descriptions are for units mapped on the finished and final product, descriptions for subdivided units can be found in the appendix.

4.1.1. Main Shield (Flank Units)

Ascraeus Mons is ~350 km in diameter and ~16 km high. 10 Flank Units have been divided across Ascraeus Mons. The basic morphological units identified around the AM flank include mottled and channeled units. The channel unit is typified by subparallel linear flows displaying sections with visible levee structures, whereas the mottled unit is typified by a hilly surface at the horizontal scale of 10s to 100s of meters. In all cases overlapping groups of similar units were mapped as the same unit. I did not delineate units that display the same morphology, but appear to be the result of a different eruptive phase. Because one of the scientific objectives for this project is to identify sources for the flank units and how they relate to other features present across the main shield, I have taken the same approach as *Bleacher* et al. [2007a, b] and *Bleacher* et al. [in prep] and subdivided channels and mottled units according to their apparent origin on the flank. These include Fan sourced, Ridge sourced, and Flank units. Flank units are those that are truncated by the caldera complex or those with an unidentifiable source, which generally occurs because the proximal section of the flow is buried by younger units [*Bleacher* et al., in prep].

Fans and ridges are positive topographic features that are up to 100 m in height [*Bleacher* et al., 2007a, b; *Bleacher* et al., in prep]. Fans are delta shaped, whereas ridges are elongated and generally oriented radially to the caldera complex. Each fan has been further identified by two types of location points: 1) a fan's apex is denoted with a yellow circle marking the highest point of the fan without a discernable vent and 2) if a vent can be clearly seen on the fan, that vent was marked with a vent feature (black triangle). A hummocky unit displays a broad, relatively smooth undulatory surface on the horizontal scale of a few kilometers. Depressions of non-impact origin include any irregular depressions, most of which do not display a raised rim, and none of which display an ejecta blanket; only depressions with diameters greater than 5 km are mapped as a unit, smaller depression on the flank are denoted by depression or scarp line features (found under Linear Features in the map legend).

Flank Units are described in more detail below:

-Afd- Flank depression- Description: Rimless depressions, sometimes arranged in sinuous to linear chains. Features vary from meters to several kilometers in size. Found on the mid-flank of AM's N-E flanks. Pit chains cut across other flow units, do not trend down slope, and show no evidence of lava tube processes near the summit of AM. Only features greater than 5 kilometers have been mapped. Features 2-4 km in diameter have been mapped with a scarp crest line feature. Several pit chains have been found and mapped as line features (Linear Features in Map Legend) near or around the collapsed terrain of the rift aprons, and may suggest a lava tube processes. Interpretation: Although depressions of non-impact origin have been cited as evidence for the presence of lava tubes, these features are likely to have a structural collapse origin related to volcano subsidence or caldera formation processes. Small sinuous pit chain features found near the rift aprons are interpreted to be skylights of collapsed lava tubes. Such collapsed features can be connected to form a channel-like appearance; however, pits can still be distinguished.

-Afc- Flank caldera- Description: Extensive group of collapse depressions located at the summit of Ascraeus Mons. These features are the largest craters in the mapping area and are only located at the summit of Ascraeus Mons. The caldera complex is 65 km in diameter, with the youngest, largest crater at 35 km in diameter. Interpretation: Volcanic calderas produced by structural collapse of the summit region becasue of magma loss or migration. AM has experienced several collapses at the summit and is described in more detail in *4.2 Caldera Complex.*

-Afm- Flank mottled- Description: A smooth to relatively rough texture at the horizontal scale of tens to hundreds of meters displaying mound-like features inferred to be at the scale of several meters in height. This unit has a medium bright albedo. Brighter albedo areas can be seen, this is where the unit is exposed to direct sunlight. The mottled unit tends to have pitted/degraded appearance on the western flank of AM. This unit is dominantly found on the summit of AM, near the caldera complex. Interpretation: This unit includes two possible interpretations, and possibly a combination of both. The mottled unit is closely associated with the summit caldera unit and with the axis of ridges (Flank-ridge sourced mottled) or fans (Flank-fan sourced mottled). These are all considered to represent local eruptive sources, whether from depth (summit region) or from surface pathways or tubes (ridges and fans). Lava flows associated with near-vent areas sometimes lack well developed channels or tube networks and advance as irregularly inflated sheets or poorly connected toes and lobes. This style of flow emplacement produces a morphology that matches with the Flank-mottled units. Conversely, this unit might represent burial of lava flow textures by a combination of ash, dust and/or volatiles. This unit dominates the summit of the west flank, and looks slightly more degraded than the other flanks. This may be becasue of higher atmospheric precipitation on the west flank or a blanket of ash and other volatiles deposited by volcanic plume with a westwardly wind.

-Afld- Flank lobate deposit- Description: A stepped type topography exhibiting the mass movement of material not related to void collapse or lava flow processes. This unit resembles the scarp etched unit, but is not associated with the same processes the scarp units. The surface of the unit is relatively smooth at the horizontal scale of several meters. Blocks of the pre-existing terrain can be seen downslope and are perpendicular to flank, creating the step-like surface. This unit is only found in one location on Ascraeus Mons, the NE flank. There are no lava flows observed embaying this unit. However, the unit may have been mantled by the mottled unit from a localized eruption just upslope. Lava channels, pits, and pit chains are present on the flow and are the youngest features present. Interpretation: Mass wasting deposit produced by slippage of material that moved downslope from some volcanotectonic event.

-Afch- Flank channeled- Description: Overlapping, subparallel linear features that are narrow and ribbon-like in nature. Individual linear features display evidence for a central trough bound by leveed structures. Linear features trend nearly parallel to slope. Channeled flows are observed from tens of meters to several kilometers in length. Widths and heights of these flows are dependent on the source of the eruption. Large tabular-like flows are found on the eastern and southern flanks, measuring 2-3 km across and greater than 25 km in length. All channeled flows are seen embaying and surrounding ridged flows and some mottled flows. These flows are assumed to be last gulp of volcanism that covered most of the main shield. Interpretation: Typical basaltic lava flow channels as seen on shield volcanoes on Earth and Mars. Flank channels are buried up slope and individual channels cannot be traced for more than a few kilometers. Because of up slope burial, these channels cannot be traced to their source and are simply identified as flank channels. Larger tabular channeled flows seen at summit of AM on the eastern and southern flanks are truncated by the corresponding calderas. These flows were most likely emplaced before the collapse of the calderas. This indicates that these flows may be older than previously assumed, but are still stratigraphically younger than the surrounding units. Except for areas near the summit caldera complex where collapse of the craters buried the source vents of these flows.

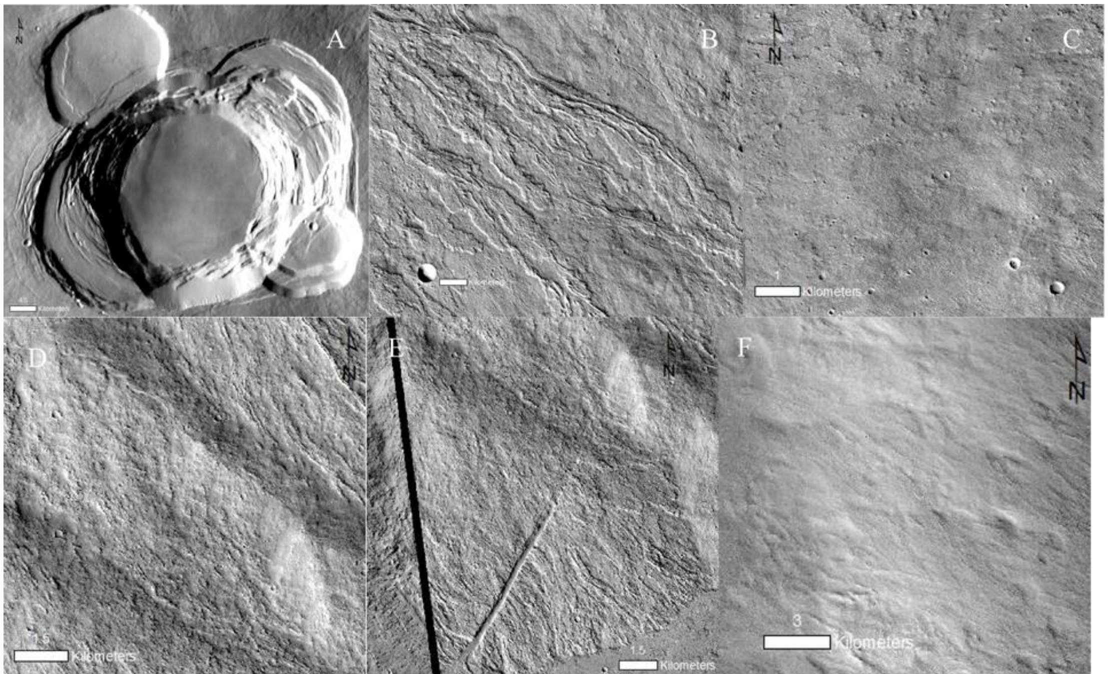
-AHfh- Flank hummocky- Description: The hummocky unit displays a broadly smooth surface sometimes showing a swale-like texture at the scale of 100s of meters to kilometers. The hummocky unit is interpreted as a thick (at least several meters) mantle of ash, dust and/or volatiles. This unit is only found near the base of the western flank of AM. Higher resolution imagery suggests that channeled flows lie buried beneath this mantle. However, this is not seen at the map scale. Interpretation: This mantle is interpreted to bury older Ascraeus Mons flank units that are now indistinguishable at the map scale. This extra deposit of dust may also be attributed to the large Poynting Crater to the SW of AM. As the large impact would mantle the surround areas with dust and ash, which can later be deposited by aeolian processes. This is also the interpretation for the Apron Muted unit.

-Affsm- Flank fan sourced mottled- Description: A smooth to relatively rough texture at the horizontal scale of tens to hundreds of meters displaying mound-like features inferred to be at the scale of several meters in height. This unit can be found on all flanks across Ascraeus Mons, but are dominantly located on the SE and NW flanks where there is a higher concentration of flank terraces. Flank channeled units are seen embaying and surrounding this unit, similarly ridged channel units are also seen embaying this unit. Fans are mapped with a location feature (Fan Apex) where the fans point source is located. Fans that shows a distinct source vent are mapped with a vent location feature. Interpretation: Flank fan-sourced units are interpreted as surface breakouts of lava tubes that produce point sources or rootless vents. These localized eruptions used weaknesses in the overlying tumulus to erupt to the surface. Fan units are generally found on or near a flank terrace where there is an abrupt change in slope.

-Affsc- Flank fan sourced channeled- Description: Overlapping, subparallel linear features that are narrow and ribbon-like in nature. Individual linear features display evidence for a central trough bound by leveed structures. Linear features trend nearly parallel to slope. This unit is found on all flanks, but is dominantly found on the NW and SE flanks of AM. This unit generally corresponds with a fan sourced mottled unit up slope. Fan sourced mottled units can transition to fan sourced channeled units if there is an increase in slope. However, some fan sourced channeled units are observed with no fan sourced mottled unit. Interpretation: Flank fan-sourced units are interpreted as surface breakouts of lava tubes that produce point sources or rootless vents. This unit is generally associated with a fan sourced mottled unit located upslope.

-Afrsm- Flank ridge sourced mottled- Description: A smooth to relatively rough texture at the horizontal scale of tens to hundreds of meters displaying mound-like features inferred to be at the scale of several meters in height. This unit is closely related to the fan sourced mottled unit, but does not form a fan shape. These ridged features are elongated tumuli that travel downslope several for several kilometers. Several of these ridges are associated with a fan sourced mottled unit at the end of the ridge or can be disrupted by a fan sourced mottled unit and continue downslope. Interpretation: Flank ridge-sourced units are interpreted as surface breakouts of lava flows along the axis of a lava tube that produces a continuous or numerous point sources along the length of the ridge. Different zones along the ridge were likely active at different times. Fan sourced mottled units found disrupting a ridged feature are assumed to be where a localized outpouring of lava was erupted from a weakness in the overlying tumulus until the eruption rate lessened allowing the crust to cool, after which the pre-existing lava tube was reactivated. Fan sourced mottled units found at the ends of ridged units can be interpreted as breakout from a weakness in the overlying tumulus or as a change in the lava properties as volatiles from the lava escaped as the flow traveled further from its source.

-Afrsc- Flank ridge sourced channeled- Description: Overlapping, subparallel linear features that are narrow and ribbon-like in shape. Individual linear features display evidence for a central trough bound by leveed structures. Linear features trend nearly parallel to slope. These channeled flows are directly sourced from the ridge sourced mottled unit. This unit is observed embaying ridged and fan sourced mottled units. Interpretation: Flank ridge-sourced units are interpreted as surface breakouts of lava flows along the axis of a lava tube that produces a continuous or numerous point sources along the length of the ridge. Different zones along the ridge were likely active at different times. These flows tend to occur where there is an increase in slope and able to flow freely down the flanks of AM. Examples of the Flank Units can be seen in Figure 3.



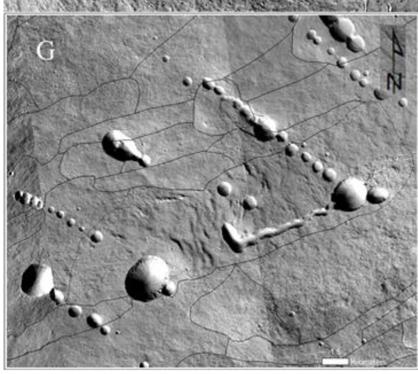


Figure 3. Type examples of common flows seen on the flanks of Ascraeus Mons. A) Depicts the caldera complex on the summit of AM, image is THEMIS Day IR, B) CTX image of channeled flows, C) CTX image of Mottled unit, D) CTX image of Ridged Mottled unit, E) CTX image showing the type example of a Mottled Lava Fan transitioning into the Fans Sourced Channeled unit, F) CTX image of the Hummocky unit, and G) CTX image of the Lobate Flow deposit.

4.1.2. Scarp and Apron Units

Two scarp units and five apron units have been differentiated. The Scarp units are divided into an Etched and a Hummocky unit. Both Scarp units are located at the base of the west flank and separate the flank units from the plains units. The Etched unit displays a muted and etched terrain with smooth plateaus and troughs that trend downslope in some cases like a step-like pattern. The Etched unit at AM is similar to the Ravine unit described by *Bleacher* et. al., [in preparation] for Olympus Mons, however Ascraeus Mons does not have ravine-like valleys that are observed on Olympus Mons. The main scarp at the edge of the Etched unit is ~350 meters in height and has an average slope ~25^{o}. The Hummocky unit is similar to the Stepped scarp unit defined by *Bleacher* et al., [in preparation] for Olympus Mons, however no step-like pattern is found at AM for this unit. This unit has a relatively low slope ~2.5^{o} and is mostly comprised of loose material that has been transported downslope, most likely by volatiles within and on the surface of AM.

Apron units include channeled, ridged mottled, smooth, smooth-platy, and muted. The channeled and ridge mottled units are similar to the flank channeled and flank ridge sourced mottled units and make up the majority of the flow found on the aprons. The Smooth unit is located at the base of the SW rift apron where dust and undifferentiated lava flows have left a smoother surface, not showing any surface features (at 1:1 M mapping scale). Smooth-platy units are interpreted as thin sheet lava flows that are generally found on slopes <1.5^{o}. These Smooth-platy flows are found NW and SW of Ascraeus Mons on the surrounding plains. Because of the thin-platy nature of these flows, individual flow margins are extremely difficult to determine and therefore are only mapped where definitive flow margins are observed in the available imagery. The Muted units are located on the NW side of the SW rift apron and are highly mantled in dust obscuring surface textures and features at the mapping scale.

Scarp and Apron Units are described below:

-AHse- Scarp etched- Description: Displays a somewhat muted and etched terrain with smooth plateaus and troughs. Some of this unit displays a step-like pattern down slope. This unit has steep cliffs where pre-existing material has been removed. Several channel-like valleys can be found in this unit. The Scarp etched unit separates the flank units from the Plains units. Interpretation: The scarp etched unit is interpreted to be erosion of the pre-existing material at the western base of AM becasue of subsurface ice melting which weakened the surface or glacial processes that eroded and transported material downslope.

-AHsh- Scarp hummocky- Description: Relatively smooth elongate sections displaying a texture similar to the Flank hummocky unit. This unit has a relatively low slope with downslope oriented elongated sections that are made up of the pre-existing bedrock. Boulders are present in the meters sized scale. Yardangs are also present on the surface of this unit. Interpretation: The Scarp hummocky unit is interpreted to be the material removed from the Scarp etched unit. Yardangs seen on this unit are the youngest feature present and are carved by aeolian processes.

-Aach- Apron channeled- Description: Overlapping, subparallel linear features that are narrow and ribbon-like in nature. Individual linear features display evidence for a central trough bound by leveed structures. Linear features trend nearly parallel to slope. Apron channeled units are similar to Flank channeled units, but are source from the rift aprons. Apron channeled units are observed at scales much larger than found on the flanks. Channeled units can be observed flowing off the mapping area for 100s of kilometers. Apron channeled units are generally found in association with an Apron ridged unit. This unit is observed embaying ridged units and other channeled units. Interpretation: This unit is interpreted to be breakout flows from Apron ridged units found on the rift aprons. Ridged units tend to produce channeled flows when there is a sudden change in slope or as the lava properties evolve further from its source. This unit is difficult to relatively age date becasue of its interfingering nature with other channeled flows and ridges.

-Aarm- Apron ridged mottled- Description: A smooth to relatively rough texture at the horizontal scale of hundreds of meters displaying mound-like features inferred to be at the scale of several tens of meters in height. This unit resembles the ridged sourced mottled unit found on the flanks of AM. Like the Apron channeled unit, the Apron ridged mottled unit is observed at scales much larger than on the flanks. The Apron ridged mottled unit has three facies units lumped into it. A smooth ridge, mottled ridge, and a smooth-platy ridge. All ridges are found near or sourced from the rift aprons. Interpretation: Like the Ridged sourced mottled units found on the flanks of AM this unit is interpreted to be elongated tumuli with an underlying lava tube. The smooth ridge is observed transitioning into both the mottled ridge or the smooth-platy ridge. The transition of the smooth ridge into a mottled ridge is characterized by a change in the lava properties as the eruption style changes from effusive to potentially explosive. The mottled ridges do show some resemblance to cinder cones found on Earth and are interpreted to be rootless cones. The smooth ridge transition to a smooth-platy ridge is dependent on the surrounding topography. As the slope decreases to less than 1 degree the smooth ridge transitions to a sinuous raised ridge resembling an inverted channel. These smooth-platy ridges are interpreted as the inflation of lava flows that produce breakout flows creating a smooth-platy texture. The smooth-platy ridges are generally found on the SE area of the map, but some are visible north of AM where the same decrease in slope occurs.

-Aas- Apron smooth- Description: A relatively smooth surface made up of undifferentiated lava flows at the horizontal scale of several meters. This unit is made up of overlapping lava flows that are most likely sourced from the SE rift apron. The surface texture of this unit resembles a mixture of the flank mottled and flank hummocky units. Where at the smaller scale the surface has rough texture and at larger scales is relatively smooth. Mottled and channeled flows can be seen at higher resolution, but are too small for the mapping scale. Depressions found on the SE rift apron greater than 5 km in diameter have also been mapped with this smooth unit. Interpretation: These flows are sourced from the SE rift apron and are now covered by a mantle of dust. Similarly, other flows in this region that are sourced from collapsed features on the apron.

No flows can be seen flowing into any collapse features and are therefore younger than the surrounding flows.

-Aasp- Apron smooth-platy- Description: A relatively smooth unit at the kilometer scale including localized zones of rough patches or linear rough zones at the 10s of meters scale. Lobate margins as seen in the Plains channel unit are generally absent. Contains infrequent non-leveed rilles and leveed channels but not in abundances high enough to be stacked and overlapping a seen within the Plains channel unit. Found in nearly zero degree slopes. Interpretation: Lava flows that entered areas of generally no slope allowing for flows to spread out and inflate. These flows are similar to sheet flows as they are relatively thin. Examples of these flows have been seen on Earth at Kilauea, Hawaii.

-Aam- Apron muted- Description: This unit is smooth and produces a muted appearance similar in nature to the Flank hummocky unit. This unit is generally found on the NW side of the SW rift apron and just to the East of the large impact crater (Poynting Crater). Structures resembling ridged and channeled flows can be inferred at higher resolution, however, no distinction can be made becasue of the mantling of the dust. This unit is inferred to originally be emplaced before the Poynting Crater impact and has been altered by secondaries and ejecta. The Aureole and Plains channeled units are seen embaying the Apron muted unit. Channels and collapse pits are observed on the unit and are the youngest features. Interpretation: The muted apron unit might represent burial of parts of the apron units by dust, ash, and/or frozen volatiles. This unit may have been mantled by dust accumulated after the impact. The hummocky/mantling nature of this unit covers what at high resolution imagery looks to be channeled flows from the flanks, just west of the SW rift apron. This would imply that the SW flank of AM extends further south, however, this dust mantling makes determining this extremely difficult. Therefore there is a dashed line marking the SW base of Ascraeus Mons. Examples of the Apron and Scarp Units can be seen in Figure 4.

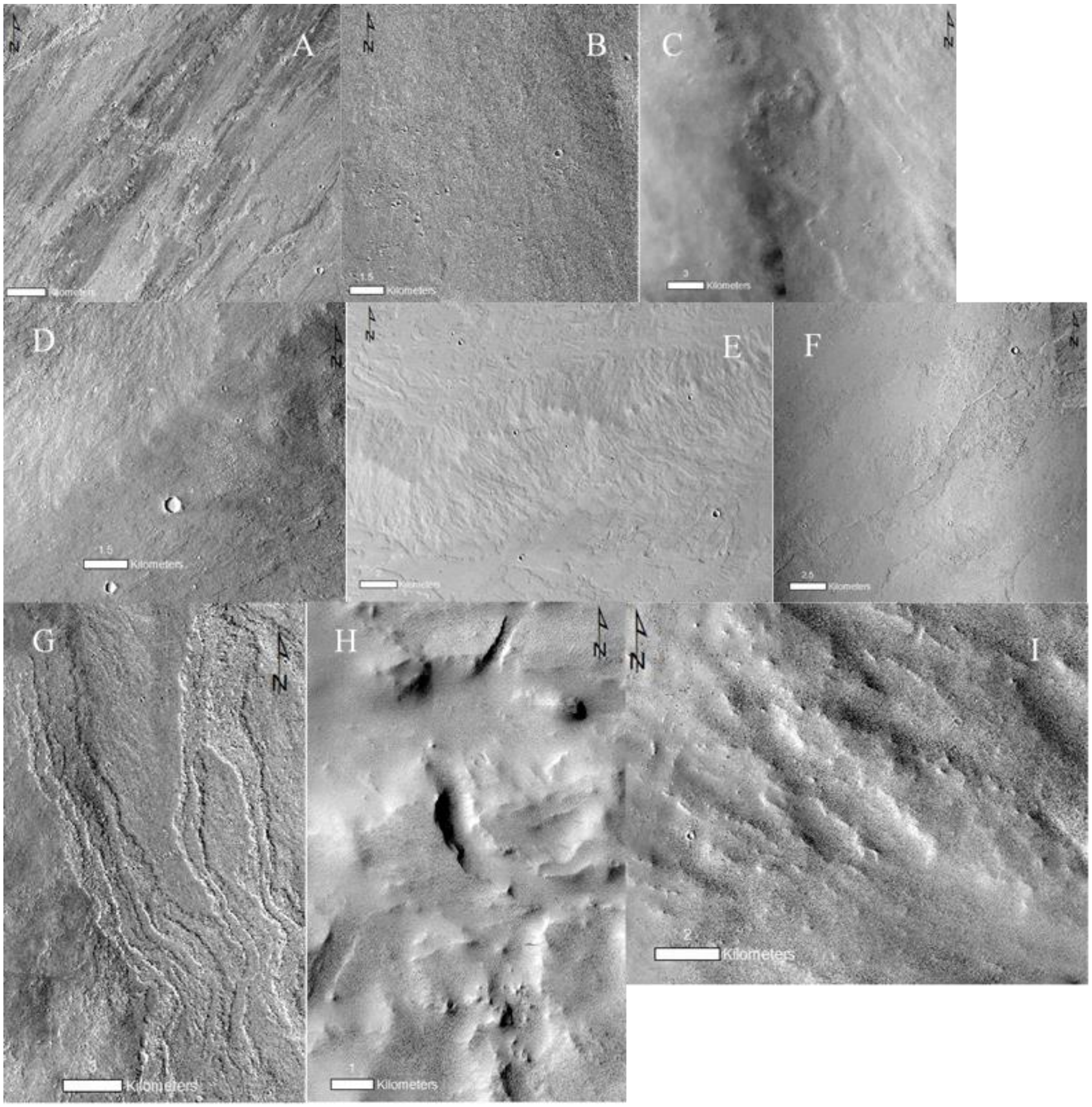


Figure 4. Type examples of the Apron and Scarp units. A) CTX image of the Smooth-platy unit, B) CTX image of the Smooth unit, C) CTX image of the Muted unit, D) is the typical example for the Apron Ridged Mottled unit that has two other facies lumped within in it represented by E and F, E) HRSC image of Ridged Smooth unit, F) CTX image of Ridged Smooth-platy unit, G) CTX image of Channeled flows, H) CTX image of the Scarp Etched unit, and I) CTX image of the Scarp Hummocky unit.

4.1.3. Plains Units

The Plains Units are subdivided into Channeled, Mottled, Tabular, Aureole, Knobby, Fissure, and Low Shield units. Plains units surround Ascraeus Mons and have sources that are generally not present in the mapping area, except for the Aureole, Fissure, and Low Shield units. These units are typically thought to be derived from separate events from the Main Shield building phase and the Rift Apron forming phase. The Channeled unit is a somewhat rough unit defined by overlapping, subparallel linear features commonly displaying sections with visible levee structures and lobate fronts, like the Flank channeled unit. The Mottled unit has a smooth to rough surface pattern similar to the Flank mottled unit. The Tabular unit has large lobate flow lobes sourced south of Ascraeus Mons at the horizontal scale of kilometers and several meters high with a rough surface texture. These flows can be traced back to their source, outside the map boundary, Pavonis Mons and are disrupted by the large Poynting impact crater. The Aureole unit is characterized by extensive arcuate ridges, troughs, and plateaus, and is believed to be material displaced from the west flank of Ascraeus Mons by mass movement processes, such as glaciation. The Knobby unit is a karst-like hilly unit found on the west plains with the Aureole unit. Fissure units are defined by an outpouring of lava sourced from a linear fracture on the surrounding plains. The Low Shield unit is described as small parasitic low shields having a central vent with radial lava flows outward following local topography of the surrounding plains. Low Shield units are typically found in clusters on the northwestern and eastern plains and at high resolution show flow morphologies similar to mapped Flank units on Ascraeus Mons.

Plains units are described below:

-Apch- Plains channeled- Description: Sub-parallel linear features commonly displaying sections with visible levee structures and lobate fronts. Plains channeled flows are vastly larger than any other lava flows found in the mapping area and originate south of the map boundary. These flows lack any evidence of secondary impacts or ejecta material from Poynting Crater and superpose all other flows from the Plains or Aprons. Such channeled flows can be seen intermingling and embaying ejecta blocks from Poynting Crater, SW corner of map. Interpretation: Lava channels that developed in flows emplaced across the Tharsis plains adjacent to Ascraeus Mons. These flows do not appear to have sourced from Ascraeus Mons, but from small vents in Ascraeus Mons' southern vent field. The lack of secondaries and the observation of flows embaying and flowing around ejected material suggests that these flows postdate the large impact event. These flows are believed to be the youngest flows in the mapping area.

-Apm- Plains mottled- Description: A smooth to relatively rough texture at the horizontal scale of tens to hundreds of meters displaying mound-like features inferred to be at the scale of several meters in height. This unit is very similar to the Apron smooth-platy unit, but has a rougher surface texture becasue of erosion from aeolian processes and impacts cratering. This unit is superposed by all other Plains units. Interpretation: This unit is interpreted to be the oldest Plains unit emplaced in an eruption style similar to the Apron smooth-platy unit. This unit now has a rough surface texture from wind abrasion and impact cratering. The source of this unit is unknown, but may have been part of a large plains volcanism event similar to flood basalts on Earth. Small yardang-like features can be seen on this unit in the NW area of the map. These features are oriented in a NW direction, which challenges wind streaks that suggest NE winds. A further investigation of these features should be looked at in a future study.

-Apt- Plains tabular- Description: Large lobate flows sourced south of Ascraeus Mons at the horizontal scale of kilometers, with heights of several meters and rough surface textures. The large lobate flows, mapped on the west side of the map, superpose the Plains mottled unit and have secondary craters from Poynting Crater. The large Tabular flow mapped on the north part of the map, flows south into the Ascraeus Mons plains and has secondary craters from the large impact crater to the NW or the map. The northern Tabular flow also superposes the Plains mottled unit, as well as the Apron smooth-platy unit. Interpretation: These flows originate from Pavonis Mons, SW of Ascraeus Mons. Secondaries found on these large flows as well as the large Poynting Crater itself disrupting these flows establishes that these flows predate the large impact event. The Tabular flow from the north originates from Ceraunius Fossae and flows southwardly into a depression on the western plains of AM. This depression is a topographic low that dictated the flow direction for the Tabular flows from Pavonis, Tabular flow from Ceraunius Fossae, the Channeled flows from AM's southern vent field, and Apron flows from AM.

-AHpa- Plains aureole- Description: Characterized by extensive ridges, troughs and plateaus. Within the Aureole is a chaotic terrain that resembles arcuate ridges. The Aureole unit is located off the base of the west flank of AM. Large arcuate ridges on the west end of the Aureole unit can be upwards of 200 kilometers long and are 10-25 meters high. Ridges on the northern end of the Aureole are not as prominent as seen in the SW portion of the unit. The Aureole unit superposes the Apron muted unit. Knobby flows or mountainous terrain can be seen within the Aureole and make up the Plains Knobby unit. Interpretation: The Aureole unit is interpreted to be material removed from the west flank of AM by glacial processes. The long arcuate ridges on the western edge of the unit resemble glacial moraines observed on Earth. Models show that when Mars was in a high obliquity the accumulation of snow and ice would be preferential on the western side of the Tharsis Montes. This high obliquity period allowed for glaciers to form at the base of Ascraeus Mons' west flank. This glaciation carved the western flank, creating the Scarp units and deposited the material into the fan shaped Aureole unit. This unit also could have formed from the collapse of the west flank becasue of surficial volatiles such as ice or groundwater. While this process may have occurred, there is no evidence for this process being the main reason for this fan shaped deposit. Had this dominantly been created by surficial volatiles, one would not see the hilly/mountainous features of the Knobby unit. Also there are no observations of flow materials embaying the Knobby unit itself.

-AHk- Plains knobby- Description: A hilly unit at the 10s of meters' scale and found on the west plains off the base of Ascraeus Mons. Does not form extensive ridges, but irregular mounds at the map scale. Unit is found in association with the Plains aureole unit. Interpretation: Close spatial association with Plains aureole unit suggests a genetic relationship, inferred here to represent burial of the aureole ridges or in some cases the Apron units. The majority of the plains surface is interpreted as lava flows and it is possible that the Plains knobby unit represents burial of aureole by lava flows producing a disrupted and knobby flow texture. Conversely the knobby terrain might represent aeolian burial of the aureole or weathering of the aureole and movement as loose debris. Or this unit might represent a combination of all three interpretations. This unit may also exhibit interaction of lava flows with glacial material. Either pre-existing lava flows were modified by later glacial processes or lava flows that were emplaced beneath a pre-existing glacier. Disruption in the large arcuate ridges suggests that both of the previous explanations may be true. Had the flow been emplaced before ice was present, there would be no disruption of the arcuate ridges and only sharp steep cliffs would be present. The fact that both of these are seen presents an argument for multistage glacial activities altering the surface.

-Apf- Plains fissure- Description: Thin flows sourced from a linear vent found on the plains surrounding Ascraeus Mons. Flows from these linear vents do not travel far, upwards of 10 kilometers at most. Flows are not visibly seen from the mapping scale, but can clearly be delineated at higher resolution. Interpretation: Fissures present on the plains are most likely failed low shields. As low shield units embay fissure units and are found in the same area of the map. Both the low shield and fissure units probably formed at the same time, with fissure eruptions waning and low shield eruptions continuing.

-Apls- Plains low shield- Description: Low shields found on the plains surround Ascraeus Mons having a central vent with radial flows outward following the local topography. The largest Low shield is ~50 kilometers in diameter and ~350 meters high. Low shield units are generally found in clusters. The highest concentration of low shields are on the NW and SE plains. Low shields embay fissure units, but can be seen almost buried by Apron units. Each shield has an oblong noncircular vent near its summit. Some vents are linear and resemble fissure vents, but are greater in diameter and was able to erupt enough material to build a dome-like feature. Interpretation: Low shield units are small shield volcanoes where lava took advantage of a weakened conduit and found its way to the surface. This unit displays effusive low viscosity eruptions similar to shield volcanoes found on Earth and Mars. Shield vents are marked with a location feature, some dome-like features have been found with no known vent and have been marked with an uncertain shield location feature. Examples of the Plains Units can be seen in Figure 5.

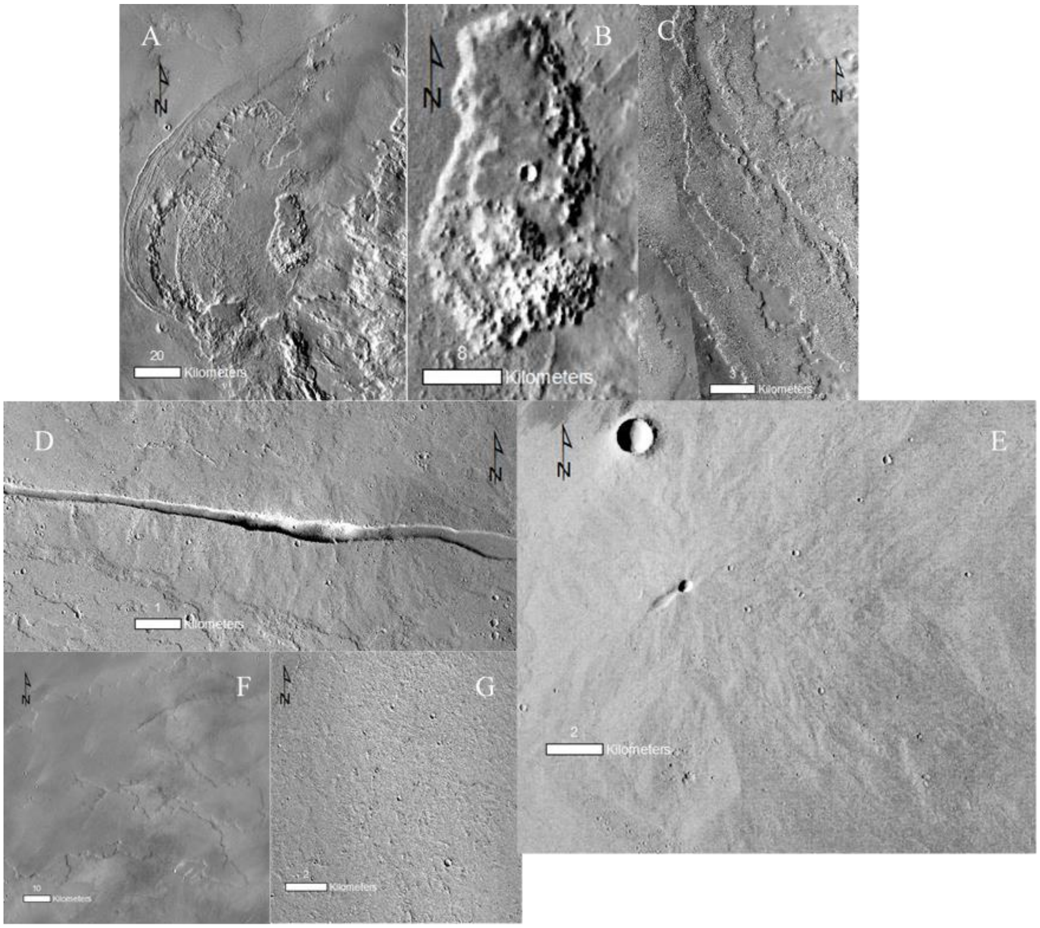


Figure 5. Type examples of the Plains units. A) THEMIS Day IR Mosaic of the Aureole unit west of AM, B) THEMIS image of the Knobby unit located within the Aureole unit, C) CTX image of a large Channeled flow, D) CTX image of a Fissure unit, E) HRSC image of the Low Shield unit, F) THEMIS Day IR Mosaic of the Tabular unit this flow originates from Pavonis Mons to the SW of Ascraeus, and G) CTX image of the Mottled Plains unit.

4.1.4. Crater Units

The Crater Units include an impact Crater Interior unit (raised rim) and the Ejecta Blanket unit. The Crater Interior unit is a circular depression that displays a topographic rim including floor materials. Crater Interiors are mapped when exceeding 5 km in diameter. The Crater Ejecta unit displays a rough texture, sometimes appearing etched with linear to sinuous elongate depressions and surrounds a Crater Interior. At this scale, the Crater Ejecta unit is only mapped where continuous and isolated patches are not differentiated, or where a large number of secondary craters have altered the pre-existing surface (Ejecta from Poynting Crater).

Crater Units are described below:

-Acc- Crater interior- Description: Circular depressions that display a topographic rim including floor materials. Depressions are mapped when exceeding 5 km in diameter. Crater rims are positive features, some crater floors have been filled with younger lavas only exposing the rime of the crater. Several larger craters, located on the East flank of AM, have central peaks. Not all craters are associated with ejecta. Interpretation: Interpreted as depressions formed via impact of a bolide.

-Ace- Crater ejecta- Description: A rough texture at the 100s of meters to kilometer scale, sometimes appearing etched with linear to sinuous elongate depressions. Surrounds crater interior unit. Interpretation: Interpreted as ejected material produced during an impact event that produced the interior unit. This unit is always found in association with the crater interior unit. Some ejecta appears to have a “rampart” appearance while other crater ejecta blankets the surrounding area. A large portion of the SW corner of the map has been marked with crater ejecta from Poynting Crater. This area has been mapped becasue of the high amount of secondaries that hit the surrounding area causing for a sever surface change in the pre-existing units. Type examples of the Crater units are shown in Figure 6.

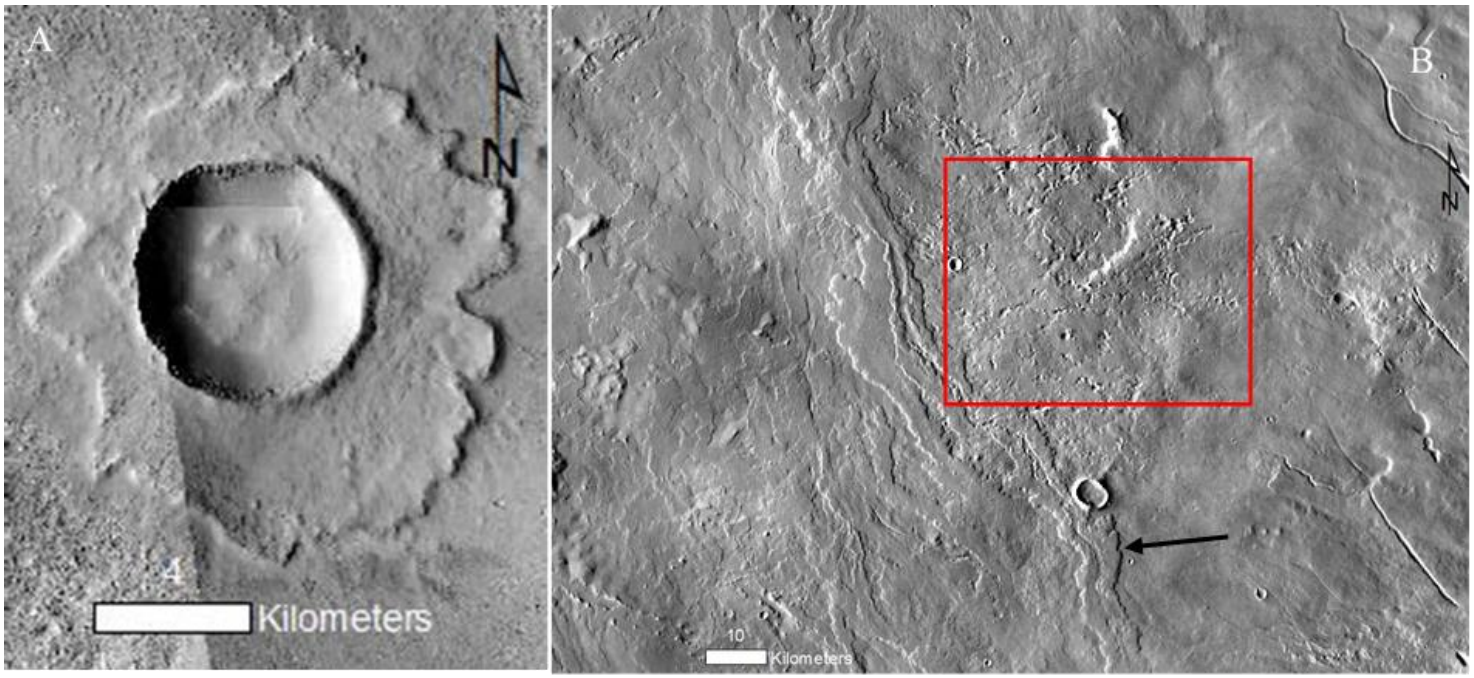


Figure 6. Examples of impact craters and ejecta found on the map. A) CTX image of a typical impact crater with a rampart ejecta flow surrounding the crater making up the Crater and Crater Ejecta units. B) Depicts a THEMIS Day IR Mosaic showing secondary impact craters that have altered the previous surface (inside red box). Note the young Plains Channeled flow unit has no secondary craters on it (center of image mared with arrow) as well as the Plains Channeled flows flowing around ejected blocks (bottom left of image).

4.2 Caldera Complex

Just south of the highest point of Ascraeus Mons is series of collapsed craters comprising the caldera complex. Unlike Arsia and Pavonis, each only having 1-2 calderas at their summits, Ascraeus Mons' summit has several collapse events similar to Olympus Mons. Stratigraphic relations and crater counting techniques have been done by previous studies [*Mouginis-Mark*, 1981; *Scott and Wilson*, 2000]. None of the earlier studies come to an agreement with the order of caldera collapses nor how many collapse events there have been. Previous studies used Viking and HRSC imagery to map and date the summit caldera complex. In this study CTX images were used to create a stratigraphic relationship among the calderas. Nine definitive collapse events occurred at the summit of Ascraeus Mons, with the potential for more.

The youngest collapse feature is the largest and deepest caldera in the center of the complex. This agrees with *Mouginis-Mark* [1981] and the crater counting ages by Robbins et al., [2011], but contradicts the findings of *Scott and Wilson* [2000]. *Scott and Wilson* [2000] argue using a Viking Orbiter mosaic that you can see a clear lava flow veneer, originating from the two SE calderas, obscuring the fault zone within the large collapsed crater. Using higher resolution CTX and HRSC images, no distinct lava flows can be seen from the two collapsed calderas on the SE of the summit complex. A shallow slope of debris (outlined in red) can be seen entering the lower, youngest, crater and is assumed to be floor and wall material from the two SE calderas and is shown in Figure 7.

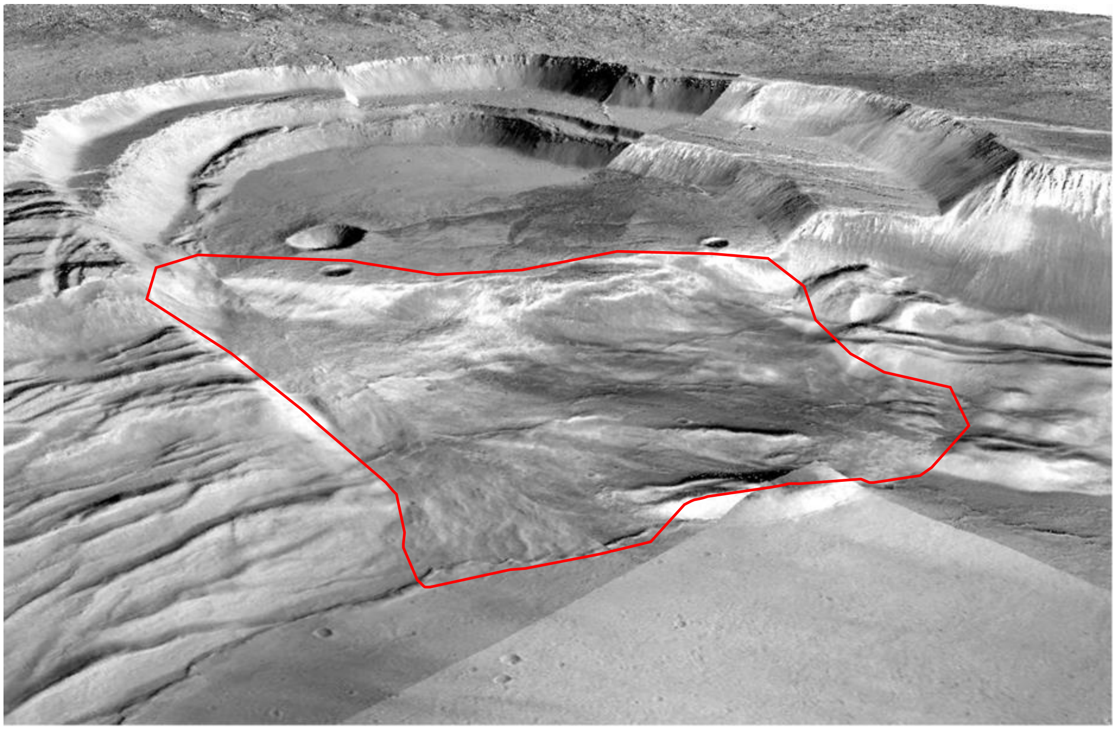


Figure 7. Perspective view looking SE at the SE calderas of Ascraeus Mons using a CTX mosaic and a HRSC DTM. The large impact crater within the smaller caldera is 1.5 km for scale with no vertical exaggeration. The height from the floor of the lowest caldera in the foreground to the small SE caldera floor is 1.4 km. Notice the shallow sloped debris from the SE calderas, using CTX and HiRISE images no lava flows can be seen, this slope of material is believed to be debris from the collapse of the youngest central crater.

The caldera floors are relatively smooth. Several of the caldera floor exhibit wrinkle ridges and appear to have once had a ponded lava lake. The youngest caldera floor, the central crater, has several wrinkle ridges and slumped blocks of material that have fallen from the crater walls, or previous craters floors. The walls of the caldera craters have several different features. The northern and southern walls of the central caldera have fluted features and are crisp and steep, while the eastern and western walls are heavily faulted and have much shallower slopes.

Flows that are truncated by the calderas do not appear to be sourced from either of the present craters, suggesting such flows are from a previous vent or caldera that is no longer visible. A thin veneer of flows can be seen on the northern summit, believed to be spillage of the caldera. This thin veneer is mantled by ash, dust, or volatiles and is difficult to make out flow margins.

The caldera sequence shown in Figure 8, was mapped by looking at stratigraphic relationships of each collapsed caldera. The first collapse event was the NE caldera, followed by a smaller diameter collapse in the same crater. The next two caldera collapse events were also in the same area, marked 3a and 3b, these collapse events are difficult to determine which event occurred first, becasue of the subsequent faulting that occurred later. The west caldera collapsed which was followed by the NW caldera. The two calderas on the SE collapsed next with the larger diameter crater predating the smaller crater. The final collapse was of the large central caldera. There is slight evidence to show there may have been two collapses in this central caldera. More work needs to go into investigating how many collapse events the central caldera has undergone.

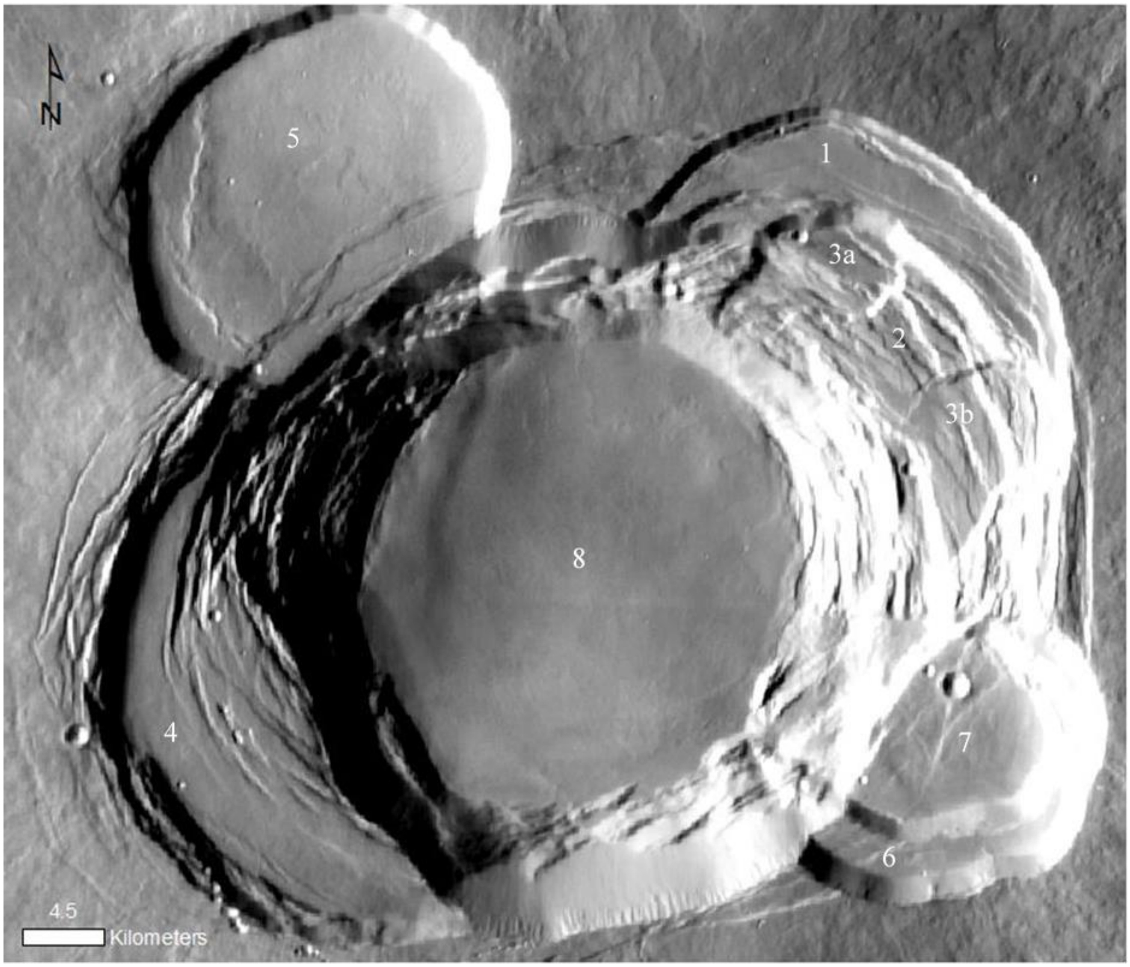


Figure 8. THEMIS Day IR Mosaic of the summit caldera complex of AM. The numbers indicate the sequence of collapse events based on stratigraphic relationships. 1 is the oldest and 8 is the youngest. There are a total of 9 definitive collapse events with the 3rd event split into two events.

Current tectonics of the summit calderas include recent geological faulting. Circumferential graben are located surround the NW, N, and E calderas. The graben on the eastern summit clearly crosscut large channelized flows. The bulk of faulting has lead to terrace walls on the eastern and western walls of the central caldera. The western wall has a jumbled pattern, while the eastern wall has nicely stepped features.

4.3 Main Shield

The main shield (labeled as *Flank* in the legend and *Units* section) has been divided into 9 different units which includes the large summit caldera complex, collapsed features, such as depressions, channel-fed flows, raised ridges, impact crater cavities, and crater ejecta. The flanks of the shield are dominated by a mottled (Afm) unit surrounding the caldera and channel-fed flows (Afch), which cover most the main shield. The mottled unit is typified by a rough surface thought to be covered by dust, ash, or volatiles making it difficult to determine distinct surface features [*Bleacher* et al., 2007a; *Bleacher* et al., 2007b]. This unit is mainly observed at the summit of AM and on the western flank.

The western flank of AM is more degraded than the other flanks. This degradation begins at the summit and is observed as far as 77 km down the western flank. This mottled unit has covered or altered pre-existing flows and structures, rendering any contacts for different units almost indistinguishable, at the 1: 1,000,000 mapping scale. Higher resolution CTX images show a very rough, pitted, surface texture. The pits in this area are not irregular with no raised rims and are not interpreted as secondaries, however some secondary impact craters are observed. The western flank has been suggested to have undergone higher atmospheric precipitation, contributing to the formation of glaciers, possibly altering the surface [*Forget* et al., 2006]. Another possibility for the large Afm unit on the western flank could be becasue of a preferential wind at the time of an eruption where a plume deposited more material down the western flank becasue of a westwardly wind. It could also be a combination of the two processes, where added volatiles from the venting of the erupting plume where precipitated out and preferentially deposited on the western flank becasue of a westwardly wind. While either option is viable, a more in depth study should be done of the region.

A relatively sharp transition occurs from the mottled (Afm) unit to channel-fed flows unit (Afch) ~77 kilometers down the western flank. Channel-fed flows are distinguished by subparallel linear channels often displaying levees [*Bleacher* et al., 2007a; *Bleacher* et al., 2007b] and is discussed in greater detail in the *Units* section. This abrupt change in lava flow morphologies occurs where the general slope of the western flank increases from 2.82^o to 8.16^o, trekking from the summit to the base. Breakouts from lava tubes are the primary source for these channel-fed flows. A transition from tube-fed to channel-fed flows is common on all flanks because of changes in slope further down the flanks as well as the changes in lava properties as flows begin to cool and crystalize [*Bleacher* et al., 2007a and references therein].

Lava fans and raised ridges are less common on the western flank, this is most likely because of the obscuring of the mottled unit dominantly found on the upper flank. The lava fan and raised ridge units mapped on the western flank were determined by looking at the THEMIS daytime IR mosaic, the lower resolution of the THEMIS camera allows to see larger structures in greater detail. Areas of interest in the THEMIS mosaic were then analyzed in the CTX and HRSC images to confirm lava fans and raised ridges were observed. There are other candidates for raised ridges and lava fans in the mottled unit, however they are not discernable at the 1:1,000,000 mapping scale. The lava fans and raised ridges mapped on the west flank smooth to mottled look, as well as steeper contact margins compared to similar features seen on the other flanks. The units appear to have an erosional look to them, especially on the margins of the raised ridges. The elevated surfaces of these units tend to look smooth to mottled in texture, this is assumed to be dust and other volatiles that are currently being deposited by aeolian processes and covering the pre-existing flows. These flows were deposited and then later altered by a period of high atmospheric precipitation as suggested by *Forget* et al., [2006]. Today the surface is altered by winds blowing dust and other particles onto the surface, giving the surface its smooth and dusty nature.

The base of the western flank is extremely modified. Steep cliffs separate the Scarp Etched unit (AHse) from the Scarp Hummocky unit (AHsh). The scarps separating the two units are ~350 meters high and ~25^o steep. The smoother Hummocky unit has an average slope of 2.5^o and is similar to the Stepped Scarp unit defined by *Bleacher* et al., (in preparation) for Olympus Mons, however there is no stepping pattern progressing downslope. The Scarp Etched unit mapped on Ascraeus Mons is similar to the Ravine unit defined by *Bleacher* et al., [in preparation] for Olympus Mons, however there is no valley-like ravines found on AM, except for the main scarp that delineates the Scarp Etched unit from the Scarp Hummocky unit on AM. The Etched unit is steeper than the Scarp Hummocky unit (7-25 degrees) and has an etched morphology. The Scarp

Hummocky unit often separates the other scarp units from the Main Flank Units. The Knobby unit (AHk) is a rough and hilly terrain on the scale of 100s meters to kilometers.

The north flank of AM exhibits the longest lava flows and coincidently is the longest of the flanks at ~260 kilometers and an average slope of ~3^{o}. The north flank, while exhibiting the longest flank flows on AM, also has fewer Raised-ridges and lava fans. *Byrne* et al., [2009] mapped flank terraces across Ascraeus Mons and concluded them to be compressional features becasue of lithospheric flexure. Mapped terraces are more prominent on the NW and SE flanks with fewer on the NE and SW flanks due to the formation of the NE/SW rift aprons [*Byrne* et al., 2009; *Byrne* et al., 2012]. While the northern flank has been mapped with several flank terraces, the terraces a further spread apart than the other flanks, thus allows for longer lava flows on the northern flank without a significant change in slope to disrupt the lava flows. Channel-fed (Afch) and Raised-ridge flows (Afrsm) begin ~35 km downslope from the caldera summit. The north flank is dominated by Channel-fed flows, as with all the flanks of AM, however the flows on the northern flank begin to change direction from a northern direction to a northwestern flow direction ~125 km down the northern flank. This change in flow direction is becasue of the topography of the northern flank. There is a distinct slope change in topography from north to northwest or northeast. Collapsed features such as, collapsed lava tubes, pit chains, and lava channels also follow this slope change in topology and is clearly noticeable on the map. All flows near the NE rift apron flow toward the northeast and flows that are just west or southwest of the NE rift apron flow to the northwest. A large channel system exists on the NW flank that has extruded a large amount of material onto the NW plains of AM. This area is under consideration for a potential failed third rift apron on AM. Further study of this area needs to be done to confirm this assumption.

Raised-ridges are prominently observed on the northeast flank and has the highest amount of channel-fed flows from said raised ridges (Afrsc). This is associated with the fewer amount of flank terraces on the NE flank [*Byrne* et al., 2009], not allowing for a significant change in slope to disrupt lava tubes and form lava fan. As the Raised-ridges form, they can create breakout of lava flows that flow down the slope of the ridge allowing for channel-fed flows to form and continue down the flank of AM.

The east flank of AM has many Raised-ridges radiating down slope away from the summit. The Mottled unit (Afm) at the summit is similar to the Mottled unit observed on the western flank, however the surface of the east flank is less degraded, where contacts between units and structures are easily discernable.

Large channel-fed flows are easily observed in THEMIS, CTX, HRSC, and HiRISE images on the east flank. These large channel-fed flows reach distances of 40 kilometers down slope vary in width from 500-2,000 meters and thicknesses of 4-25 meters [*Hiesinger* et al., 2007]. *Hiesinger* et al., [2007] mapped 25 of these larger, younger lava flows using early HRSC, THEMIS, and MOLA data. Basaltic to andesitic yield strengths were calculated (~1.4 x 10^3- ~5.1 x 10^4 Pa) comparable to basaltic a'a flows observed on Earth [*Hiesinger* et al., 2007 and references therein] and were likely emplaced within a few days to months. Several of these large channel-fed flows are truncated by the collapse of the NE caldera and are cut by concentric graben just east of the NE caldera as well. This suggests that these large channel-fed flows predate the collapse of the NE caldera.

The summit of the east flank also exhibits a thin sheet-like channel flow on the northeast of the NE caldera, which is interpreted to be spillage of lava from the caldera that is similar to flows that have been observed on Kilauea, Hawaii [*Bleacher* et al., 2007b and references therein].

The Mottled unit reaches distances of ~70 km downslope, however covers a smaller area than observed on the west flank, as stated above. The Mottled unit on the east flank does not appear to embay the larger, more pronounced channel-fed flows, suggesting that the Mottled unit is older than the large channel-fed flows. This only holds true further down slope; the Mottled unit tends to obscure and mantle channel-fed flows at the summit <10 kilometers from the caldera complex. This result suggests that later stage mantling of dust, volatiles, and ash has covered these larger channel-fed flows and provides further evidence of a more explosive style of eruptions towards the later stages in Ascraeus Mons history. Another process for the mantling near the summit could be generated by the collapse of the caldera complex.

Raised-ridge units are cut by lava fans that generally coincide with where a terrace is located on the east flank. Many of these lava fans lead to one or multiple other raised-ridges further down slope, which are then again disrupted by a flank terrace and produce one or multiple lava fan units. Some of these ridged units can be observed as long, possibly, continuous flows that evolve as they reach further distances from the summit caldera complex.

Bleacher et al. [2007a] mapped a thin N/S strip of Ascraeus Mons, investigating how the morphology of lava flows change the further the flows are from the summit caldera complex. They found that whereas no channel-fed flows completely cover Ridge units, but there is a transition from earlier stage long-lasting tube-fed eruptions to later stage channel-fed eruptions. This holds true for the east and west flanks, which were not mapped in the previous study. Channel-fed flows are observed embaying Ridged and Fan sourced units.

All flows at the base of the east flank are embayed by large flows originating from the NE or SW rift aprons. Superposition states that the embayed flank flows are older than the younger apron flows. By the same relative age method as above, even younger flows are observed emanating from channels at the base of the east flank.

The south flank of Ascraeus Mons has large, young channel-fed flows reaching distances ~40 kilometers and were included in the study by *Hiesinger* et al. [2007]. Several of these large channel-fed flows are truncated by the SE caldera at the summit. The Mottled unit has an older relative age distally from the caldera complex and overlaps or merges with the younger channel-fed units near the summit.

The SE and NW flanks have the highest concentration of Lava Fan and Ridge units, which coincides with the higher concentration of flank terraces [*Byrne* et al., 2009]. This SE/NW orientation also coincides with the low shield units located off the base of AM to the southeast and northwest. The concentration of low shields may be the result of dikes being diverted becasue of the extra mass of thrusted material creating the flank terraces.

The southwest flank is dominated by channel-fed flows, very few raised-ridges are observed and almost no fan units have been identified. There are fewer flank terraces, which has been determined to be a result of the SW rift apron [Byrne et al., 2009]. The lower abundance of Ridge units is concerning, perhaps they have been obscured by similar processes on the west flank? CTX and HRSC image quality of this region is poorer and may have rendered finding these features more difficult. This portion of AM has a larger number of wind streaks and has a dustier surface appearance than the rest of the volcano. To the SW of AM is Poynting Crater, a large impact crater with a diameter of 70 kilometers and impact ejecta that extends 100s km, covering most of the SW Plains and Apron units (Muted units). This ejecta material may have been carried by winds and deposited on the SW flank of AM, mantling and obscuring units and features.

4.4 Rift Aprons

Ascraeus Mons has two large rift aprons on the NE and SW flanks (see map Figure 2) and are the main source for the large amount of lava flows seen on the plains surrounding AM. These apron flows have been divided into 4 different units: channeled (Aach), muted (Aam), smooth (Aas), smooth-platy (Aasp), and ridged (Aarm). Many of these units have facies changes, but have been lumped together for the mapping scale. For more detailed descriptions, see *4.1 Unit Descriptions* section.

Bleacher et al. [2007a] calculated previous estimates of how much material was extruded from the rift aprons of the Tharsis Montes, the estimated volumes decrease from Arsia to Ascraeus ~7×10^{14} to ~9×10^{13} m^3 (respectively). They also suggest that there was a hiatus period between the main shield forming phase and the emplacement of the rift apron flows that contradicts *Crumpler and Aubele* [1978] where both the main shield and rift aprons were emplaced concurrently. I find that nowhere around the main shield and within the collapsed terrain do I see embayment of flank flows over apron flows nor within the collapse terrain, suggesting that volcanism from the main shield formation had ceased, at least distally from the caldera complex before emplacement of rift apron flows and the collapse terrain, agreeing with *Bleacher* et al. [2007b].

The NE rift apron is dominated by ridged flows and channeled flows. Superposition of the ridged and channeled flows is difficult to determine due both flow types embaying one another. Channeled flows tend to be more common distally from the NE flank of AM, where the slope of the rift apron increases. These channeled flows transition to large tabular flows where the slope of the surrounding plains is less than 1 degree (outside map boundary). Ridge flows from the rift aprons are 10s m to 100s m in height and can be traced for 100s km. Ridged flows generally transition to channeled flows that embay other ridged flows suggesting that both flow types were emplaced concurrently.

NE rift apron flows follow the topography of the apron, flows at the center of the apron flow NE, flows on the west side of the apron flow NW-W, and flows that are on the east side of the apron flow NE-SE. The flows that follow the NW-W trend begin as ridged flows and transition to channeled flows where there is a sudden break in slope or a sudden outpouring from a vent located on the ridged flow. Flows to the far west of the NE rift apron transition to smooth-platy flows where there is essentially no slope $<1^{o}$, this also occurs to the SE side of the rift apron. The smooth-platy flows dominate the N-NW plains surrounding the NW flank of AM. Some structures are can be seen in the THEMIS mosaic, however at higher resolution these structures are distinguishable as small channeled and tabular flows, however these are too small to be mapped at the 1:1,000,000 mapping scale and have been lumped into the smooth-platy flow unit. Smooth-platy flow margins are uneasy to map becasue of their platy nature making a single flow unit look like multiply flows. The SE side of the NE rift apron began as ridged flows and transitioned to smooth-platy flows with less channeled flows present. Channeled flows can be observed at higher resolution than the mapping scale. The flows oriented to the S-SE embay low shield units off the base of the east flank of AM. Flows from the NE rift apron are separated from flows from the SW rift apron by a cluster of low shields present on the eastern plains (within the map boundary). Several other low shields are present east of the map boundary. Further east of these low shields ~135 km from the eastern flank of AM, the NE and SW rift apron flows coalesce. Both rift apron flows can be traced for 100s km to the NE. THEMIS and CTX imagery shows SW rift apron flows embaying NE rift apron flows, suggesting the SW apron flows are younger, or perhaps erupted for a longer period. This also could be a local bias, as the SW apron flow, which embays the NE apron flows, may be the last flow for that region, still allowing for both apron flows to have been emplaced simultaneously, but in different areas.

The morphology of ridged flows change within the NE apron, three different surface textures have been observed, a smooth ridge, a mottled ridge, and a smooth-platy ridge. Because mapping all of these features at this map scale would have made the map too cluttered, all apron ridge units have been lumped together in the final printed version. A more detailed map can be seen in the Appendix where these units are not lumped together. The smooth-ridge flows are most prominent in the NE rift apron. These flows are relatively long flows with a raised center, some exhibiting a collapsed tube at the center, with small breakout flows down the sides of the ridge. The mottled-ridge flows have a rugged texture, containing chains of mounds interpreted as potential rootless vents having explosively erupted and mantling the ridge with ash and other volatiles. Many of these mounds have similar characteristics to small cinder cones found on Earth. The smooth-ridge has been observed transitioning into a mottled-ridge suggesting a change in the lava properties distally from the apron.

The smooth-platy-ridged flows occur at very low slopes $<1.5^{o}$. Similar flows have been found and observed at Kilauea, Hawaii by *Orr* et al. [2014], southwest of Arsia Mons, Mars by *Crown* and *Ramsey* [2016], and in the Eastern Tharsis Plains of Mars by *Bleacher* et al. [2016]. These flows are generated by the inflation of an active lava tube creating a sinuous tumulus, or sinuous ridge, that have breakout flow lobes becasue of over pressure of the underlying lava [*Orr* et al., 2015]. Only a few of these flows are observed on the NW rift apron, but are very common on the SE corner of the map (within the map boundary) from the SW rift apron where slopes transition to $<1^{o}$. Typically, this type of ridged flow begins as a smooth-ridged and transitions to a smooth-platy ridged flow, a good example of this is in the SE plains of the map

All apron ridged flow types are seen transitioning into channeled flows, some channeled flows are upwards of 150 km and extend off the map boundary, while other channeled flows are 10s km. There is no obvious correlation to the type of apron ridged flow with the total volume of channeled flows associated with it. Further study should be done at greater detail and may perhaps be able to shed light on relative ages of the different morphological types of ridges found in the rift aprons.

Collapsed terrain located at the base of the east flank has younger smooth and smooth-platy ridged flows overlying main apron flows from the NE rift apron. Potentially being a last gulp of eruptions from the apron magma source, located near AM.

5 Geologic History

Mapping of Ascraeus Mons has led to a new understanding of how complex the history of this large shield, and the other Tharsis Montes, formed. Observed changes in lava flow morphologies across the main shield, rift aprons, and the surrounding plains provided clues to determine different lava flows and eruption styles to create stratigraphic correlations among the mapped geologic units defined in this study.

The main shield of Ascraeus Mons formed by overlapping lava flows, both tube-fed and channel-fed. Mapping shows that tube-fed and channel-fed flows erupted concurrently. Changes in the magma properties caused the eruption style to transition from tube-fed flows to a more dominant channel-fed flows at the later stages of shield development. Flank channel flows (Afch) dominate the flanks of AM (see map Figure 1). Channel flows have been observed embaying all features on the main shield, except for the more recent tectonic features such as collapse features and graben, and current aeolian features. While channel flows do not completely cover ridge features, they can be seen embaying the sides of ridges. No flows can be found draping or filling any collapse features on the main shield. This suggests that all tectonic features are younger than flank flows and that eruptions may have ceased shortly before their formation. However, there is the possibility that tectonic features and eruptions occurred concurrently, while AM was in a later stage and less volcanically active. However, superposition relations still support tectonic activity that post-date eruptions.

Many fan features are located where flank terraces are observed, and are thought to form because of the sudden change in slope allowing for an outpouring of lava from a pre-existing tube or channel. It should be noted that not all fans are observed with a definitive channel or tube, these pre-existing tubes or channels may have been buried by later eruptions. Flank terraces have been previously described as extensional and compressional features; the most recent study states these features to be compression becasue of flexure of the underlying lithosphere [*Byrne* et al., 2009; 2012]. This interpretation suggests the development of flank terraces occurred during the main shield building phase. Some terraces mapped by *Byrne* et al., [2012] are not accompanied by fan features or changes in flow type, suggesting the process for generating flank terraces continued after volcanism ceased on the main shield.

The flanks of AM are embayed by rift apron flows that surround the volcano. This study agrees with *Bleacher* et al., [2007a] in that no flank flows have been observed overlying or entering any collapsed channels on the main flanks or near the rift aprons. Superposition relations with the embaying of rift apron flows over flank flows and the lack of flank flows in collapsed channels dictates that apron flows are younger than the main shield building phase. The lack of any interlayering of flank flows with the collapsed terrains allows for the assumption that the main shield building phase had stopped before the emplacement of apron flows.

A massive volume of material was emplaced via Ascraeus Mons' rift aprons. Apron flows follow the topography of the plains and lava flow types change accordingly. Ridge and channeled flows emplaced by the rift aprons are interbedded and does not allow for a great understanding for relative ages of these flows. Lava flows from the rift aprons are much larger than their counterparts on the flanks. Apron flows have been mapped for >100 km and continue off the mapping area towards the N/NE. The general trend of flows from the aprons begin as ridged flows which then transition to channeled flows and/or smooth-platy flows, dependent on the topography of the terrain. Steeper slopes will tend to generate channeled flows while slopes <1 degree will generate smooth-platy flows. Most ridged flows can be traced back to a collapsed channel along the main rifting zones of AM. Channels and smooth-platy flows do not tend to be sourced directly from these collapsed channels and originate specifically from the ridged flows showing a change in lava properties as the flows travel further distances. These changes in the lava can occur becasue of cooling properties of the flows and/or loss or addition of volatiles in the flows. These smooth-platy flows are also observed as break out flows from sinuous ridges. Such sinuous ridges resemble an inverted channel and have been observed on Kilauea, Hawaii by *Orr* et al., [2015].

The SE rift apron flows generally begin flowing S-SE and then flow north, following the pre-existing topography, or perhaps depressions on the plains becasue of the compression and flexure of the underlying lithosphere creating topographic lows. Apron Muted flows, located off the SW flank of AM, are stratigraphically younger than Flank flow, but older than the Aureole and Plains units, based on superposition. The muted appearance of these flows is believed to be dust accumulated by aeolian processes that mantled the pre-existing channeled and ridged flows. This extra layer of dust seems to be becasue of the large impact crater, Poynting Crater, to the southwest of Ascraeus Mons. Impact ejecta and secondaries are observed on the Plains, Apron, and Flank units. Intermingling of Apron channeled flows are observed in the continuous ejecta blanket on the SW corner of the map. The Apron channeled flows can be seen embaying and flowing around displaced blocks from the impact event, suggesting the impact predates these channeled flows.

Plains units are found on top of Apron units except for the Fissure and Low Shield units. Low Shields are observed being embayed and almost buried by apron flows. This relationship however does not rule out whether the Low Shields and Apron flows where emplaced concurrently. The Apron flows most likely erupted for a longer period of time allowing for flows to embay the flanks of the Low Shield unit. Plains Fissure eruptions are observed on the Plains Mottled and Apron smooth-platy units. Fissure units are superposed by the Plains Channeled and Tabular units and were emplaced just before or at the same time as the Low Shield unit.

The Plains Mottled, Tabular, and Channeled units are observed to be the youngest units in the area and are located on the West side of the mapping area. Plains Tabular and Mottled flows do not originate from AM. The Tabular flows superpose the Mottled flows and appear to originate from vents North of Pavonis Mons. Both the Mottled and Tabular flows have secondary impacts from Poynting Crater. The large Tabular flows are disrupted by Poynting Crater itself. This suggests that the Tabular flows were emplaced before the impact occurred. The Plains Channeled unit, located to the East of Poynting Crater, has no secondary impacts or ejecta from the large impact event. The nearly 700 km long Channeled flow appears to be the youngest lava flow in the mapping area and puts the impact of Poynting Crater between the emplacement of the large Tabular flows from Pavonis and the emplacement of the Plains Channeled unit.

Scarp units are located at the W-NW base of AM and are associated with the Aureole unit. The long arcuate ridges at the western edge of the Aureole unit overlap the Apron Muted unit, as can be seen in Figure 9. The Knobby unit has been modified by the Aureole unit, and was emplaced while ice was present on the surface. The Knobby unit

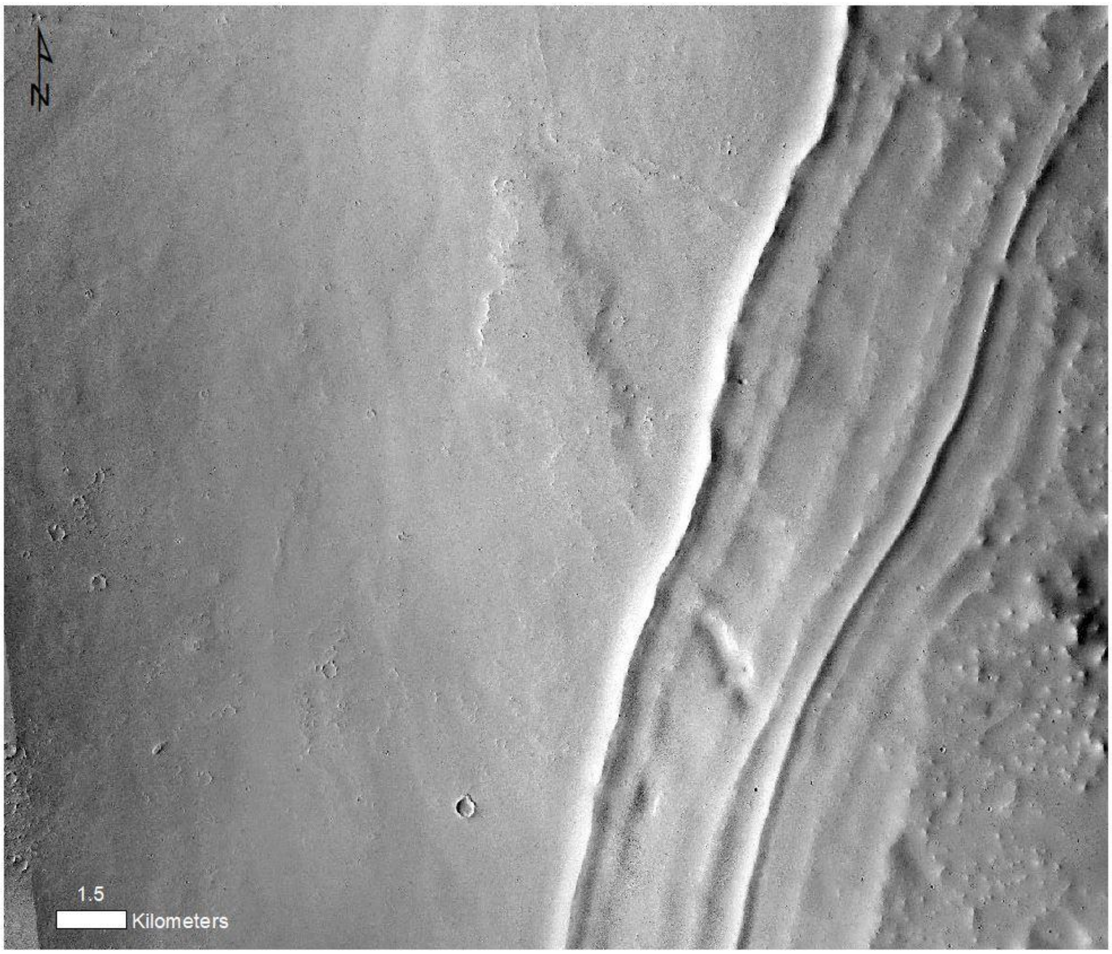


Figure 9. CTX image displaying the Apron Muted unit with Aureole ridges overtop of it. This contact relationship shows the Aureole unit postdating the Muted unit.

is interpreted to be lava flows that were emplaced beneath a sheet of ice leaving behind a hilly/knobby surface. Evidence of the Knobby unit being emplaced while ice was present can be seen near the western part of the Aureole unit, east of the arcuate ridges. A portion of the Knobby flow parallels the ridges, has been severely modified, and underlies the arcuate ridges. Definitive evidence for the lava flows being emplaced beneath the ice sheet is seen at the toe of the Knobby unit where the flow disrupts the arcuate ridges, as seen in Figure 10. Had the ridges formed at later, after the flow was emplaced, the ridges would not be disrupted or altered, such as seen where ridges are present over the Muted units. This potentially displays evidence for multiple stages of glaciation or mass wasting. Inward of the paralleling Knobby flow is another set of ridges. These ridges appear to have a chaotic surface texture and suggests a mixture of debris flow and glacial processes carved the base of AM and part of the Knobby flows and transported material into the Aureole unit.

Figure 10. CTX image displaying disrupted arcuate ridges on the west side of the Aureole unit. The Knobby unit can be seen altering and breaking up the ridges that resemble glacial moraines found on Earth.

Tectonic and Aeolian features are presently altering the Ascraeus Mons surface and the surrounding plains. Concentric graben are located near the summit and at the base of AM. Continued faulting is causing parts of the caldera complex to collapse and form terraces at the summit. Graben at the base of AM form near the rift aprons and are exposed becasue of the extension from the overlying weight of AM. Large pit chains and pits are observed on the flanks of AM and also form circumferentially from the summit. These are believed to be collapses of void spaces below the surface of AM. Some pit chains, in smaller scales, do form radially and are usually associated with a lava tube or collapsing channel. Generally, found near the collapse terrain of the rift aprons. Several N/S oriented graben are present in the mapping area and appear to be extensions of the Ceraunius Fossae located to the North of Ascraeus Mons.

Dunes are observed within large channels. Wind streaks are dominantly present on the NW plains and have a NE orientation, suggesting a NE wind direction. Small yardang-like features are present on the NW Plains and Apron flows. These features are oriented to the NE, which does not match up to the wind direction shown by wind streaks.

Figure 11 displays the Correlation of Map Units, used to help understand how each unit relates to one another. Units are broken into 4 sections: Plains Assemblage, Scarp and Apron Assemblage, Crater Materials, and Flank Assemblage. Ages are in order of what is observed to be youngest to oldest from left to right in each section.

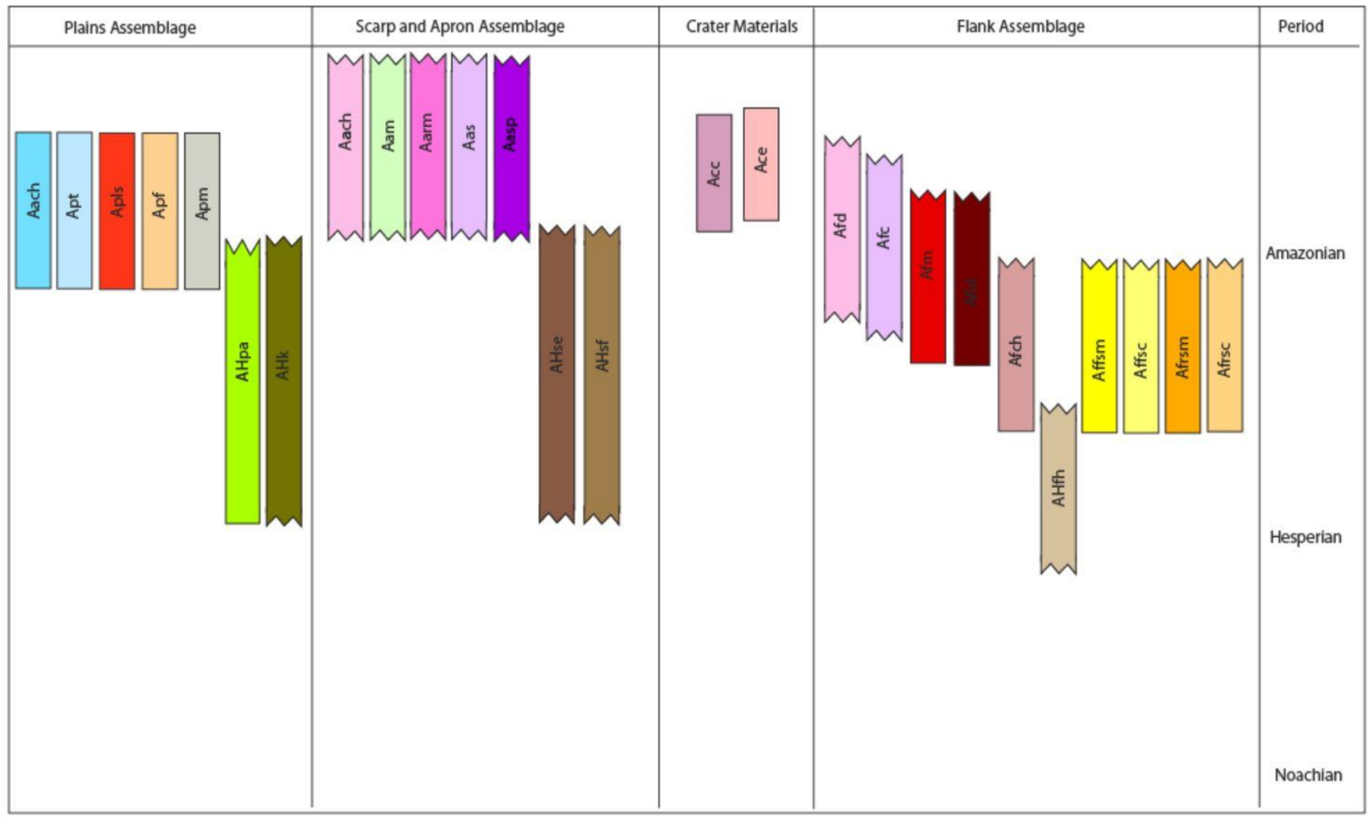


Figure 11. Correlation of Map Units for the Geologic Map of Ascraeus Mons. Units are broken into the same four sections found in the Results section.

6 Conclusion

Geologic mapping of Ascraeus Mons has revealed the dynamic and complex evolution of this large volcano. The overall main sequence of events has not changed from that first described by *Crumpler & Aubele* [1978] and modified by *Bleacher* et al., [2007a;b]: 1) main shield forms, 2) eruptions from the NE/SW rifts emplace long lava flows that surround main shield, 3) eruptions wane and build up the rift aprons and shield fields, 4) glaciers deposit aureole unit material, and 5) localized recent eruptions along the main flanks, in the calderas, the small-vent field, and possibly within the glacial aureole deposits. However, this study has shown in greater detail the different types of eruptive styles across the main shield, rift aprons, and the surrounding plains to better understand the history and evolution of the Tharsis rise. Different features on the flanks of AM show other processes were at work to help shape the main shield. The western flank, being more degraded, suggests the possibility of higher atmospheric precipitation altering the surface or the possibility of a preferential wind depositing a higher concentration of ash that geochemically altered the surface. The NW and SE flanks have a higher concentration of lava fans that correspond with the higher density of flank terraces suggesting the weight of the volcano is spreading in a NW/SE orientation, corresponding to the NE/SW rift zones. The preferential NW/SE orientation of low shields and fissures found on the plains may also be a result of the overlying stress of AM affecting pathways for subsurface dikes. These low shields and fissures are embayed by apron flows, suggesting they predate apron eruption, or ceased before emplacement of the apron was complete.

This study agrees with *Bleacher* et al., [2007a;b] that the early shield building phase was dominated by effusive lava flows, such as tube-fed flows and emplacement of ridged flows. Later stage eruptions had more viscous lava flows that developed leveed channels and subsequently dominated the flanks of Ascraeus Mons. Several small cinder cones are present on the flanks, suggesting there was a stage of localized explosive eruptions. These cinder cones are interpreted to be rootless cones and erupted before the latter stage of channeled flows occurred on the flanks.

The Aureole material shows large arcuate continuous ridges resembling glacial moraines found on Earth. This unit has several lava flow units that have been substantially altered by the possibility of lava/ice interaction. The knobby flows disrupt the arcuate ridges which suggests these flows were emplaced while ice was present at the surface. Parts of the knobby flows do show steep scarps with some material lost to the Aureole unit, leading to the interpretation that there were multiple glacial events that deposited the Aureole material.

This study has proven higher resolution data sets help us better understand processes that shaped other planetary bodies. These data sets enabled confirmation that eruptions across Ascraeus Mons and the surrounding plains evolved over time, originating with a less viscous more effusive eruption style to a more viscous less effusive eruption style. This is important for the future of planetary study because it helps provide a sense for mapping of future celestial objects in the Solar System and giving better insight to the evolution and development of these bodies.

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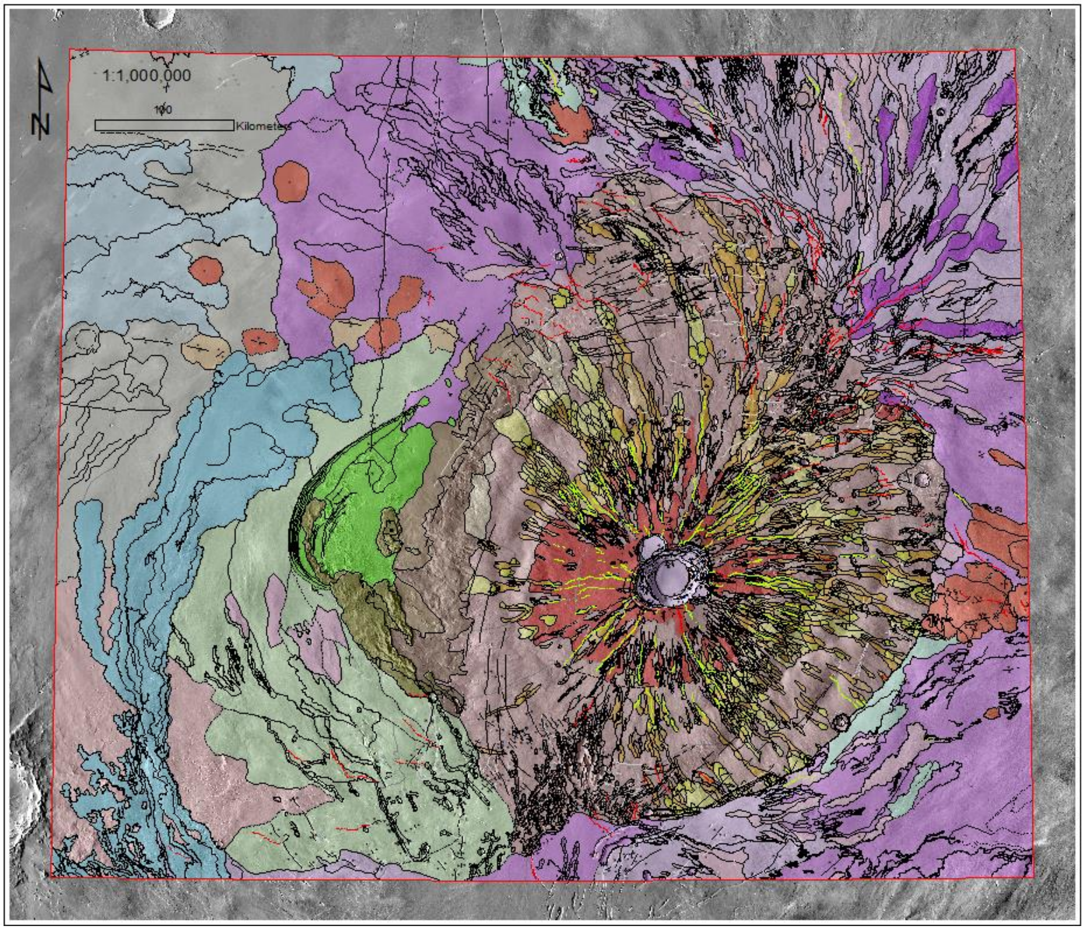
APPENDIX A

COMPLETED MAP DISPLAYING ALL LINEWORK AND UNITS.



Appendix A. Full line work and units from the study. Note that the units are the same as in Figure 2, but with the Apron Ridged units delineated. Apron Ridged Smooth in pink, Apron Ridged Mottled in purple, and Apron Ridged Smooth-platy in turquois.