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Hydrologic evolution of two Martian deltas in the Ismenius Cavus system

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ABSTRACT:

Ismenius Cavus (33.76° N, 17.05° W) is a large Martian basin that has been interpreted as an ancient paleolake. It is situated in the middle of the path Mamers Valles traces from the Cerulli Crater to the Borealis Basin. This ancient lake served as a key deposition area (or depocenter) for multiple lake chains originating in the southern highlands. The collected water was then transported downstream to the Borealis Basin. The ancient hydrologic activity of this zone is evidenced in the widespread appearance of valley networks and fretted channels, but especially in the presence of deltaic deposits converging in Ismenius Cavus. We made a hydrological and geomorphological analysis of two of these deltas, which compose a three-crater lake chain system. It was interpreted that both deltas, although being close to each other, were created by different processes and at different times. The Aracataca Delta was deposited during the Noachian by a valley network system. The Ariguani Delta, in turn, was the result of the discharge of a fretted channel carved by groundwater sapping. The transformations of the hydrologic systems in the Ismenius Cavus region were established by analyzing the change in the deltaic pulses over time. It was determined that the first hydrologic stage was dominated by widespread valley networks that probably represent subglacial hydrologic systems, a second stage started when these systems were replaced by groundwater activity; and finally, when the water sources were exhausted, a final stage of glacial processes prevailed until the present.

Keywords: Mars; planetary geomorphology; hydrology; cartography.

Evolución hidrológica de dos deltas Marcianos en la región de Ismenius Cavus

RESUMEN

Ismenius Cavus (33.76° N, 17.05° W) es una gran cuenca Marciana que ha sido interpretada como un antiguo paleo-lago. Está situada en la mitad del trayecto que recorre Mamers Valles desde el Cráter Ceruli hasta la Cuencas Borealis. Este antiguo lago sirvió como un punto importante de deposición (depocentro) para múltiples cadenas de lagos originados en las tierras altas al sur. El agua recolectada en este lugar era luego transportada hasta la Cuenca Borealis. Hay varias evidencias que demuestran la existencia de un antiguo sistema hídrico en la región, incluyendo la aparición continua de redes de drenaje y canales anchos, además de la presencia de deltas que desembocan en Ismenius Cavus. En este estudio realizamos un análisis hidrológico y geomorfológico de dos de estos deltas, los cuales hacen parte de un sistema lacustre de tres cráteres. Se encontró que a pesar de su cercanía, ambos deltas se formaron por procesos diferentes y en tiempos distintos. El Delta Aracataca se depositó durante el Noeico por un sistema de drenajes superficiales, mientras que el Delta Ariguani se formó por la descarga de un canal encañonado producto de la erosión de aguas subterráneas. La transformación de los sistemas hídricos de Ismenius Cavus fueron establecidos al analizar los cambios en los pulsos deltaicos a través del tiempo. Se encontró que una primera etapa estuvo dominada por redes de drenajes superficiales, probablemente provenientes de sistemas subglaciales; la segunda etapa comenzó cuando estos sistemas mermaron, siendo reemplazados por un dominio de aguas subterráneas; y finalmente, cuando las fuentes de agua se agotaron totalmente, una última etapa de procesos glaciares tomo lugar, la cual ha dominado la zona hasta hoy.

Palabras claves: Marte; geomorfología planetaria; hidrología; cartografía

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1. Introduction

The Mars northern dichotomy has always served as evidence for the wet past of the planet. Multiple landforms like valley networks, paleolakes, and fretted channels, point in this direction. Of special significance is the Borealis Basin, a massive depression that encompasses the north pole, which may have hosted an ancient ocean (Baker et al., 1991). Several fluvial systems occur across the limit between the Borealis Basin and higher lands, but deltaic features may be the most interesting and significant of them, as they require a constant flux of water and a deep reservoir to form. A total of 52 deltas have been observed on Mars (Di Achille & Hynek, 2010). This research analyzed two of those features associated with paleolakes located in the Ismenius Lacus quadrangle.

The two analyzed deltas are close to each other and were named informally during this investigation as the Aracataca Delta (34.31° N, 18.11° W) and the Ariguani Delta (33.93° N, 17.52° W). The basement of the region is heavily cratered and has been dated as late Noachian, around 3.88 Ga - 3.92 Ga (Benedix et al., 2020). Two features dominate the zone: Deuteronilus Mensae, an area made of ancient plateaus in the transition to the Borealis Basin; and Mamers Valles, a large canyon that crosses the entire zone (Figure 1). Within Mamers Valles lies Ismenius Cavus, a paleolake where the two studied deltas drained (Dehouck et al., 2010). Both features were first identified by Cabrol (1999), while Ori et al. (2000) made initial interpretations about its deltaic origin. The more recent and accurate HiRISE and HRSC data provided an opportunity to better analyze this complex system, which preserves the evolution of the hydrologic activity of the quadrangle.

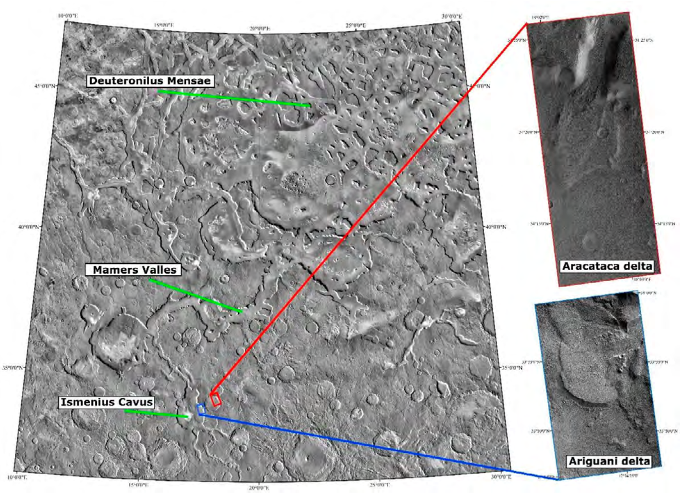


Figure 1. Location of the Aracataca and Ariguani deltas in the Ismenius Lacus quadrangle. The main landforms of the zone are indicated with green lines.

2. Data and Methods

The geomorphological analysis was made on three scales. At a regional scale, visible images of Viking with a resolution of 232 m/pixel, THEMIS daytime infrared with 100 m/pixel, and MOLA digital elevation model (DEM) with 463 m/pixel were used (Edwards et al., 2011). At the medium scale, HRSC multispectral images (takes: 5249 and 5267) with spatial resolution between 10 and 20 m/pixel and DEMs with 100 m/pixel were used (Geng et al., 2017). Finally, in the detailed scale, the two deltas were studied with two HiRISE datasets with a resolution of 50 cm/pixel (Aracataca Delta spotted by HiRISE product ESP_026915_2145 and Ariguani Delta by HiRISE product ESP_013531_2140).

The geomorphologic units defined in this work adhere to the criteria established by Tanaka et al. (2009) and Wilhems (1972). The defined bodies are discrete and follow the superposition principle and the crosscut laws. The name of the units is generally informal, but some names such as Ismenius Cavus, Borealis Basin, and Mamers Valles are official nomenclature. Geomorphological units were established at all scales, the identification criteria were texture, albedo, topography, color, stratigraphic relationships, drainage network, and surface morphology variation. At the local and detailed level, we also considered the morphogenesis of the units during the classification. The interpretation was made in the software ArcGIS 10.5.

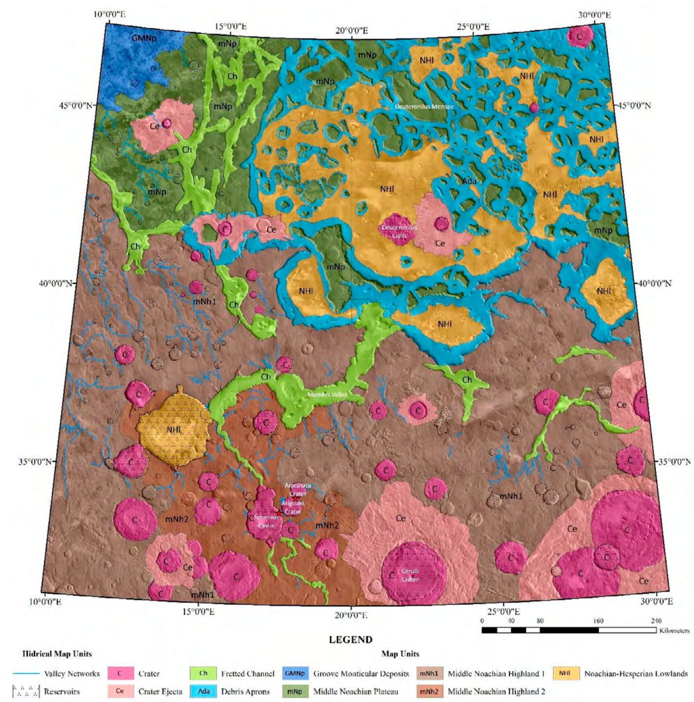


Figure 2. Regional geomorphological map of the study area. Valley networks are represented as blue lines and fretted channels as green polygons. The two red stars in the southwestern part show the location of the deltas inside Ismenius Cavus. The basemap was the THEMIS daytime infrared.

3. Results

The geomorphology of the zone, as well as other regions of similar latitudes, is the result of the activity of water and ice over the Martian history (Irwin, 2004; Alemanno et al., 2018; Chuang & Crown, 2009). Other landforms related to the influence of eolian activity are present to a lesser extent in the study area. To reconstruct the geological history of the region, it is crucial to determine which geologic processes were responsible for making the observed landforms, and how they evolved as the environmental conditions of the location changed. The influence of these forces and the changes they made over time can be traced at different scales. First, we made a regional description, then we focused on the Ismenius Cavus zone and the possible paleo-basins in it, and finally, we described the deltaic features inside the craters selected for this study. An extended version of the maps produced in this work at each scale is provided in the supplementary material.

3.1 Regional scale

The basement of the Ismenius Cavus quadrangle is made of Middle Noachian rocks (Benedix et al., 2020), most of which were modified by posterior geological processes. Preserved landforms of this age are found at the western margin of the region, north of the dichotomy. In this zone is present the *mNp* unit (Figure 2), which has been interpreted as large lava floods (Lucchitta, 1978; McGill, 2002) and is moderately dissected by valley networks and impact craters. The Deuteronilus Mensae zone is characterized by the presence of tall plateaus and knobs of the *mNp* unit, which are surrounded by homogeneous lowlands of the *NHl* unit (Figure 3a). It has been thought that this morphology was formed by the melting of ice trapped in aquifers and the subsequent collapse of topping layers (Zegers et al., 2010). However, the abundance of glacial deposits as those of the debris aprons (*Ada* unit) and the distance between plateaus indicate a subsequent fluvial and glacial transformation (Sinha & Murty, 2013).

South of the Borealis Basin domain, channels and lacustrine deposits are more common. In this zone, the basement is made of the *mNh1* and *mNh2* units. These units are similar to *mNp* to the north, but in this case, the plains are heavily dissected by valley networks and fretted channels, the major of them being Mamers Valles. The latter has a well-developed morphology of a fretted channel with a length of around 1000 km. It extends northwards, cutting the highlands, reaching the northern dichotomy, and disappearing inside Deuteronilus Mensae. Several moraine-like deposits were identified on top of the valley floors, similar to other martian locations (Chuang & Crown, 2009; Lucchitta, 1978).

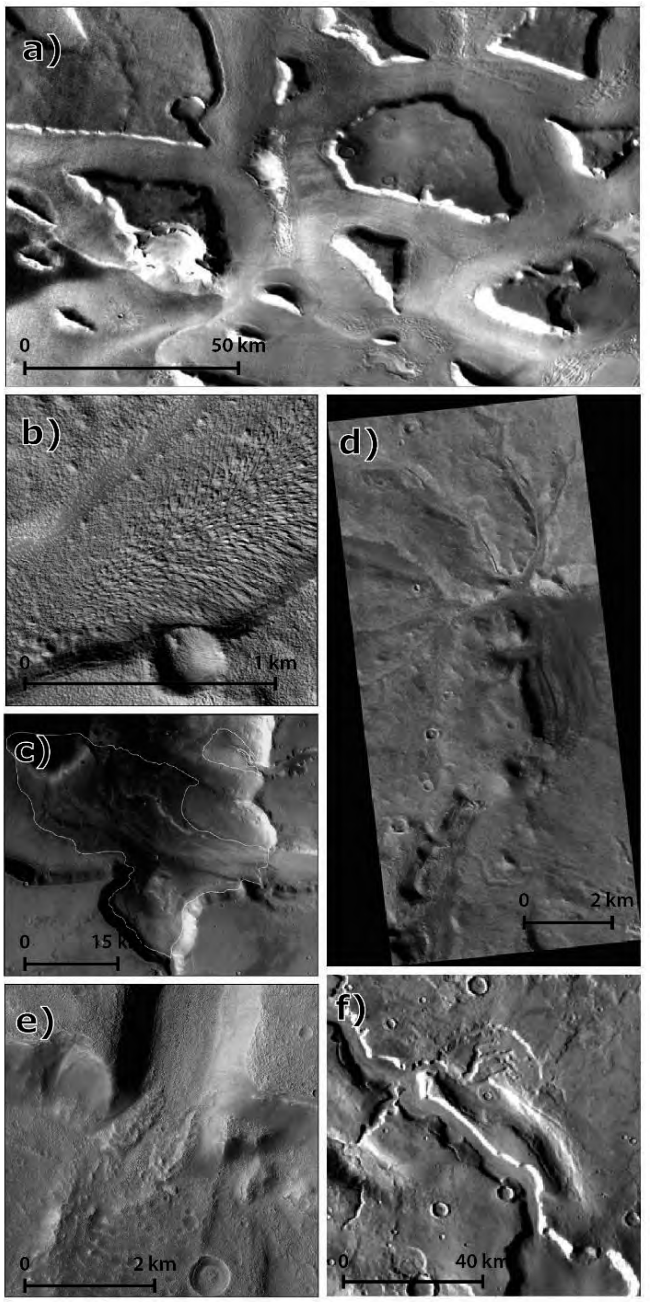


Figure 3: Several landforms representative of the zone. a) Plateau from the MNp units. b) Sublimation features showing glacier activity. c) Other deltas inside Ismenius Cavus and phyllosilicates deposits in black. d) Valley networks flowing towards Ariguani Crater. e) Moraine cutting the deposits of the Aracataca Crater. f) U valley cutting fretted channels.

3.2 Medium scale

Ismenius Cavus is located in the southern highlands of the study area, Mamers Valles crosses it, and it was a local depocenter of the surrounding areas (Figure 4). The zone is characterized by the presence of large impact craters, with nine of them exceeding 5 km in diameter, and almost all of them seem to have superimposed water activity.

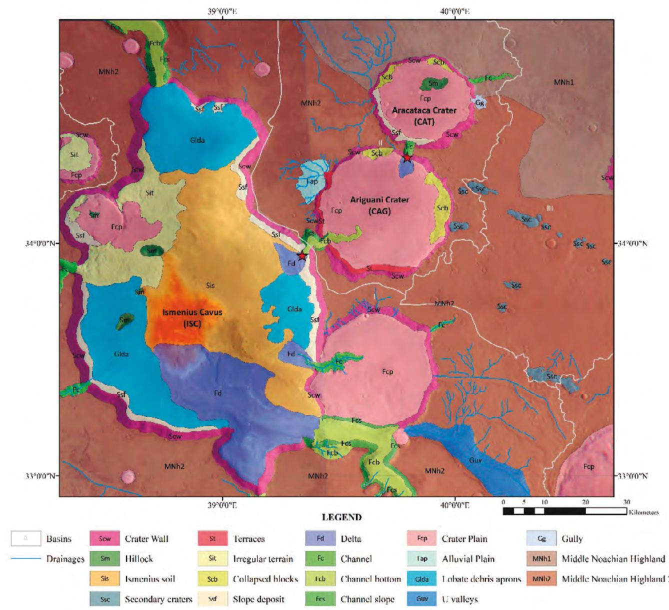


Figure 4: Geomorphological map of the area around Ismenius Cavus. Valley networks are represented as blue lines, fretted channels as green polygons, and basins are delimited by white lines. The two red stars show the location of the deltas inside the Ariguani and Aracataca craters. The basemap were HRSC takes 5249 and 5267.

Two types of hydrologic activity are recognized in the area: valley networks, related to fluvial action (Hoke et al., 2011), and fretted channels, associated with groundwater sapping (Goldspiel and Squyres, 2000). The valley networks are well developed and are highly integrated between them. However, the later action of meteoritic impacts, wind, and glaciers have modified them. Most of these features have a Middle Noachian maximum age according to the youngest geologic unit that they cut (Alemanno et al., 2018). On the other hand, the fretted channels are wide and poorly integrated valleys with a relatively straight morphology. Using cross-cutting relationships, we determined that these features were developed after the valley networks. Finally, there are glacial features that are coetaneous to previous structures, indicating that glaciers were involved at the different hydrologic stages of the region (Figure 3e).

Ismenius Cavus is the biggest and deepest depocenter in the region with 66.5 km in diameter and was analyzed in detail by Dehouck et al. (2010) as a paleolake. Besides the activity of Mamers Valles, features such as fretted channels, valley networks, phyllosilicates, and several deltaic structures have been interpreted inside it (Figure 3c), which attests to the fluvial and groundwater activity that modified this ancient crater. This structure, with the Aracataca and Ariguani craters, makes the three-crater lake-chain system that contains the target deltas of this study. The Aracataca and Ariguani craters measure 26 km and 34 km in diameter, respectively, with crater rims between 400 m and 600 m high. Several dendritic valley networks converge into those two craters, and big alluvial terraces fill both to their south margins (Figure 3d). To the southwest, both craters have openings in their rims, from which the two deltas formed.

At least two other deltas (*Fd* units in Figure 4) have been identified inside Ismenius Cavus (Leeder, 2011; Ori et al., 2000; Dehouck et al., 2010) and valley networks (*Fap* unit) are also common in the surrounding areas of the biggest craters. Furthermore, there are also fretted channels (*Fct* and *Fcf* units) that connect lake chains all over the region and are usually found surging from the Noachian plains. From this, we can tell that the backward erosion of valleys by groundwater sapping was widespread and intense in the region posterior to the formation of the valley networks, as fretted channels superimpose and cut the valley networks.

We observed debris aprons (*Glda* unit) in the floor of the channels, and U valleys (*Gvu* unit) cutting and being cut by channels (Figure 3f), which implies glacial activity was widespread across the zone (Koutnik et al., 2021). This setting points to a seasonal progradation and retreatment of glaciers over geological time, a phenomenon that has been observed in other Martian regions (Ori et al., 2000; Grau Galofre et al., 2020; Laskar et al., 2002; Head et al., 2003).

Due to the widespread presence of valley networks around Ismenius Cavus, we decided to reconstruct the limits of possible paleo-basins by adjusting manually the output of the Basin tool included in ArcGIS, using the topography and the mapped drainage (Figure 4). We identified four paleo-basins. Basin I is related to the incoming flow of Mamers Valles, basins II is associated with the deltas, and III whit the higher lands behind them. These three basins eventually drain inside Ismenius Cavus, in basin I. Valley networks and fretted channels are present in all the basins. Basins II and III are of special significance to the deltaic systems, as they have flow patterns that drain towards the lake chain that contains the Aracataca and Ariguani deltas. This lake chain is formed by the Aracataca crater, Ariguani crater, and Ismenius Cavus. All of them are connected by openings in their rims (Figure 4).

3.3 Detailed Scale

The analysis of the deltas was made using HiRISE imagery. They are only 36 km away from each other. Both were deposited at the discharge end of two possible big paleolakes, but despite their closeness, they are different in shape, size, and associated landofrms. The deltas are made of at least three recognizable and well-developed pulses, where all their major structures are preserved (Figure 5 to Figure 8). We mapped the units of each pulse according to their spatial position in the sub-environments defined by Nichols (2009): Delta tops (*Fadt*), Delta slopes (*Fads*), Delta fronts (*Fap*), and Prodeltas (*Ffdr*).

The Aracataca Crater is supplied by multiple valley networks originating from basin II and notably lacks any fretted channels in the area. Consequently, it suggests that the formation of the Aracataca Delta occurred within a fluvial system. The delta is situated within the Ariguani Crater, where the Aracataca crater rim broke (Figure 7a). The origin of this incision is not clear, but as no structural pattern dominates the zone, we propose that it is the result of fluvial erosion of a formerly weak zone, due to the filling and overflow of the crater. We identified three main deposition pulses (Figure 5, Figure 7), two of which have an elongated shape, with a length-wide ratio of 1.6. This configuration resembles a river-dominated delta (Nichols, 2009), which indicates that the dominant system was the incoming flow from the Aracataca Crater. Both delta slope zones (*Fads2* and *Fads3* units) have high slopes, indicating a coarse grain size. The most recent pulse has a more fan-like shape (*Fadt1*), which points to a less energetic incoming flow. All fans have well-developed subenviroments but no paleochannels were identified. This is probably due to the overlying glacial activity, which generated lateral moraines and sublimation pits over the previous fluvial activity (Figure 3b).

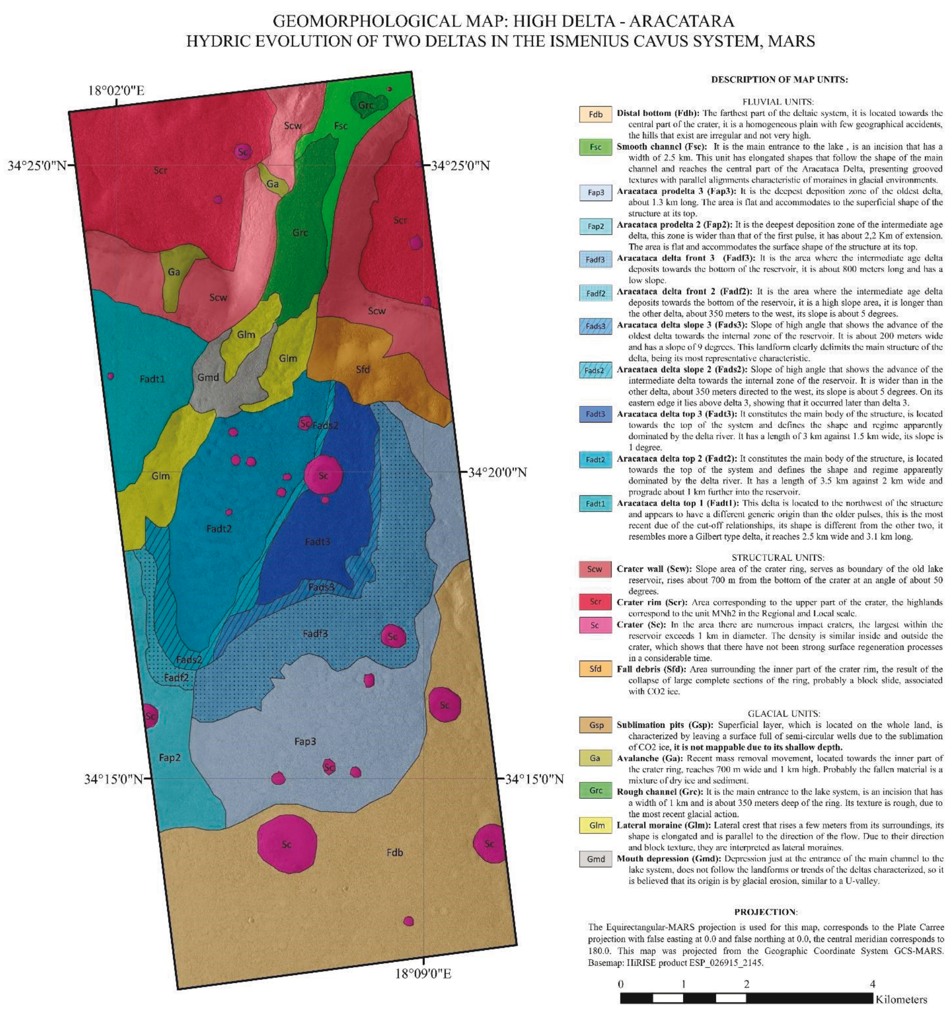


Figure 5: Geomorphological map of the Aracataca Delta. The basemap was HiRISE capture ESP_026915_2145.

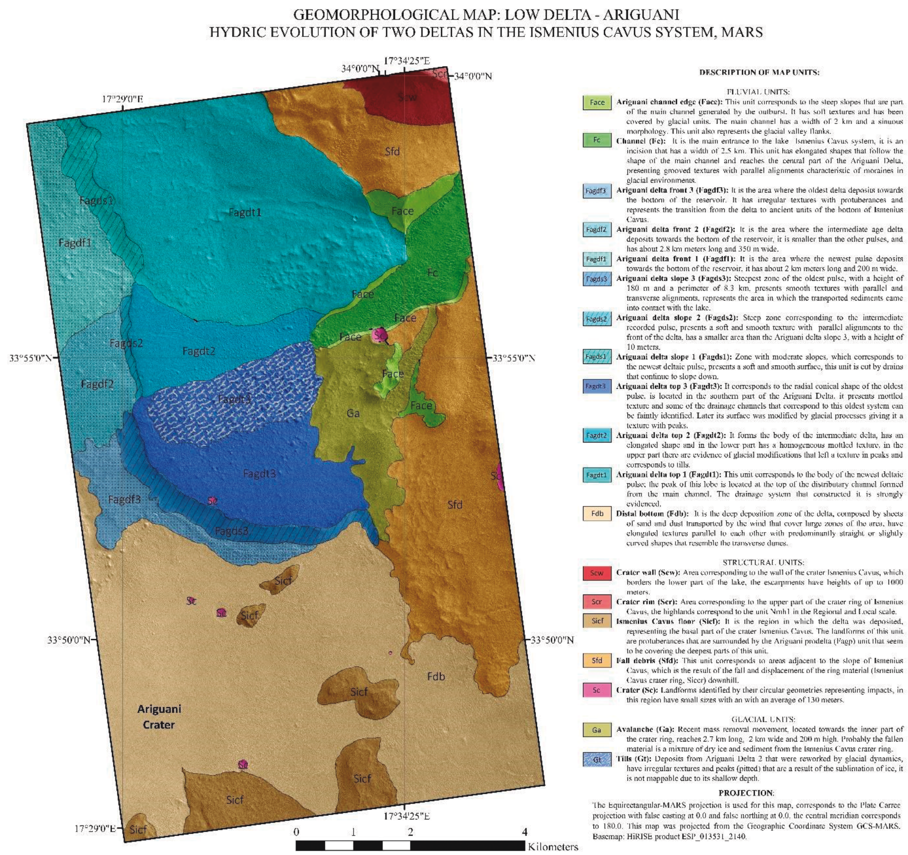


Figure 6: Geomorphological map of the Ariguani Delta. The basemap was HiRISE take ESP_013531_2140.

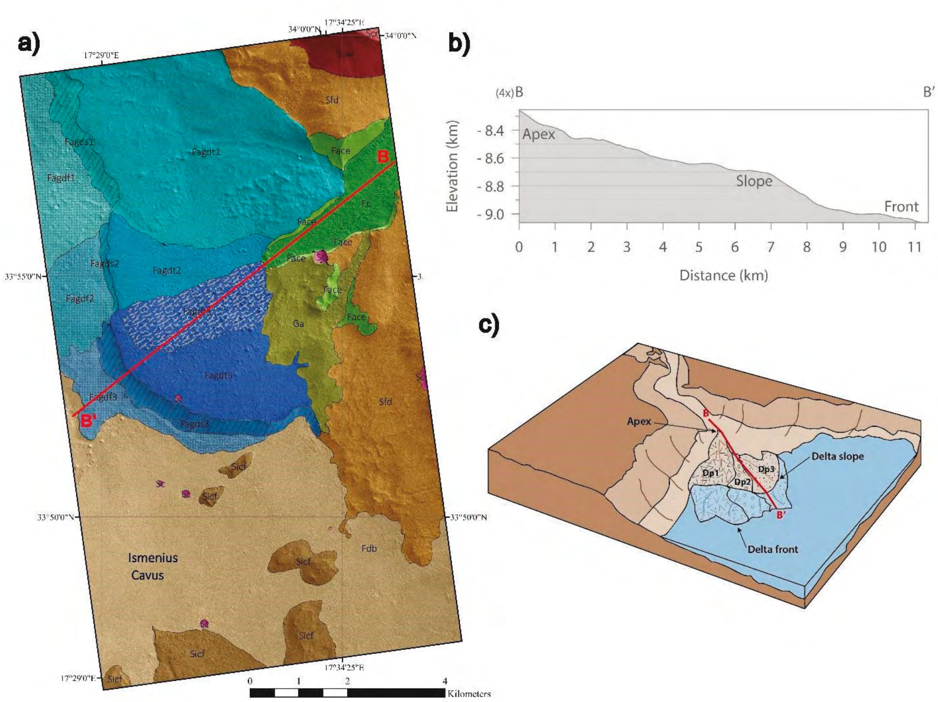


Figure 7: a) Geomorphological map of the Aracataca Delta. b) Elevation profile of the delta taken from the HRSC DEM, the lateral moraine that cuts the delta is visible to the left. c) Tridimensional interpretation of the river-dominated delta. Dp1, Dp2, and Dp3 are the three identified pulses.

The Ariguani Delta was formed inside Ismenius Cavus, at a fracture point in the Ariguani crater rim. In contrast to the Aracataca Delta, the Ariguani Delta is directly associated with a fretted channel (Figure 2). The channel starts 10 km inside the Ariguani Crater and then extends southwest towards Ismenius Cavus, eventually bisecting the crater rim (Etic) and depositing the Ariguani Delta (Figure 6, Figure 8). It is noteworthy that certain valley networks flow towards the Ariguani Crater from the east side of Basin II, evidencing some degree of fluvial activity along the fretted channel. This delta is composed of three pulses, all resembling a Gilbert-type delta, due to their high delta slopes (*Fagds1*, *Fagds2*, and *Fagds3* units) of 11°, and a considerable basin depth (Nichols, 2009; Ori et al., 2000; Rees et al., 2017). These deltaic structures are also covered by glacial debris and recent sublimation pits.

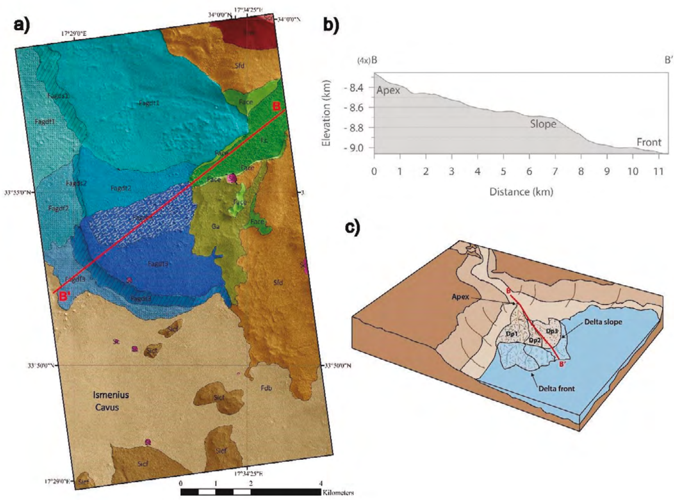


Figure 8: a) Geomorphological map of the Ariguani Delta. b) Elevation profile of the delta taken from the HRSC DEM, the structure of the delta is well conserved, and its main parts are highlighted. c) Tridimensional interpretation of the Gilbert-type delta. *Dp1*, *Dp2*, and *Dp3* are the three identified pulses.

4. Discussion

4.1 Geologic evolution

From the prior analysis, it was established that the Ismenius quadrangle had a complex geologic evolution due to the changing effects of the hydrologic systems within this region. This zone has been active since the earliest periods of Mars, being the Noachian-Hesperian limit the moment in which its major features developed.

4.1.1 Noachian

During this period, around 3.88 Ga - 3.92 Ga, the oldest geomorphological units of the zone (*mNp*, *mNh1*, and *mNh2* units) formed in the northwestern region of Arabia Terra (Figure 2) (Benedix et al., 2020; Chuang & Crown, 2009; Tanaka et al., 2009). These units appear as extended plains, characterized by their cratered surfaces and the display of highly integrated valley networks. All the Noachian units underwent alterations as a result of subsequent processes such as impact cratering, erosion, tectonic activity, groundwater sapping, and glacial flows. These processes influenced the later development of the polygonal plateaus and knobs in the Deuteronilus Mensae region (Chuang & Crown, 2009).

The primary activity during the Noachian period was impact cratering. Over the *mNh* unit, the impact of massive asteroids formed the main craters of the region (around 20 km in diameter), including the Ariguani and Aracataca craters. These two craters are simple structures, with only a few valley networks and channels associated. On the other hand, the irregular shape of the Ismenius Cavus structure may be the result of multiple superimposed impact craters modified by fluvial, glacial, and eolian processes. The channels associated with Ismenius Cavus connect all the hydrologic basins of the region with the Mamers Valles system and eventually with the Borealis Basin. After the formation of the main craters, the late Noachian was dominated by fluvial activity in the form of valley networks, leading to the formation and development of lake chains and sedimentary basins inside the craters. The main channels had a northeastward flow, leading to the lowlands after the northern maritan dichotomy in the Deuteronilus Mensae region. This water activity led to the erosion of the north *mNp* unit (Figure 2). As a result, the lands near the dichotomy became irregular valleys, facilitating the flow of water and connecting the ocean with the southern units, thus consolidating the hydrologic system of the Ismenius quadrangle.

At the detailed scale, relations are more complex. Valley networks are recognized across the area surrounding Ismenius Cavus and seem to be dissected by the Mamers Valles main channel. This implies that the valley networks were abundant before the main groundwater-sapping event happened and that they probably followed the current course of Mamers Valles.

Cabrol (1999) classified the craters in this zone as lake chains, open systems of paleolakes that are connected to a broader hydrologic system coming from basins I and II. On the other hand, Di Achille and Hynek (2010) defined them as closed basins. Our analysis makes it clear that the system is open, as Aracataca Crater was fed to the north by the ancient basin III through a small canyon (Figure 4), then drains to the Ariguani Crater, which in turn released its charge into Ismenius Cavus. This shows a continuous system between the Noachian highlands and the Borealis Basin.

The Aracataca delta is the product of different pulses of sedimentation. We propose that at the beginning, the Aracataca Crater was a closed lake until the water volume overcame its rim. This created a spillover flow that continued through Ariguani Crater, which in turn must have also been filled, as a delta would only form in an aqueous environment. Due to the number of valley networks and the absence of fretted channels in basins II and III, we consider the development of the Aracataca delta older than the main phase of groundwater activity with a completely different genesis to the Ariguani delta (Figure 9a, 9b). However, it is not clear if this system was connected at this epoch with Ismenius Cavus, as the Ariguani delta is associated with a posterior event, and any possible process that could have occurred before has been erased by its occurrence.

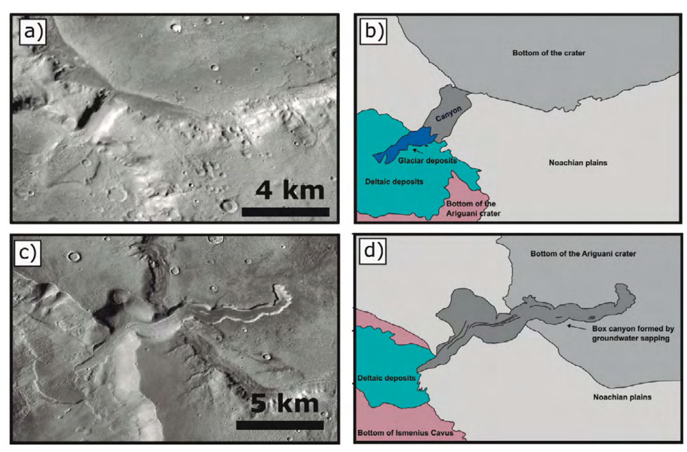


Figure 9: Genetic difference between both deltas. a) Plan view of the Aracataca delta. b) The Aracataca delta does not have a canyon associated upstream, implying a formation from surficial water activity. c) Plan view of the Ariguani crater. d) The Ariguani delta was formed by groundwater sapping, a channel was also carved by groundwater erosion upstream after the lake at the Aracataca crater evaporated.

4.1.2 Hesperian

The Noachian-Hesperian transition and early Hesperian period, around 3.8 Gy - 3.7 Gy, is of great importance for the evolution of the region. This period is usually considered as the moment in which the wet conditions of the Noachian were replaced by scarce remnants of surface water. This phenomenon was driven by the gradual loss of the internal heat of the planet, the reduction of its magnetic field, and the consequent loss of the atmosphere of the planet (Bullock & Moore, 2007). As a result of this process, the superficial sources of water started to disappear, leaving only groundwater in aquifers. This exhaustion of valley networks left groundwater sapping as the main erosive agent, creating the extended fretted channels and denudation processes on the highlands (Lamb et al., 2008; Warner et al., 2011).

Fretted channels are widely spread in the zone, Mamers Valles is the biggest of them. Its formation erased previous fluvial features of a similar scale, as both fluvial and fretted channels seem to converge. Although the development of the fluvial systems occurred mainly during the Noachian, the lacustrine activity in Ismenius Cavus has been dated to Hesperian (Dehouck et al., 2010). Given Ismenius Cavus's proximity to the north dichotomy of Mars, the transition from a fluvial to a groundwater regime appears likely to have been gradual. During the Noachian period, the entire region was abundant in surface water, indicating high levels of infiltration. Subsequent to the cessation of fluvial activity, the groundwater component could have started shortly after, possibly obviating the need for a complete shutdown of the hydrological system, only to be reactivated later by the thawing of subsurface ice.

As the weather became colder and dryer, the water in the Ariguani Crater started to evaporate until it was completely dry. At this point, the main lake chains only had groundwater input. The Ariguani Delta was deposited inside Ismenius Cavus during this period, by sediments transported by a channel carved by groundwater erosion (Figure 9d). This channel was carved in a southwestern direction within the Ariguani Crater downslope, extending to the residual lake within Ismenius Cavus and shaping the Ariguani Delta. It suggests that the Ariguani Crater had emptied prior to the formation of the Ariguani Delta, as the channel could not have developed underwater. It remains unclear whether the connection to Ismenius Cavus existed prior to this event; however, it is evident that the Ariguani Delta is younger than the Aracataca Delta. The progressive vanishing of water in the lake chain could be related to the altitude gradient, as Ismenius Cavus is below both craters, the continuously lower phreatic level first disappeared in the lake chain.

Some U valleys appear across the area. These are associated with glacial erosion and some of them seem to predate fretted channels (Figure 3f). This is not strange, as interglacial/glacial cycles have been abundant on Mars because of the high variation in the angle of the rotation axis (Montmessin, 2006).

4.1.3 Amazonian

Glacial processes were the main surface modifiers of the Amazonian period (Head et al., 2003). We identified numerous features of the glaciations of the Amazonian. Lateral and frontal moraines are common in the interior of the channels, indicating that glacier masses were flowing inside the features that were once carved by water flows. Ice flow traces are common near the dichotomy; this was expected as ice follows a downslope direction. One of the glacial forms that are ubiquitous all over the surface is the pitted texture (Figure 3b), which is formed by the holes left by the sublimation of CO_2 ice, later covered with wind deposits.

At the regional scale, numerous glacial units were identified. Debris Aprons (*Ada* unit), moraines, and grooves-crevasses are commonly found superimposing the Noachian units. At the detailed scale, eolian activity is evident in the Ismenius Cavus floor, where transversal dunes are preserved in the superficial eolian deposits.

4.2 Spatial and time frame of the observed landforms

The hydrologic activity in the region is more varied and time-gated than the first analysis may tell. The strong dissonance between the genesis of both deltas is an example of a more regional contrast. Across the different scales, we encountered two main morphological stages associated with water flow, a first stage dominated by valley networks and a posterior occurrence of widespread fretted channels (Figure 10).

The first stage has a great footprint in the Noachian terrains. The valley networks are common in all the units of the basement, probably supplying the Borealis Basin. This, at first, is concordant with the idea of a wet early Mars (Baker et al., 1991; Dehouck et al., 2010). Nevertheless, Grau Galofre et al. (2020) showed that a vast majority of the channels near the northern dichotomy can be classified as fluvial or subglacial in origin, with a predominance of the last type. This suggests the presence of glacier masses near the dichotomy during the fluvial activity; therefore, an environmental scenario with colder temperatures. The evidence of widespread glacial activity involved at the different hydrologic stages of the region indicates that the valley networks of our study area could possibly represent subglacial hydrologic systems. In this case, this supports the idea of a wet but cold Mars, concordant with the results obtained by Grau Galofre et al. (2020) and Kite et al. (2014).

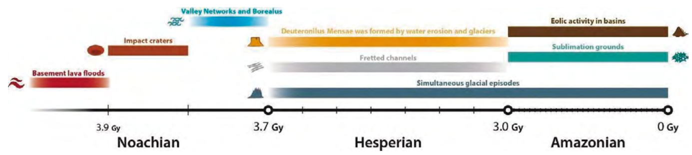


Figure 10: A timeline recording the change of the surface processes across the Martian geological time. The Noachian Period was dominated by valley networks, the Hesperian Period by fretted channels, and the Amazonian Period by eolic and glacial activity.

The Aracataca Delta is a clear result of the activity of the first stage. The crater drained a vast area via valley networks and the morphology of the delta resembles a river-dominated delta, meaning strong water and sediment influx. The newest pulse of the Aracataca Delta is small and neutral-shaped. It can be inferred that as the paleolake influence over the delta was likely constant over time, the incoming flux, and therefore all the surficial hydrologic system, was getting weaker during the formation of this last pulse. Furthermore, for the Ariguani Delta, we previously stated that due to its origin from a fretted channel, it could not have formed before the Aracataca Crater was empty (Figure 9). These interpretations imply that the drying of the two upper lakes of the chain represents a drastic reduction of the water table in the zone. Similar lake chains to the west and the south likely got empty. After this event, around the early Hesperian (Dehouck et al., 2010), groundwater runoff took place at a large scale, carving Mamers Valles and the several fretted channels near the dichotomy, most likely over previous depressions. This resurgence of strong water activity has been reported in several places on Mars for this period (Duran & Coulthard, 2020), where the groundwater sources replaced the now weak atmosphere as the primary sustain of surface channels.

It was at this time when the Ariguani Delta formed inside Ismenius Cavus, which in turn registered another continuous decrease of the water supply, now for the second stage. Due to the explosive and fast-eroding nature of fretted channels (Lamb et al. 2008), the first deltaic pulse shows the biggest amount of sedimentation. As the system evolved, the number of sediments and the areal extension of its deposits decreased, as the result of a weaker erosive capacity of the runoff during its later events, probably caused by a decrease in the groundwater supply. Finally, once the groundwater sources were also exhausted, the lake inside Ismenius Cavus evaporated, and the study zone turned into the cold and glacial-dominated environment we see today.

5. Conclusions

The Ismenius Cavus system and its associated deltaic features record the hydrologic evolution of this part of the northern Martian dichotomy. This history is recognizable in the geomorphology of the Aracataca and Ariguani deltas, and the pulses of sedimentation they made. It is feasible that the late Noachian valley networks, which probably originated in a sub-glacial environment, were transitionally replaced by fretted channels coming from groundwater runoff during the Hesperian, and eventually faded away as the Martian atmosphere was not able to support a hydrologic cycle anymore. The widespread hydrologic systems of early Mars are now shut down, but below the current glacial and eolian features, it is possible to identify their ancient activity. Water-only generated landforms like deltas are key to understanding the geologic history of the planet. Future analysis of similar environments around Mars could help to better define how these systems worked, how they evolved in time, and their role as former habitable environments and the search for life.

6. Data Availability

Datasets related to this article are freely available in different repositories. The geodatabases and maps produced in this work can be reached at (Suarez-Valencia et a., 2023). MOLA and THEMIS data can be found at https://astrogeology.usgs.gov/search?pmi-target=mars, a planetary catalog of the USGS; HRSC data is available at https://pds-geosciences.wustl.edu/missions/mars_express/hrsc.htm, at the Geoscience Node of the Planetary Data System (PDS); and HiRISE takes are found at https://www.uahirise.org/catalog/, a catalog at the University of Arizona.

References

Alemanno, G., Orofino, V. & Mancarella, F. (2018). Global Map of Martian Fluvial Systems: Age and Total Eroded Volume Estimations. Earth and Space Science, 5(10), 560–577. https://doi.org/10.1029/2018EA000362

Baker, V. R., Strom, R. G., Gulick, V. C., Kargel, J. S., Komatsu, G. & Kale, V. S. (1991). Ancient oceans, ice sheets, and the hydrological cycle on Mars. Nature, 352(6336), 589–594. https://doi.org/10.1038/352589a0

Benedix, G., Lagain, A., Chai, K., Meka, S., Anderson, S., Norman, C., Bland, P., Paxman, J., Towner, M. & Tan, T. (2020). Deriving Surface Ages on Mars Using Automated Crater Counting. Earth and Space Science, 7(3). https://doi.org/10.1029/2019EA001005

Bullock, M. A. & Moore, J. M. (2007). Atmospheric conditions on early Mars and the missing layered carbonates. Geophysical Research Letters, 34(19). https://doi.org/10.1029/2007GL030688

Cabrol, N. & Grin, E. (1999). Distribution, Classification, and Ages of Martian Impact Crater Lakes. Icarus, 142(1), 160–172. https://doi.org/10.1006/icar.1999.6191

Chuang, F. C. & Crown, D. A. (2009, November 17). Geologic map of MTM 35337, 40337, and 45337 quadrangles, Deuteronilus Mensae region of Mars [Map]. U.S. Geological Survey. https://pubs.usgs.gov/sim/3079/sim3079_map.pdf

Dehouck, E., Mangold, N., Le Mouélic, S., Ansan, V. & Poulet, F. (2010). Ismenius Cavus, Mars: A deep paleolake with phyllosilicate deposits. Planetary and Space Science, 58(6), 941 946. https://doi.org/10.1016/j.pss.2010.02.005

Di Achille, G. & Hynek, B. M. (2010). Ancient ocean on Mars supported by global distribution of deltas and valleys. Nature Geoscience, 3(7), 459–463. https://doi.org/10.1038/ngeo891

Duran, S. & Coulthard, T. J. (2020). The Kasei Valles, Mars: a unified record of episodic channel flows and ancient ocean levels. Scientific Reports, 10(1). https://doi.org/10.1038/s41598-020-75080-y

Edwards, C. S., Nowicki, K. J., Christensen, P. R., Hill, J., Gorelick, N. & Murray, K. (2011). Mosaicking of global planetary image datasets: 1. Techniques and data processing for Thermal Emission Imaging System (THEMIS) multi-spectral data. Journal of Geophysical Research, 116(E10). https://doi.org/10.1029/2010JE003755

Geng, X., Xu, Q., Xing, S., Lan, C. & Xu, J. (2017). A Novel Pixel-Level Image Matching Method for Mars Express HRSC Linear Pushbroom Imagery Using Approximate Orthophotos. Remote Sensing, 9(12), 1262. https://doi.org/10.3390/rs9121262

Goldspiel, J. M. & Squyres, S. W. (2000). Groundwater sapping and valley formation on Mars. Icarus, 148(1), 176–192. https://doi.org/10.1006/icar.2000.6465

Grau Galofre, A., Jellinek, A. M. & Osinski, G. R. (2020). Valley formation on early Mars by subglacial and fluvial erosion. Nature Geoscience, 13(10), 663–668. https://doi.org/10.1038/s41561-020-0618-x

Head, J. W., Mustard, J. F., Kreslavsky, M. A., Milliken, R. E. & Marchant, D. R. (2003). Recent ice ages on Mars. Nature, 426(6968), 797–802. https://doi.org/10.1038/nature02114

Hoke, M. R. T., Hynek, B. M. & Tucker, G. E. (2011). Formation timescales of large Martian Valley networks. Earth and Planetary Science Letters, 312(1–2), 1–12. https://doi.org/10.1016/j.epsl.2011.09.053

Irwin, R. P. (2004). Sedimentary resurfacing and fretted terrain development along the crustal dichotomy boundary, Aeolis Mensae, Mars. Journal of Geophysical Research, 109(E9). https://doi.org/10.1029/2004JE002248

Koutnik, M. R., & Pathare, A. V. (2021). Contextualizing lobate debris aprons and glacier-like forms on Mars with debris-covered glaciers on Earth. Progress in Physical Geography: Earth and Environment, 45(2), 130-186. https://doi.org/10.1177/0309133320986902

Kite, E. S., Williams, J. P., Lucas, A. & Aharonson, O. (2014). Low paleo pressure of the Martian atmosphere is estimated from the size distribution of ancient craters. Nature Geoscience, 7(5), 335–339. https://doi.org/10.1038/ngeo2137

Lamb, M. P., Dietrich, W. E., Aciego, S. M., DePaolo, D. J. & Manga, M. (2008). Formation of Box Canyon, Idaho, by Megaflood: Implications for Seepage Erosion on Earth and Mars. Science, 320(5879), 1067–1070. https://doi.org/10.1126/science.1156630

Laskar, J., Levrard, B. & Mustard, J. F. (2002). Orbital forcing of the Martian polar layered deposits. Nature, 419(6905), 375–377. https://doi.org/10.1038/nature01066

Leeder, M. R. (2011). Sedimentology and Sedimentary Basins: From Turbulence to Tectonics (2nd ed.). Wiley-Blackwell.

Lucchitta, B. K. (1978). A large landslide on Mars. Geological Society of America Bulletin, 89(11), 1601. https://doi.org/10.1130/0016-7606(1978)89%3C1601:ALLOM%3E2.0.CO;2

McGill, G. E. (2002, May). Geologic map transecting the highland/lowland boundary zone, Arabia Terra, Mars; quadrangles 30332, 35332, 40332, and 45332 (No. 2746). U.S. Geological Survey.

Montmessin, F. (2006). The Orbital Forcing of Climate Changes on Mars. Space Science Reviews, 125(1–4), 457–472. https://doi.org/10.1007/s11214-006-9078-x

Nichols, G. (2009). Sedimentology and Stratigraphy (2nd ed.). Wiley-Blackwell.

Ori, G. G., Marinangeli, L. & Baliva, A. (2000). Terraces and Gilbert-type deltas in crater lakes in Ismenius Lacus and Memnonia (Mars). Journal of Geophysical Research: Planets, 105(E7), 17629–17641. https://doi.org/10.1029/1999JE001219

Rees, C., Palmer, J. & Palmer, A. (2017). Gilbert-style Pleistocene fan delta reveals tectonic development of North Island axial ranges, New Zealand. New Zealand Journal of Geology and Geophysics, 61(1), 64–78. https://doi.org/10.1080/00288306.2017.1406377

Sinha, R. K. & Murty, S. (2013). Evidence of extensive glaciation in Deuteronilus Mensae, Mars: Inferences towards multiple glacial events in the past epochs. Planetary and Space Science, 86, 10–32. https://doi.org/10.1016/j.pss.2013.09.002

Suárez-Valencia, J. E., Guerrero-Gutiérrez, D. A., Soler-Aragon, N. K., Ramirez-Diaz, D. F., Nocua-Benítez, I. A., Escobar-Tarazona, C. A., & Gómez-Ruiz, J. D. (2023). Hydric evolution of two Martian deltas in the Ismenius Cavus system: Supplementary files. https://doi.org/10.5281/zenodo.8298614

Tanaka, K. L., Skinner, J. A., Crumpler, L. S. & Dohm, J. M. (2009). Assessment of planetary geologic mapping techniques for Mars using terrestrial analogs: The SP Mountain area of the San Francisco Volcanic Field, Arizona. Planetary and Space Science, 57(5–6), 510–532. https://doi.org/10.1016/j.pss.2008.06.012

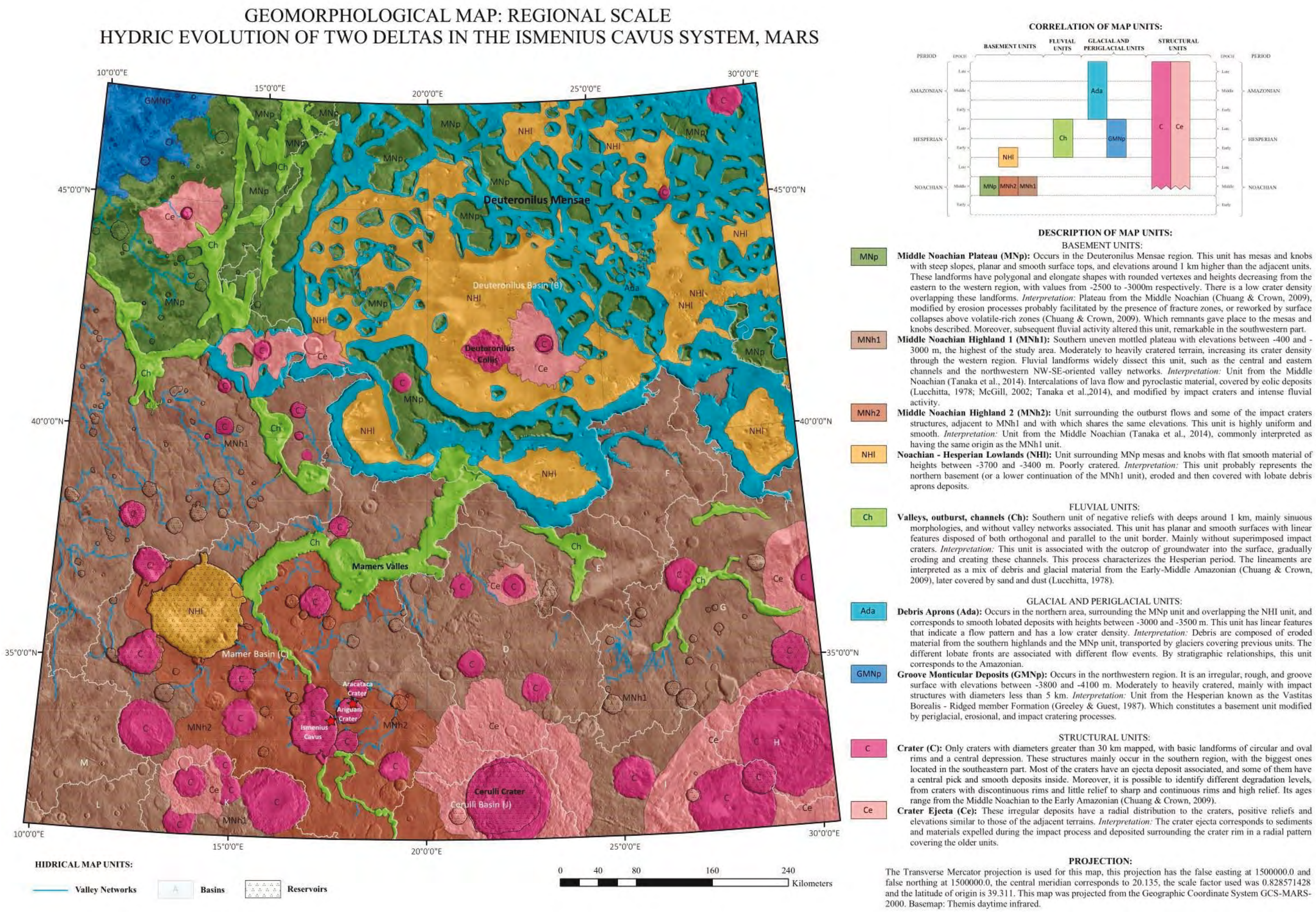
Warner, N., Gupta, S., Lin, S. Y., Kim, J. R., Muller, J. P. & Morley, J. (2011). Correction to "Late Noachian to Hesperian climate change on Mars: Evidence of episodic warming from transient crater lakes near Ares Vallis." Journal of Geophysical Research, 116(E9). https://doi.org/10.1029/2011JE003850

Wilhelms, D. E. (1972, October). Geologic mapping of the second planet. (No. 55). Geological Survey for the National Aeronautics and Space. https://www.lpi.usra.edu/resources/USGS-Reports/Astro-0055.pdf

Zegers, T. E., Oosthoek, J. H., Rossi, A. P., Blom, J. K. & Schumacher, S. (2010). Melt and collapse of buried water ice: An alternative hypothesis for the formation of chaotic terrains on Mars. Earth and Planetary Science Letters, 297(3–4), 496–504. https://doi.org/10.1016/j.epsl.2010.06.049

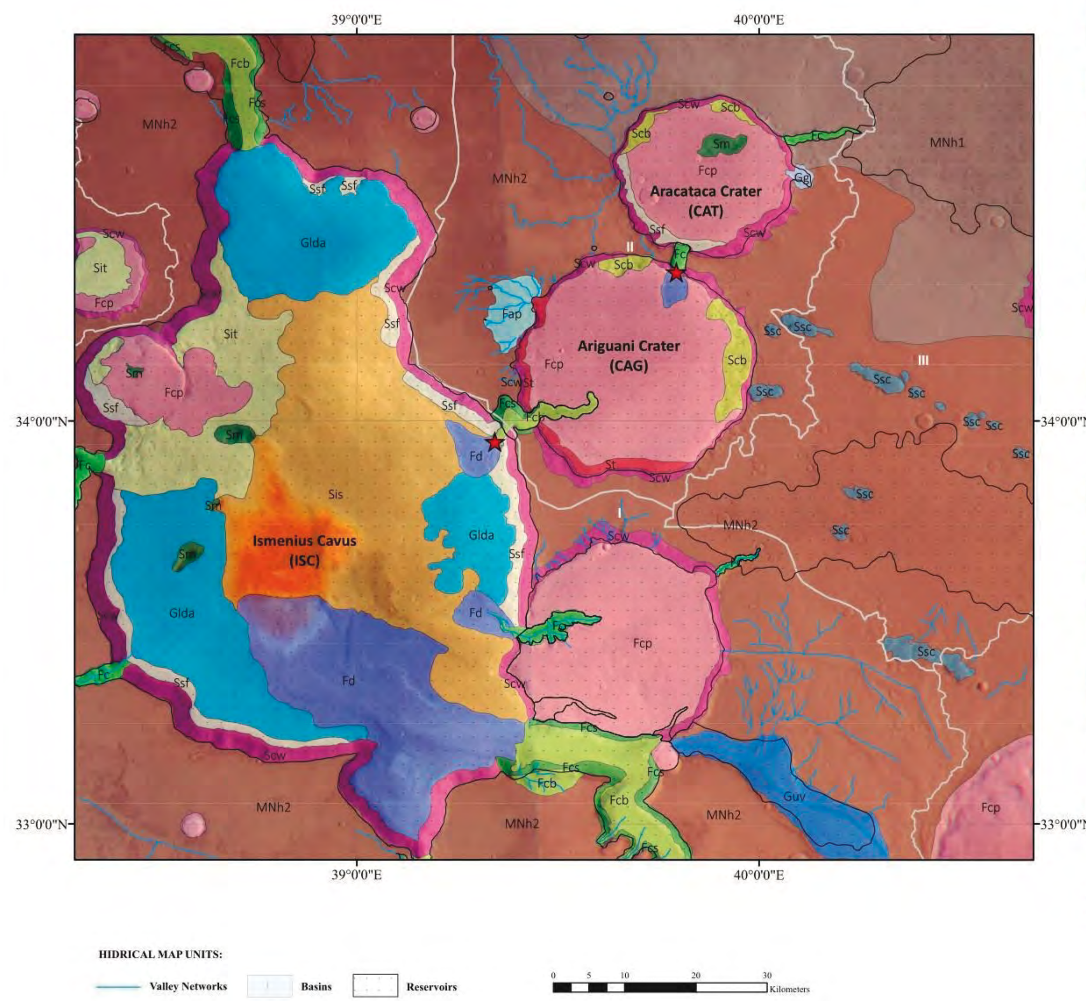
Appendix

Appendix A: Geomorphological map of the Ismenius quadrangle.



Appendix B: Geomorphological map of Ismenius Cavus and its surroundings.

GEOMORPHOLOGICAL MAP: LOCAL SCALE
HYDRIC EVOLUTION OF TWO DELTAS IN THE ISMENIUS CAVUS SYSTEM, MARS



DESCRIPTION OF MAP UNITS:

STRUCTURAL UNITS:

Scw — **Crater Wall (Scw):** Part of the impact crater structures of steep slopes with circular to oval shapes surrounding a central depression.

Sm — **Hillock (Sm):** Blocks stand out from the filling material of the impact crater structures, located in peripheral zones of the central depressions. These landforms are present in the CAG, CAT, and ISC structures. *Interpretation:* This unit has been interpreted as an extension of the Sis unit (Dehouck et al., 2010) and as remnants of hills or sedimentary structures eroded, maybe associated with the formation of carbonates (Cabrol & Grin 1999).

Sis — **Ismenius soil (Sis)**: Smooth and lightly irregular surface mainly located in the eastern area of ISC. This unit has principally gray tones of reflectance. However, there is a central darker area that could correspond to eolic dunes and a dark mantle covering the deepest zones of the depression (Dehouck et al., 2010).

Ssc — **Secondary craters (Ssc)**: Unit located in the eastern part, comprising elliptic depressions with the semi-major axis oriented NW-SE, and with the same orientation between each depression, which is radial to the Cerulli Crater, located in the eastern part of the study area. *Interpretation:* This unit represents part of the ejecta deposits generated during the CC formation.

St — **Terraces (St)**: Parallel lineaments with black and gray reflectance tones in the western and southern parts of the CAG rim. This unit corresponds to planar zones that break the terrain slope. *Interpretation:* In the CAG structure, terraces and coastal lines have been reported (Cabrol & Grin 1999).

Sit — **Irregular terrain (Sit)**: Dark rough surfaces, sometimes with linear features, located in the western part of ISC and the northwestern crater of the study area. *Interpretation:* This unit could correspond to ejecta deposits modified due to the linear patterns present (Dehouck et al., 2010). However, this unit is not radial to any impact crater structure identified.

Scb — **Collapsed blocks (Scb)**: Irregular surfaces with light tones located close to the crater rims in the CAG and CAT structures. *Interpretation:* These deposits could represent fall material from the adjacent walls where they are located, which could correspond to unconsolidated brechas with a low resistance to erosion (Ori et al., 2000).

Ssf — **Slope deposit (Ssf)**: Dark unit located close to the slope base of the ISC and CAT structures. In ISC this surface is mottled and has linear patterns parallel to the crater edge, while in CAT this unit is homogeneous *Interpretation:* In both locations (ISC and CAT) these features have been previously interpreted as terraces and coastal lines (Cabrol & Grin 1999).

FLUVIAL UNITS:

Fd — **Delta (Fd)**: Located in the channels mouth, where they meet the impact crater structures of CAG and ISC. These features have semicircular shapes, mostly planar surfaces and scarps surrounding them (Ori et al., 2000). Inside ISC there are three fluvial deposits, two of them have morphological features of a delta (northern and southern), while the last one (middle) has a smooth topography, and for this reason it could correspond to either a shallow delta, and an alluvial fan (Dehouck et al., 2010). Furthermore, the biggest deltaic deposit, located in the southern region of ISC, has channel features on its surface. *Interpretation:* In ISC, the fluvial and lacustrine activity was developed in Hesperian times (Dehouck et al., 2010), while the delta located in CAG has a Noachian age. The northern ISC deposit corresponds to a Gilbert-type delta (Ori et al., 2000).

Fc — **Channel (Fc)**: This landform corresponds to little sinuous depressions constituted by both channel's bottoms and slopes located in ISC and CAT. Their dimensions are around 9 km of longitude and 2 km of width. *Interpretation:* These structures correspond to outburst flow channels.

Fcb — **Channel bottom (Fcb)**: Plains located in the channel's floor, with sinuous and rectilinear shapes and commonly with glacial features as moraines and sublimation pits. This unit is surrounded by the Fcs unit, with which constitutes the channel structures.

Fcs — **Channel slope (Fcs)**: Steep slope walls surrounding the Fcb unit, it constitutes the channel structures.

Fcp — **Crater Plain (Fcp)**: Uniform and smooth surfaces located inside impact crater depressions, with low crater density superposed and slightly variable reflectance tones. *Interpretation:* Probably this unit corresponds to fluvial deposits that filled the deepest regions and then were covered by a dust and sand mantle.

Fap — **Alluvial Plain (Fap)**: Located adjacent to the western region of the CAG rim. *Interpretation:* Landform developed during the Noachian, showing a water source for the CAG structure.

GLACIAL AND PERIGLACIAL UNITS:

Glda — **Lobate debris aprons (Glda):** Homogeneous surfaces with linear patterns indicating flow directions, located in the northern and western part of ISC and over the deltaic deposits and their associated channels. *Interpretation:* This unit corresponds to moraines, viscous flows of ice.

Guv — **U valleys (Guv):** U-shaped valley located in the eastern part of the study zone, with depths around 400 m, and with elevations of -7740 m in the deepest areas. *Interpretation:* Landforms produced in glacial environments, by the erosive action of the ice that constitutes moraines.

Gg — **Gully (Gg):** Located in the eastern part of the CAT rim, with dimensions of 3 km x 3 km. *Interpretation:* It corresponds to the Amazonian period, and its formation is related to mass movements generated either by melting of water ice or sublimation of CO_2.

BASEMENT UNITS:

MNh1 — **Middle Noachian Highland 1 (MNh1):** Southern uneven mottled plateau with elevations between -400 and -3000 m, the highest part of the study area. Moderately to heavily cratered terrain, increasing its crater density through the western region, and locally within its walls it is possible to observe stratification. This unit is widely dissected by fluvial landforms, such as the central and eastern channels and the northwestern valley networks oriented NW-SE. *Interpretation:* Unit from the Middle Noachian (Tanaka et al., 2014). Product of lava flows with intercalations of pyroclastic materials, covered by eolic deposits (Lucchitta, 1978; McGill, 2002; Tanaka et al.,2014), and modified by impact craters and intense fluvial activity.

MNh2 — **Middle Noachian Highland 2 (MNh2):** Southern terrain, adjacent to the MNh1 unit with which shares the same elevations. Surrounding the outburst flows and some of the impact craters this unit is highly uniform and smooth. *Interpretation:* Unit from the Middle Noachian (Tanaka et al., 2014), commonly interpreted as having the same origin as the MNh1 unit.

PROJECTION:

The Equirectangular-MARS projection is used for this map, corresponds to the Plate Carree projection with false easting at 0.0 and false northing at 0.0, the central meridian corresponds to 180.0. This map was projected from the Geographic Coordinate System GCS-MARS. Basemap: HRSC multispectral images (Takes: 5249 and 5267).