Landform hierarchy and evolution in Gorgonum and Atlantis basins, Mars

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Landform Hierarchy and Evolution in Gorgonum and Atlantis Basins, Mars

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Abstract

This paper describes the evolution of landforms in Atlantis and Gorgonum basins, using a geomorphologic approach which interprets landform distribution and hierarchy. Rather than looking at the distribution of large-area (> $10^6$ km$^2$) geologic sequences, this study focuses on interpreting the local-scale (<$10^3$ km$^2$) cratered terrains, tectono-structural basins, and local manifestation of exogenic processes. Specifically, the evolution of fluvio-lacustrine landforms is interpreted as being functionally subordinated to the evolution of the cratered terrains and to the tectono-structural modifications of the landscape. Results show that three major phases of landscape evolution in Atlantis and Gorgonum basins can be identified: a) major impact cratering during the heavy-bombardment period; b) tectonic displacements in response to volcano emplacement in the Tharsis region, and simultaneous landform creation by fluvial and lacustrine processes; and c) exogenic modification of the older landforms through weathering and aeolian processes. Our results show that the smaller morphological features, which form on the older geological units, are not necessarily old themselves and can in fact be relatively recent (e.g. Amazonian). The main implication of these results is that Martian morphology did not form only during a period immediately following the heavy bombardment, as commonly postulated, but rather that landform evolution continued throughout the entire Martian history.

Key words: MARS, SURFACE; GEOLOGICAL PROCESSES; TECTONICS
1. Introduction

This paper uses an approach based on geomorphology to interpret the history of the Gorgonum and Atlantis basins on Mars. The approach differs from conventional geologic mapping and interpretation commonly found in literature, in which chronostratigraphic series distribution subordinates the interpretation of smaller landforms that comprise them. The geologic series are identified on large areas ($10^6$ km$^2$) and interpreted based on visual similarities of orbital images and crater counting. To illustrate the geomorphological approach, this paper first describes the formation, distribution and genetic linkages among different landforms in Gorgonum and Atlantis basins. Subsequently, cross-cutting relationships between landforms are used to present the succession of processes and trace a pattern of evolution.

Martian geologic studies have traditionally involved concepts and procedures developed for the geologically simple Moon (Shoemaker and Hackman 1962, Wilhelms 1990). In the geologic interpretation, surface materials are interpreted to be a variety of volcanic and brecciated deposits that underlie distinctive and mappable surface morphologies. In contrast with the geologic interpretation, it is now generally recognized that many landforms consist of reworked older materials, and differ in texture because of more recent erosion and deposition rather than the conditions of their formation, so stratigraphic units may not be identifiable. More recent datasets released after 1990 (high-resolution satellite images, meteorite analysis, \textit{in situ} observations, e.g. orbital datasets of MGS, Mars Odyssey, Mars Express, MRO missions, and rover missions), refine the interpretation of surface structures at regional and local scales of study, and focus the analysis on water-related landforms because of its possible biological
implications. The refinement in interpretation was possible because spatial resolution improved from ~ 1 km per pixel in the 1970s to 30 cm per pixel in 2008. These progressive increases in resolution permitted the interpretation of finer-scale landforms that superpose on older geologic sequences. In the southern Martian highlands, Irwin et al. (2004) combined the geologic and morphologic interpretations (based on MOLA elevation data- 128 pixels/degree), and described the formation of an Eridania basin paleo-lake at elevations lower than 1100-950 m on late Noachian deposits. Inside Eridania basin, Howard and Moore (2004) used higher resolution datasets (image spatial resolution on MOC images- up to 2m/pixel) and described the formation of an ice-capped paleo-lake at the bottom of the Gorgonum basin on late Hesperian and Amazonian deposits. Finer erosive benches, about 50 m wide, were described and the texture of surface deposits was interpreted as representing deposits reworked by an ice cap. On high resolution datasets, gullies and small alluvial fans are identified and interpreted to be formed after the last obliquity cycle (Malin et al. 2006, Costard et al. 2002), with ages that span only the last 10,000 years. Thus, as the spatial resolution of images increases, the evidence for of younger landforms contradicts the previous geologic reconstruction of evolution of Martian terrain that tends to generalize the interpretation on a large geologic scale in early periods of evolution. The observed landforms thus resulted from modification of the crust throughout most of Martian history. As Williams (1990) suggested, each process modifies the inherited surface crust. For example, each new impact throws ejecta, modifying the age and morphology of nearby deposits; or, ongoing eolian processes blanket large areas with new deposits and obscuring older ones.
As in the terrestrial case, where planetary-scale distribution of geologic deposits in the form of cratons and oceanic basins are visible, Mars comprises impact basins, major volcanoes and crustal dichotomy. On a regional scale, the terrestrial images show structural relief, structural basins, and watersheds, while in the Martian case impact craters, intercrater basins, and faults are visible. At local scale, Martian channel networks and watersheds can be discerned and, particularly, depositional and erosional structures less than 100 m² are visible at higher spatial resolution (Figure 1).

It should be noted that, regardless of the scale of study, the planetary datasets do not directly describe the succession of geologic units. Rather, spatial and temporal succession must be inferred from the current landform assemblages. Moreover, the subsurface distribution of planetary deposits and landforms has always been inferred from interpretation of visible orbital images and never confirmed to its full extent in situ.

In this paper we propose an approach that, similar to terrestrial landform interpretation, analyzes the distribution of geologic deposits and associated landforms from the large-scale regional sequences (highland cratered-terrain distribution, tectono-structural modification of the upper crust), to the small-scale disposition of exogenic landforms on top of larger sequences. However, instead of looking at planetary- or regional-scale geologic patterns, this paper focuses on Atlantis and Gorgonum basins, and analyzes the distribution of the different types of landforms that comprise the surface morphologies in these basins to establish a comprehensive chronology of their history.

Key geologic and morphologic evidence is presented and the hierarchy of processes and landforms is evaluated. Cross-cutting relationships between different landforms are used
to establish the succession of events in the Gorgonum and Atlantis basins. The resulting hierarchy of landforms is described and correlated into a pattern of evolution. Evidence for the succession of geologic and landforming events is presented and contrasted with previous interpretations. The description is made at a regional context of both basins and incorporates both the large-scale planetary influences (e.g. membrane-flexural loading of the Tharsis dome; Andrews-Hanna et al. 2008) and the local description of key processes within the basins that have not been described before (e.g. strong correlation between fluvial resurfacing and Tharsis-generated tectonic modifications of the upper lithosphere in these basins). Three stages of evolution are proposed, which correspond to the action of major processes that shaped the planetary surface: impact bombardment, tectono-structural formation of the intercrater basins, and late periodic exogenic modification of the landscape.
2. Current geologic and morphologic interpretation of geologic deposits in Atlantis and Gorgonum basins

Geologic mapping of Mars has mainly been based on Viking orbiter mosaic images, (typically at 150-300 m/pixel, with some areas at an order of magnitude higher resolution) (Tanaka et al. 1992). In the southern hemisphere of Mars, where the Atlantis and Gorgonum basins are located, the disposition of geologic sequences comprises a succession of plateau materials, ridge plain materials and, rather surprisingly, lowland materials of the chaotic-terrain assemblage. The succession of materials spans the Noachian and Hesperian periods, based on mapping of similar deposits distributed across the entire southern hemisphere (Scott and Tanaka 1986, Figure 2).

The cratered southern highlands of Mars are largely formed of a unit that Scott and Tanaka (1986) call the plateau sequence. The plateau sequence starts with Nplh materials, a hilly rugged area in the central Gorgonum basin comprising the oldest materials on Mars that probably formed the initial crust. Nplh materials, i.e. the cratered unit, are distributed in the northern Gorgonum basin and eastern Atlantis basin, and are interpreted to be a mixture of lava flows, pyroclastic materials, and impact breccia, on which fractures, faults and small channels are common. Npl2 materials, i.e. the subdued cratered unit, form plains marked by subdued and partly-buried old crater rims. These deposits occupy the intercrater depressions and large areas in the western Gorgonum basin. The Hesperian deposits consist of three main associations of geologic structures. First, the plateau sequence continues with Hpl3 materials, a smooth unit that occupies the Atlantis basin flanks, and is also found on a tectonic trench in the southern Mariner crater. The deposits are interpreted to be thick interbedded lava flows and eolian deposits that bury
most underlying rocks. Ridged plain materials Hr occupy the eastern Gorgonum basin and are interpreted to be extensive flows of low-viscosity lava erupted from many sources at high rates, the ridges being compressional structures imprinted in lava strata. The main occurrence of these deposits is in Lunae Planum, east of the Tharsis volcano dome (Scott and Tanaka 1980). The Gorgonum basin, located 2000 km southwest of Tharsis, does not present signs of extensive volcanic activity, but the similar appearance of surface deposits between the two provinces presents, in Scott and Tanaka’s interpretation, an argument for the occurrence of volcanic deposits. However, the Gorgonum basin is highly concave, a feature not seen in basin floors resurfaced by volcanism (Irwin et al. 2004). The Hesperian sequence ends with a deposit, Hcht, that resembles chaotic assemblages of mesas and valleys commonly found near Valles Marineris. Chaotic materials are the collapsed structures associated with aquifer migration, and form an irregular pattern of surface materials at the origin of large outflow channels (Rodriguez et al. 2005b). In the Atlantis and Gorgonum basins, however, the Hcht deposits occupy the lowest position of shallow depressions and are not associated with outflow channel development, which may suggest a different origin, as described below. In the remaining pages we retain the name “chaotic terrain” for ease of reference, but we put the quotation marks around to highlight the possible incorrectness of this nomenclature.

Smaller geologic deposits are superposed on top of these large geologic sequences and are associated with local distribution of inner-crater materials: crater rim materials (unit c), smooth crater materials (unit s), and the volcanic structures (unit v) of undefined ages. On the most recent geologic maps at 1:500,000 scale in the Gusev area, 500 km
northwest of this paper’s area of study, the smallest deposits (the large Ma’adim channel floor, and many craters larger than 10 km in diameter) are assigned the intermediate ages of Noachian-Hesperian and Hesperian-Amazonian eras, partly based on the superposition relationships with surrounding deposits, and partly based on better crater counting on high-resolution satellite images (Kuzmin et al. 2000).

Regardless of scale, even smaller (<10 km²) erosional and depositional patterns that are generated by the action of fluvial, lacustrine and periglacial activity have commonly been assigned the maximum age of the deposits on which they are superposed, based on cross-cutting relationships on both sets of geologic maps. The associated interpretation is that channels cut into the mixture of deposits that form the oldest materials on the southern Martian highlands, and were as a consequence attributed to the same stratigraphic position (Scott and Tanaka 1986). However, Malin and Edgett (2000) and Head et al. (2001) emphasized that it is difficult to explain the coexistence of valley networks or other small channels in the cratered highlands, which are at most several tens of meters deep, with the 0.2 - 1 km deep impacts that occurred during the Noachian period. Just as we would not assume that small (< 100 m) fresh craters superposed on Noachian materials have been preserved since 3.7 Gy ago, we should not conclude that small channels date back to that distant period. The traditional geological approach to investigating the surface of Mars contains an inconsistency that was described by Wilhelms (1990). Large geologic units (> 10⁵ km²) are defined based on their observed surface morphologies, but the smaller-scale landforms which comprise those morphologies are not treated separately on the existing maps. In addition, the dating methods used to estimate ages of the units are based on the craters superposed on the
larger unit itself, and do not address the ages of the smaller landforms comprising the surface morphology. Indeed, the traditional crater-counting technique is not well suited to dating these smaller landforms. Thus, in the geologic mapping paradigm described by Wilhelms (1990) the smaller more recent features are frequently ignored. The approach developed in this article intends to correct this problem. However, absolute dating of small landforms would require an improved dating technique, which is beyond the scope of this paper. Instead we focus on a developing geomorphologically consistent interpretation of the landforms that constitute the regional landscape to derive a relative history of their succession. As in the terrestrial case, landforms are the visible and mappable structures at the surface of Mars. Thus, following pages we describe the existing landform distribution, and we reconstruct the relative succession of landforming events, based on geomorphological principles such as superposition and cross-cutting.

3. Observations and Interpretations

Orbital datasets have spatial resolutions that range in value from approximately 1 km/pixel (Mariner mission 1970s) to 18-100 m/pixel (Mars Odyssey in 1990s), and 30 cm/pixel (Mars Reconnaissance 2008). As the resolution of datasets increased over time, more erosional and depositional structures have been identified, besides the ubiquitous craters that were visible in Mariner images. THEMIS orbital datasets are the first images that cover the entire planet at 100 m/pixel resolution, and cover some areas at 18 m/pixel spatial resolution in visible spectrum. As such, they provide an excellent opportunity to study the succession of different-scale landforms at the regional scale of the Gorgonum and Atlantis basin (Figure 3).
An evaluation of landforms within these basins reveals the emplacement of cratered topography in the northern and eastern Gorgonum basin, a regional pattern of faults that cross-cut the cratered structures, and the presence of lobate depressions in the basins. Mass movements, fluvial landforms, and chaotic morphologies occupy smaller areas on the top of these structures. A possible volcanic structure is present in western Gorgonum. As is commonly the case in terrestrial landform identification, our analysis first presents the large-scale assemblages of structures that dominate the landscape (the impact cratered and tectono-structural landforms), and subsequently to analyzes smaller landforms superposed on them (the exogenic landforms).

3.1 Impact craters

Within the area of study, large impact structures (> 100 km) are distributed at the periphery of the Gorgonum and Atlantis shallow basins and occupy the highest altitudes (Figure 4). The Atlantis and Gorgonum basins themselves do not present major fresh impact craters superposed on their shallow structures. Larger craters that border the basins are heavily eroded, modified by tectonic faults, tilted or filled with sediments (Figure 4).

Other similar-sized craters that were probably emplaced toward the center of the basins are barely visible on satellite images, their presence being indicated by smooth circular rims or shallow, almost flat depressional structures (Figure 4, in the northern Gorgonum basin). Toward the center of both basins, visible craters are less than 2 km in diameter and are fresh (i.e. have a more intact, less eroded morphology), indicating a possible late Hesperian - Amazonian time of emplacement (Howard and Moore 2004). These basins therefore postdate the period of heavy impact-cratering.
The morphology of different-size craters suggests the heterogeneity of impact cratering processes, different times of their formation, as well as possible different environmental conditions that contributed to their modification (Figure 5). Indeed, the most suggestive evidence that erosional and environmental conditions changed during the evolution of the Martian system is shown by the morphology of craters. The difference in crater morphology for the same-size craters within only 200 km radius in the northern Gorgonum basin suggests that the temporal and spatial mixture of impact cratering and externally-driven processes were complex. Only smaller craters superposed on larger ejecta blankets, crater interiors or intercrater depressions have the rampart morphology interpreted as being due to fluidized ejecta (Mouginis-Mark 1979, Barlow and Perez 2003, Osinski 2006). Other same-size craters in the same area do not have fluidized ejecta, and some of them do not exhibit any ejecta at all due to extensive erosion. Also, some craters are filled up to their rims with sediments. This mixed morphologic appearance of the same-size craters indicates that stages of erosion and deposition selectively affected craters depending on the moment of their emplacement and the prevailing environmental conditions. The superposition relationships with larger-scale craters and depressional areas also indicate that these resurfacing processes postdated the period of heavy-impact cratering (see the description of fluvial landforms, below).

Overall, the absence of major impact craters from the Atlantis and Gorgonum basins suggests that another type of process affected these shallow depressions after the end of heavy meteoritic bombardment (Berman et al. 2008, Forsberg-Taylor et al. 2004, and references therein)

3.2. Tectonic landforms
Signs of tectonic movements affect large areas and appear to fit a broad regional pattern on Mars (Anderson et al. 2001). Faults located within the area of study have a longitudinal and latitudinal pattern (Figure 6a). Longitudinal faults are located parallel to Sirenum Fossae graben in the northern Gorgonum basin. They affect larger impact-cratered structures and have repercussions on the displacement of the upper crust (Figures 6b and 7). Within the Gorgonum basin, Sirenum Fossae splits into three almost-parallel faults. The northernmost one continues in the Atlantis basin where it forms a large trough. The northern Gorgonum and central Atlantis basins are affected by another longitudinal fault structure, which does not continue in the heavy-impact terrain eastwards (fault 1 on Figure 6). Within the northern Gorgonum basin the fault dissects some impact craters.

In the southern Mariner crater another important latitudinal-oriented fault is present (Figure 6a, dotted-point line). It is the largest tectonic trench in the area, and its superposition relationships with Mariner’s ejecta indicate that it formed later than the crater. All faults are superposed on the cratered structures and large intercrater depressional areas, which show that they are younger than the larger geological units. In the case of Sirenum Fossae faults, they intersect fresh deposits that lie on the bottom of Gorgonum and Atlantis, which are possibly early Amazonian in age (Howard and Moore 2004). The split of the Sirenum Fossae itself, after protruding into the Gorgonum basin (Figure 6c), indicates that the fault is an “en echelon” structure. The direction of echelon propagation (oblique black arrows, Figure 6c) shows that after the protrusion into Gorgonum, Sirenum faults developed from south to north. The cross-cutting relationship with the fluvial channel indicates that the channel developed prior to the emplacement of
fault 2 (Figure 6).

Another set of faults that affect the area of study is disposed perpendicular to the radial faults that originate from the Tharsis volcanic dome (Figure 1). It comprises two major tectonic displacements of the Atlantis flanks (the western and eastern flanks) and is perpendicular to the Sirenum Fossae graben. In western Atlantis two parallel displacements of surface structures are visible. The surface deposits affected by faults resemble large slides that have moved toward Atlantis, having the scarp leaning in the opposite direction to their dip (Figure 8). The surface deposits from the back-side of the slide have continuity in the northern Atlantis area at the base of “chaotic” morphology. The western slide affects the largest impact crater (crater A, Figure 8) that is emplaced in the northwestern flank of Atlantis. The escarpment structure is visible also on the central part of the crater. The structural relationships of the tectonic displacement with the crater indicate that the crater is older.

Similar slides affect the eastern flank of Atlantis. Here, the tectonic structures at the base of sliding sheets start from the north, where it shows typical characteristics of a thrust-fault (a hanging wall that has been raised relative to the eastern foot wall). Southward, the tectonic structure is hidden by more-recent impact ejecta, and then continues along a linear trend, developing a horst and graben morphology in south-western Magellan crater. This morphology resembles a monocline passing into a fault on the eastern flank of the Atlantis basin, because the throw is different at the edges of the structure (Figure 8, southwest of Magellan). Alternatively, the observed throw may be an effect of local fluvial erosion that deepens the grabens northwards.

Three slides are visible on the western flank of the tectonic structure (Figure 8a, numbers
1-3). The lowest one is visible at the bottom of the Atlantis flank and is bordered on its highest end by foot slopes that are dissected by gullies. The upper slide affects the flanks of the horst and graben structure, and continues southward, superimposing on a large (>50 km in diameter) landslide (Figure 8b). The upper slides that affect the surface deposits continue into southern Atlantis several hundreds kilometers (Figure 8a).

Similar gravitational slides occur on the western flank of Gorgonum (Figure 9). These structures were mentioned by Howard and Moore (2004) and interpreted as marginal tectonic or structural scarps. The amplitude of the slides is large (see below, Figure 10), possibly in part because of the presence of three parallel faulting structures of Sirenum Fossae. Sirenum Fossae could trigger vertical movements of upper faulted strata.

The magnitude of the gravitational slides increases in the area of fault occurrence, suggesting an active involvement of the faulted basement in formation of surface slides and also an increase in relative altitude of the slide scarps.

The difference between the types of tectonism in the two basins resides in the direction of tectonic displacement and on the depth of deposits affected by the displacement. In Gorgonum, where the faults are associated with possible dike emplacement (Anderson et al. 2001), the throw is larger. Parallel faults, which stem from Tharsis volcanoes 2000 km away, affect different types of deposits (large impact craters, intercrater basins). In the Atlantis basin where the faults’ throw is smaller on its eastern side (Figure 8), the faults are more complex and associated with graben development and possible thrust-faulting mechanisms. On the western side of the Atlantis basin, the displacement is similar in magnitude to that of Gorgonum which might suggest a similar type of origin, caused by the stresses generated by Tharsis volcano, which pushed the upper deposits concentrically.
over faulted crust, generating compressional structures at its southwestern periphery (Grott et al. 2007, Andrews-Hanna et al. 2008).

3.3. Volcanic landforms

In western Gorgonum and southeastern Atlantis basins, a possible volcanic structure is located north of the intersection of the Sirenum Fossae and the orthogonal faults that flank Atlantis (Figure 11). This feature was also mapped as a volcano by Scott and Tanaka (1986). The alternative explanation is that the crater structure is a meteorite crater whose ejecta have been extensively eroded. However, here the volcanic interpretation is favored, because of two reasons. First, on a regional scale, it is noted that the structure occurs at the intersection of two tectonic lineaments, about 2500 km westwards of Arsia Mons, which suggests that magma could have reached the surface through the faults. Second, on a local scale, a chain of pit craters is observed on the southwestern flank of the structure, which may indicate collapsed magma chambers and lava tubes. These pit craters are oriented radially toward the cone, rather than along the Sirenum Fossae trench that cross-cuts the southern part of the structure. Furthermore, there is a sharp transition between two deposits at the bottom of the volcano’s crater, which could suggest a transition between two volcanic flows (Figure 11, THEMIS image). Other studies have also favoured the volcanic interpretation, albeit for different reasons. Anderson et al. (2001) suggested that Sirenum Fossae formed at the top of a dike extending from Tharsis. At the periphery of the flexural volcanic domes, crustal fracturing (or faulting) might have produced conditions for local emplacement of intrusive and volcanic structures. Alternatively, Wilson and Head (2002) suggested that the volcanic structure in western Gorgonum could be related to the emplacement of a radial dike swarm under Sirenum.
Fossae (Wilson and Head 2002). Local plumes along the graben could have formed at the intersection of fault extrusions of magma, as seen in central Atlantis basin in form of a magmatic dike (Figure 8).

Although the map by Scott and Tanaka (1986) suggests the emplacement of other volcanic structures in the area, higher resolution satellite THEMIS images do not confirm their existence.

3.4. Fluvial, lacustrine and periglacial landforms

The morphologic difference between terrestrial fluvial landforms and their Martian counterparts has long been recognized (Carr and Clow 1981, Baker and Partridge 1986) and has generated many disputes referring to their mechanism of formation. The Martian term for channel is somewhat confusing because terrestrial fluvial channels are filled with water. The other confusing aspect of the Martian “fluvial resurfacing” is related to the mechanisms of channel formation and evolution. Many Martian channels lack tributaries and watersheds, instead originating from ejecta structures (suggesting a sapping evolution) or originating from crater interiors (suggesting a runoff evolution). Furthermore, the channels often end abruptly in flat areas on which their depositional structures are barely visible or lacking entirely. Martian valleys are often filled partly with eolian sediments that bury the majority of channels. In most cases terraces are absent. Direct tributaries are short and resemble sapping channels.

The mechanism of formation for these “fluvial” landforms does not indicate the mature terrestrial type of the overland flow, but sparse channels with small watersheds or debris flows, gullies and mudflows, which reflect either brief overland or hillslope drainage. The source of water for this brief overland drainage is, in most cases, related to
accumulation of water in underground aquifers in the weathered crust (Howard et al. 2005, Márquez et al. 2005) that was released at the surface by sapping (Carr 1984).

This situation is common in northern Gorgonum basin where channels form at the periphery of most impact craters on their ejecta flanks (Figure 12). In the intercrater depression, channels and valley systems develop at the periphery of major impact structures that border the depression. THEMIS images superposed on DEM show a continuity of fluvial activity toward a flat lobate area (the possible paleo-lake structure), which on the geologic map I-1802-A (Scott and Tanaka 1986) is assigned a volcanic origin (Hr deposit) (Figure 12). Channels are visible on MOC images, although their distribution is sparse and does not have continuity along the entire valley system (mostly because the channels were covered by another deposit, probably eolian in origin).

Most valleys present sapping characteristics: stubby large quasi-linear valleys (or sapping channels) that start abruptly from underneath crater ejecta lobes, where surface erosion has uncapped the upper local aquifers (Figure 13). The lobate crenulated aspect of the depressional area in the upper left part of the THEMIS image (Figure 13) suggests the presence of a mudflow. The surface water provided by these channels accumulated in the flat areas between crater rims where fine-textured appearance of the surface deposits suggests a paleo-lake existence (Figure 12). On the top of this flat surface, north-south oriented striations suggest late movement of surface deposits toward the west (Figure 13 linear ridge oriented north-south on the left part of the figure). The MOC image depicts fresh layers of sediments (possibly uncapped by eolian erosion) in the eastern part of the flat area. Interpretation of the THEMIS images suggests that a channel developed westward (because there is a contrast in appearance of surface deposits that could imply
the existence of aquifers associated with the fluvial channel development, Figures 5 lower left, 12 and 13). The presumptive channel cross-cuts the perpendicular striations. At the west end of this deposit that covers the flat area, a channel developed draining from the depression.

The most important valleys developed in the southern Vy crater (crater A Figure 14a), where channels stem from medium-size highly-evolved craters and their ejecta blankets. They organize into a dendritic system and are confined by a major valley that protrudes deep into the Gorgonum basin. All major craters from northern Gorgonum contributed to the formation of tributaries by supplying water from their porous ejecta blankets or from crater interiors. After collecting all the tributaries emerging from the northern Gorgonum temporary paleo-lakes, the main valley split into two valleys that show well-preserved channels (Figure 14a MOC image). The depth of the main valley is 200 m and the secondary valley 150 m (Figures 14b, and 15, transversal profiles).

When reaching a linear structure oriented perpendicular to the valley, the volume of water and sediment was diverted eastwards. Beyond this structure, filamentous channels develop towards the center of Gorgonum (Figure 14b). By comparison, the depths of the channels that develop along the main direction of larger channel are 5-15 m (Figure 15, transversal profiles). In the east, the terrain is highly disorganized as it experienced a large volume of water accumulation (Figure 14c). The channel continued along the northern periphery of Gorgonum, where it intersected and filled a large impact crater (Figure 14c). Water spilled southward at several locations (Figure 14d), but continued to erode and deposit materials at the edge of Gorgonum. Here the structural control over the young channels is evident (see CTX caption 1), the subsequent collecting channel
migrating west. The western collecting subsequent channel crosscuts the northern graben of Sirenum (see CTX caption 2). Another channel ends in northern median Sirenum Fossae trench, being cross-cut by the other Sirenum fault (Figures 6 and 14e). This suggests that the channel was formed in a relative short period of time period between the formation of the two trenches. The long profile of the entire fluvial channel indicates the presence of two temporary paleo-lakes along the channel (Figure 15, long profile along the channel). The disorganized appearance of terrain in these regions could be an indicator of the temporary presence of standing bodies of water along the valley. The dendritic channels that emerge from the northern Gorgonum craters (Figure 14a) could suggest that major overflow events formed the largest fluvial structures.

Alternatively, the presence of a single channel inside the valley could indicate subsequent fluvial head-erosion due to underground water mobilized later, possibly by impact craters. Locally, the presence of channels inside the valley could suggest that the fluvial landform evolved over time, forming floodplains, similar to channels on Earth (MOC image Figure 14a). Most of the channels and tributaries inside the valleys could have been eroded or buried by subsequent processes. The most important characteristic is that the main channel developed along the northern edge of Gorgonum, not toward the center of the basin where the present-day gradient is high. This suggests that at the time of channel (and valley) development the steepest gradient was oriented toward east, where the tectonic trench of Sirenum Fossae developed at approximately the same time, as indicated by the cross-cutting of the northern trench by one younger channel, but not by the older median trench (Figures 6c and 14e).

At a finer scale of analysis within the Gorgonum shallow depressional area, only gullies
and short channels developed, originating from fresh, tilted structures toward the Sirenum trench. Also, within the largest impact structures, channels emerge from layered deposits on the rim. The volume of water necessary to cut these channels was small and probably provided by the remnant water/ice trapped in upper weathered and layered regolith. The fresh appearance of gullies, channels and depositional structures that are visible on the highest resolution imagery (MOC and HiRISE) indicates a relatively recent mobilization of water from upper aquifers (Figure 16).

Fluvial channels in the Atlantis basin have a different type of formation. Channels and valleys have mainly developed on the eastern flank of the basin, where tectonic structures are developed. In the northeastern Atlantis basin, channels are superposed on the slide structures or develop along the graben morphologies (Figures 17 and 18a). An important observation that can be made on the THEMIS mosaic images is that there is continuity in the texture of deposits along the channels (gullies) and within the Atlantis slides, at the base of those erosional structures. On the Atlantis flank, the channels resemble gully or sapping structures that have been fed by aquifers. The major channels cross-cut the horst and graben structures, originating from a pair of depressions located south-west of Magellan (Figure 18a).

These flat depressional areas present homogenous fine materials that resemble lacustrine deposits (Figure 8, southwest of Magellan crater). The southern one is slightly lower than the northern one. Eastward of the northern depression, other channels cut deep into Magellan’s crater rim and advance into the depression. The morphology of materials deposited inside Magellan suggests combined action of an earthflow (see Figures 8 and transversal profile A-B, Figure 18b) and gully formation. The divergent type of fluvial
resurfacing within these depressions suggests changes in base level, and different time of formation. If the Atlantis basin existed at the time when earthflow from Magellan crater developed, as the structural relationships suggest, the runoff would not be diverted toward the crater because it is 1100 m higher than the controlling base level of Atlantis (Figure 18b). In the Martian case, base level has a different connotation than its terrestrial counterpart: in the absence of an ocean level that controls material movement, gravity acts and moves the deposits toward the lowest local elevation. Thus, it is suggested here that water accumulating outside the crater rim as an intercrater lake was able to flow into Magellan via the saturated subsurface, creating the earthflow deposit before tectonism changed the topography of the depression itself. Horst and graben morphologies formed after the emplacement of the thrust-faults. Trellis and parallel channels developed afterwards on the flank of Atlantis and along the grabens, confining the flow toward the newest base level (Figures 8, 17 and 18).

In southern Atlantis, another fluvial process is present in the form of a large outflow channel or a developed valley (see Figure 3 for context, and Figure 19). There, the large valley seems to emerge from a transverse set of fractures. The main channel or valley collects the water along the fractures or from surface aquifers in the case of tributaries. Where the valley intersects the latitudinal fracture it changes its orientation toward Atlantis (white arrow, Figure 19). The flank of Atlantis that is tilted toward the centre of the depression is made up of large sheet slides that have continuity from the northern counterpart of the Atlantis basin (described above in section 3.2, and visible on THEMIS context image). Smaller channels develop on top of the slides, but the structural relationships indicate that the gravitational movements have been produced afterward
(black arrows, Figure 19). The mechanism of water overflow could be similar to that described by Tanaka and Chapman (1990) and Ghatan et al. (2005) for Mangala Vallis, where a large outburst of water originated from Memnonia Fossae.

The smallest visible fluvial-type structures within the Atlantis basin are very similar to the Gorgonum ones and can be associated with the development of gullies or mudflows that extend over short distances. The former appears frequently along crater rims and originates from layered strata, whilst the latter appear at the edge of the “chaotic terrain”.

Development of alluvial fans and undulated basal structures of the contact slopes show that the process involved water and ice-sediment mobility (Figure 20). As in the Gorgonum case presented above on HiRISE images (Figure 16), these structures are small (several tens of m² at most) and young (very few impact craters are superposed on them), proving the youth of water mobility in these locations.

The presence of water in upper deposits during relatively recent times, i.e. Amazonian, is also suggested by the development of a fresh mudflow that originates from the dissected structures in western Atlantis (Figure 21). The “chaotic material” that provided water for mudflow development is seen as the youngest geologic structure in the area, based on geologic interpretation and cross-cutting relationships with the surrounding structures (Figure 2, the geologic map of Scott and Tanaka, 1986, and Figure 8 for morphologic context). Thus, the highest resolution images (THEMIS, MOC and HiRISE), prove the continuity of water-related processes in recent times and contradict the prevailing hypothesis that stipulated water mobility during Noachian-Hesperian eras only (Irwin et al. 2004).
Besides the underground aquifers that provided water for most fluvial channels, runoff can be accounted as the other mechanism that formed fluvial morphologies. Runoff also provides water for reloading underground aquifers, as is suggested by the high-altitude position of many channels that originate close to the rim and high elevated impact crater ejecta. The source of water could be liquid or solid precipitation (Craddock and Howard 2002).

Water could accumulate at the surface during runoff periods in the form of temporary lakes inside depressional areas and craters (Cabrol and Grin 1999), when impact fractures or intercrater depressions were capped with finer sediments due to extensive weathering and deposition. Where condition for stable water accumulation at the surface occurred, transitory reservoirs such as inter- and intra-crater lakes could form. Some craters from northern Gorgonum basin present the most evident signs of lacustrine evolution (Figure 5, craters 2-3). Rampart ejecta structures of medium-size craters (< 1 km) within larger craters are indicators that water was present in upper inter-crater deposits, being possibly connected with temporary lakes (Figure 5, solid arrows). Sugita and Schultz’s (2003) interpretation that fluidized ejecta are the result of impact into a dry target in a reduced carbon dioxide atmosphere does not contradict the mechanism of formation that involves underground aquifers, as it can be applied to more recent periods when water content at the surface was reduced, and for some craters that do not present signs of fluvial modification. In fact, most channels originate directly from craters (Figure 14a), or cross-cut the crater structures (Figure 14d), showing that the craters contained temporary lakes during a period of their evolution. Because only few larger craters (> 30 km in diameter and 300 m in depth) present the rampart morphology, which may be related to the depth
of aquifers (Osinski 2006), the water-related origin of the rampart ejecta is favored herein.

However, the volume of water accumulation inside the craters and depressions was small and preferentially distributed within craters and at the bottom of depressional areas. Although Irwin et al. (2004) suggested that a large paleo-lake formed at the end of the Noachian period, no shorelines have been proven. The mechanisms of paleo-lake overspill in a single event have been dismissed, based on Ma’adim Gilbert delta mode of formation and on the presence of terraces along the valley (Kleinhans et al. 2005). The extent of the channels in the depressional areas could indicate the extent of temporary lakes, but because their lower ends is variable in altitude, they rather indicate successive runoffs than a single lake-infilling period. Tectonism certainly also played a role in the mobility of surface deposits, as described above, so the minimum altitude of the channels can not be accounted as an indicator of the lakes extension. Furthermore, most channels end directly in or close to the “chaotic” areas (Figures 17, 19 and 22), or are diverted by tectonic faults (Figure 14a), or emerge from the “chaotic areas (Figure 21), at elevations much lower than the presumptive Eridania lake shoreline (see below). Thus, the mechanisms of formation for these channels, which can be related to lake formation is much more complicated and developed over time, and cannot be explained by a single period of lake formation as was suggested by Irwin et al. (2004).

Howard and Moore (2004) suggested that an ice-capped paleolake developed at the bottom of Gorgonum basin at the end of Hesperian and beginning of Amazonian epochs. Their interpretation that 2500 m of ice covered the paleolake is still not certain, as the source of water and ice necessary to build such a large body of ice cannot be identified on
images. Moreover, the actual water-related morphologies imprinted in surface terrains do not indicate massive pluvial (lacustrine), nival, and glacial accumulation at surface but rather short-lived runoff and local temporary lake formation.

Surface and underground deposits could trap water released during pluvial/nival periods (Howard et al. 2005), although the amount is difficult to estimate. Water could also migrate gravitationally and accumulate as aquifers. One process that is correlated with the presence of water/ice in surface deposits is terrain softening. Terrain softening is a widespread mechanism that affects crater ejecta lobes, crater interiors or hillside areas (Head et al. 2005, Pathare et al. 2005). This process affects low areas in the Atlantis basin, eastern Gorgonum and the intercrater depressions, where water accumulated gravitationally to the bottom of large flat areas and caused modifications in crater morphology and terrain appearance (fluidization of craters ejecta and carters interior due to creep on ice-rich permafrost- Figure 14d and 14e, debris aprons produced by mass wasting, Figures 16 and 20).

At the lower edge of all fluvial patterns in Gorgonum and Atlantis basins there are the “chaotic morphologies” (Figure 23a). A volume of water released by outflow events could have been incorporated into surface deposits. The water could be delivered through Sirenum Fossae and small channels (Figures 14b, 14e, 22 for Gorgonum basin and 17 for Atlantis basin) and formed, when mixed with sediments, a water-mud mixture. At the bottom of shallow depressions in Gorgonum and Atlantis basins, water-table levels controlled the formation of saturated aquifers. The actual extent of the “chaotic” morphologies in both basins suggests the maximum coverage of the mixture of water-sediments in the area of study. The chaotic terrain is in fact a misnomer for the structures
in Gorgonum and Atlantis basins. As Howard and Moore (2004) stated, the morphology is caused by erosion, not by collapse of upper sediments due to aquifer migration. As the basins underwent a process of subsidence, the surface deposits could be broken in pieces along tensional fractures.

Subsequently, the trenches widen by wall collapse and material removal or by successive thaw-freeze mechanisms, as newer strata were uncapped. The extent of the knobby morphologies (Figure 23a) is probably related to water/ice table extent. Periodic recharge of the upper aquifers could be possible during the periods of high obliquity on these latitudes (Costard et al. 2002), and accumulation of water in the lowest possible depressional areas. Our interpretation is that knobby "chaotic" terrains are produced by dynamics of fractured materials in a tectonic unstable environment.

One aspect of the knobby areas in both basins is related to the presence of smooth quasi-circular depressions in the center of each of the desiccated areas. The altitude of the smooth depression is 200-250 m lower that the surrounding areas. These areas could be the remnants of ice-capped lakes at the bottom of the Gorgonum (Howard and Moore 2004) and Atlantis basins (de Pablo and Fairén 2004) that evolved as playas after the water sublimated from lakes and underlying sediments and colder and drier atmospheric conditions prevailed but the temporal extent of this process is difficult to set, although the number and diameter of craters indicate that is more recent than Hesperian (Figure 23a).

3.5. The complex response of Martian terrains to the action of external processes

The complex response of weathered crust to the action of landforming processes is related to a series of conditions that acted on the Martian surface through time. Each
impact crater created new stratigraphic conditions by modifying the structure of geologic deposits. Accumulation of materials in intercrater depressions and large shallow depressions of Gorgonum and Atlantis partly or totally filled the largest craters at their peripheries. Slide development on the flanks of basins moved large amounts of material down the gradient. Desiccated structures evolved under atmospheric control. A combination of these factors created diverse weathered crust responses to the action of planetary landforming processes.

Continued weathering under diverse conditions altered the surface deposits with intensities controlled by the depth of the porous layer (regolith and mega-regolith) and by atmospheric characteristics. Adjustment of topographic gradients due to impact cratering and tectonism, as well as mass movements, which buried or exposed different deposits, made them susceptible to further exogenic modifications.

This suggests a succession of events starting with the formation of large impact structures, continuing with weathering of surface deposits (coupled with erosion and deposition in different stages depending on the moment of crater emplacement), and finishing with extensive erosional and depositional processes (which may include fluvial and lacustrine resurfacing, mass movement, periglacial, and eolian activity).

In the preceding sections, diverse scale morphologies have been evaluated and their spatial extent presented. The difference between the traditional geologic interpretation and the current morphologic interpretation resides in the scale of study and approach. Large-scale geologic interpretation refers to inferred geologic strata that are overwhelmingly dominated by impact craters. Landform assessment shows the location and repartitioning of each surface morphology that is visible on orbital datasets. In the
following section, cross-cutting relationships between these landforms will be evaluated in order to depict the evolution of terrain assemblages in Atlantis and Gorgonum basins.

4. Discussion

4.1. Landform hierarchy

The assemblage of specific conditions throughout Martian history created the mosaic of actual landforms, which can be analyzed by using satellite images and the MOLA DEM. The areal disposition and morphologic characteristics of diverse genetic landforms, as well as the assemblage of specific landforms inside Atlantis and Gorgonum suggest that a hierarchy of landforming processes, past and current, is displayed here. The impact-cratering process excavated deep into the primordial crust, with amplitudes that on MOLA datasets are bigger than 1000 m, and which probably were higher at the moment of their emplacement (Figure 24).

At the periphery of major impact craters (Mariner, Vy, Magellan, Uv), intercrater depressional areas occupy low areas between crater rims. Superposed on these intercrater depressions are smaller craters (< 10 km) whose morphologies present signs of erosion and deposition due to the action of external processes (which may include fluvial and lacustrine resurfacing, mass movement, periglacial, and eolian activity). The lack of major craters in the shallow depressions of Gorgonum and Atlantis suggests that these regions suffered active modification after the end of meteorite bombardment. The geologic interpretation of these large areas is that they are subdued cratered terrains. These deposits sit transgressively on the cratered structures. Subsequent erosion and accumulation of materials within these areas is indicated by the aspect of the major
craters from their periphery and interior and continuous decrease in dimension toward the centre of the depressional areas.

Before the extensive erosion took place, the early period of large crater formation established the regional topography and crustal structure, and defined the watersheds, flow directions, and crustal porosity (Hartmann 1973, Segura et al. 2002). The cratering process has a twofold role in modifying the Martian landscape: it brings energy, material and water into the Martian system (Melosh 1989), and also brecciates the upper lithosphere, disrupting the pre-existent weathered mantle. It is obvious that the crater-generated watershed boundaries evolved through time, being controlled by other processes of similar magnitude, such as tectonism.

However, for some locations, the craters played an important control for the manifestation and evolution of subsequent external processes and associated morphologies (e.g. craters in the northern and eastern parts of Gorgonum and in the eastern Atlantis basins).

In southern and western Arsia Mons the tectonic modifications of crust are visible in the form of large ridges roughly concentric to Tharsis (Wilson and Head, 2002) (Figure 25). These are presumably large thrust fault blocks (Grott et al. 2007). The pattern of the Tharsis-radial graben and orthogonal normal and reverse blocks extends as far as the Atlantis and Gorgonum basins and affects both Noachian and Hesperian structures (Anderson et al. 2001). The upper-crust structure can be inferred from the surface distribution of ridges and faults. In Gorgonum and Atlantis basin, the pattern of perpendicular faults indicates that the geologic strata have been affected by large-scale geologic mechanisms such as formation of folded and faulted structures associated with

Place Figure 25 here
lateral tectonic stress emerging from Tharsis. Thrust faults concentrically align to Tharsis dome indicates that the displacement of geologic structures is concordant with the compressive stress generated by the growing Tharsis dome (Meige et al. 2003).

The graben structures that flank the Atlantis basin on both sides, which are superposed on the thrust-faulted morphologies, indicate that the upper crust has been fractured due to contraction of the brittle crust at the base of the upper weathered crust. The same mechanism of thrust-fault formation is present in western Arsia flank, at the contact with the cratered terrain, where graben morphology developed at the toe of the thrust-fault. This indicates also the fracturing of upper deposits in front of the tectonic structure (Figure 26). The combination of tensional and compressional features may be explained by the model in Figure 27. Tensional faulting evolved recently into grabens at the toe of thrust-fault blocks.

Surface materials moved on these undulated structures, generating slides in both basins. In Gorgonum, the slide of the upper materials has been increased by the action of Sirenum Fossae emplacement (Figures 9 and 10 indicate the amplitude of the movement near Sirenum Fossae, profile c). These large-scale movements contributed to the formation of two large tectono-structural basins flanked and cross-cut by faults (Figures 6 and 25). The tectono-structural basins have been disposed discordantly on the top of the cratered structures.

Impact cratering and tectono-structural modifications of the crust thus constitute the higher hierarchical events that acted in the Gorgonum and Atlantis basins. The action of these processes formed large landscape assemblages, visible at the regional context on THEMIS orbital images (Figure 1, the regional scale of analysis).
At a lower level of hierarchy, exogenic processes acted to modify the pre-existing landscape. An important contribution was the interface between weathered crust and the atmosphere. Continuous evolution of physical and mechanical characteristics of the weathered crust, correlated with the topographic characteristics, played a major role in the complex response of the weathered crust to the action of geologic and landforming processes. External processes locally modified the inherited topography that comprises the initial deposition of geologic materials. The spatial extent of all landforms generated by the action of gravity, fluvial and lacustrine resurfacing and periglacial activity is sparsely distributed within larger landscape assemblages, and can be seen in increased resolution imagery (Figure 1- the local and landform scale of analysis). An example of the distribution of different-scale morphologies is provided by the cross-cutting relationships between the fluvial and the geologic deposits, indicating the succession of events throughout the entire area of study.

The intercrater depression extending north from northern Gorgonum, mapped as Npl2 series, presents a succession and a continuity of paleo-processes which acted after the formation of the main cratered terrain (Figure 12). This suggests a transition of erosive and depositional patterns superposed on different chrono-stratigraphic series. Tributaries emerging from crater ejecta deposits (Npl1) have a continuity of evolution on the floor of the depression (Npl2), where they formed an integrated fluvial and lacustrine pattern. On Npl1 materials, the channels start from the ejecta structures. On the Npl2 materials at the bottom of the depression, distinct sinuous channels are visible on THEMIS and MOC images, forming an integrated structure of valley networks (e.g. Figure 14). The channels
and valleys continue downwards on Npl$_1$ structure and then end in a flat depression that is interpreted to be a Hesperian ridged area. The channel ends in a medium-sized crater on Npl$_1$ deposits westward (Figure 12). The continuity of fluvial resurfacing among these three chrono-stratigraphic series clearly indicates that it formed long after the moment of geologic deposit emplacement. Westward, the major channels and valleys that originate from craters continue deep inside the Gorgonum basin, crosscut two successive chrono-stratigraphic series (Npl$_1$ and Npl$_2$) (Figure 28). There, the fluvial landforms are superposed also on top of fresh deposits that constitute the flank of Gorgonum basin. The relative youthfulness of those deposits is indicated by the number, diameter and freshness of craters superposed on these structures (Howard and Moore 2004) (Figure 14 high resolution MOC and CTX images). In the Atlantis basin, fluvial channels that dissect Npl$_1$ and Hpl$_3$ deposits protrude deep within the basin, also crosscutting two geologic series (Figure 28).

The desiccated structure that was misinterpreted as “chaotic terrain” in the geologic nomenclature is located at the end of all fluvial patterns. From the youngest Hcht deposits originate one of the best-preserved alluvial features that develop in the area of study (Figures 21 and 28), which end in the older geologic structure of Hesperian smooth deposits. Thus, the succession of fluvial, lacustrine and periglacial events clearly indicates that these small surface morphologies do not reflect the disposition of geologic strata.

In summary, the larger landscape assemblages, created by impact cratering, volcanism and tectonic events, are superposed with smaller ones caused by exogenic forces: fluvial
and lacustrine resurfacing, mass movements, eolian, periglacial and dry cold weathering ones.

4.2. Evolution of landforms in Gorgonum and Atlantis basins
The landform hierarchy and genetic linkages that exist among the diverse landforms in the Gorgonum and Atlantis basins set conditions for the evaluation of their evolution, as described above. Two key contact areas permit a reinterpretation of the succession of processes that shaped the Gorgonum and Atlantis basins.

First, the development of the channel in Gorgonum basin at its northern edge, the crosscutting relationships with surrounding fresh deposits and the connection with the Sirenum Fossae, all reinforce the interpretation that fluvial resurfacing acted concomitantly with, and sometimes postponed, the tectonic modification of the basins (Figures 6c and 14e). The development of Sirenum Fossae corresponds to Noachian-late Hesperian eras (e.g. stage 1-3 Anderson et al. 2001). In southeastern Atlantis, the channel development predates slide development, and could be related to the advance of Sirenum Fossae in this area (Figure 19). All the channels and valleys in the area of study are superposed on deposits that are affected by mass movements and reduced post-Noachian cratering. As Sirenum Fossae affects Amazonian strata in western Arsia Mons (Figure 25) (Scott and Tanaka 1986) and remained active in our area of study affecting young knobby deposits (Figure 28a), it is assumed that the long term evolution of the graben extends to more recent times (Amazonian). Second, the development of a debris flow in Magellan and tectonic-controlled gullies toward Atlantis suggests base-level variation in north-eastern Atlantis. This indicates that the Atlantis basin was not developed at the time
of earthflow formation inside Magellan crater.

Both situations suggest that fluvial and lacustrine events are linked with planetary mechanisms of control that formed Atlantis and Gorgonum, and both are related to the evolution of the upper part of the Martian regolith (e.g. the inherited major impact structures). The cratered structures in the area of study had been transformed by the modification of marginal upper-crust structures due to Tharsis volcanism. Consequently, small-ranked fluvial and lacustrine landforms superimposed on major impact structures may have developed more recently than Noachian, considering that they affect just medium-size craters and have superimposed on them only minor craters of which the current literature assigns a Hesperian and Amazonian time of formation (Hartmann and Neukum 2001).

Specific geologic and morphologic descriptors that describe the appearance of surface structures on Atlantis and Gorgonum basins permit an evaluation of stages of evolution. The evaluation is based on crosscutting relationships between landforms. Three stages of evolution can be depicted at the regional scale of the study area (Figure 29):

Stage I: During the heavy-bombardment period, major craters were formed establishing the main direction of energy and mass movements and sedimentation. It is possible that Atlantis and Gorgonum originally formed during the initial stage as major impact craters (Frey 2005) but later impacts or other processes removed any obvious signs of their crater morphology, leaving only the shallow depressions visible nowadays on the orbital images (Figure 4). The lobate plan forms of both basins suggests that the depressional areas had a different genesis than that generated by meteoric impact, unless they were originally each composed of several impacts (Howard and Moore 2004, Frey 2005).
Stage II: The emplacement of the Tharsis volcanoes triggered the tectonic displacements along Sirenum Fossae and also formed the arcuate thrust-fault blocks, well developed near Mangala Vallis (Tanaka and Chapman 1990, Ghatan et al. 2005), but now shown to be present in the study area as well (Figure 25). Atlantis and Gorgonum basins started to form as tectono-structural depressions between these inverse fault blocks. In the southern Mariner crater tectonism formed a large trough (Figure 6a, trench indicated by the white arrow). Local base levels for exogenic processes changed, and water accumulated temporarily inside large craters and intercrater depressions in northern Gorgonum. A paleolake formed behind southern Magellan’s crater rim, that later flowed through fractures and formed an earthflow and gully complex inside Magellan (Figure 18). As the Sirenum Fossae protruded into Gorgonum, release of water from the faults, aquifers and intercrater structures formed temporary paleo-lakes and filled low-standing aquifers. The northern Gorgonum channel developed, while the Atlantis upper deposits slid along marginal fractures. On the Atlantis’s western flank, tectonism fractures the large craters (Figure 8, crater A). On the eastern flank, gravity and changes in base levels triggered a massive landslide (Figure 8). Tectonism affected the south-western Atlantis flanks, and water released along it formed an outflow channel. Sirenum Fossae advanced into southern Atlantis, forming deep tectonic trenches, and diverting the outflow mentioned above (Figure 19). Water mixed with surface sediments formed thick mud deposits at the bottom of both basins. Impact craters were highly modified by these fluvial and lacustrine paleo-events.

Stage III: A thinning atmosphere and dropping temperatures contributed to the sublimation of water from surface deposits. Initially, terrain softening was extensive,
affecting subsurface deposits across the entire depressional areas. Freeze-thaw cycles and thermal creep contributed to enlarge cracks and exposed more strata to weathering. Desiccation of surface mud-ice deposits occurred. As a result of continuous sublimation, desiccated terrain formed at the base of Atlantis and Gorgonum basins (Figure 23). Small impact craters (<1 km), eolian deflation and deposition, creep, gullying and gravity slides are the current morphologic processes which affect the entire area (seen in the following high-resolution images: Figures 9b, 11, 13, 14 c and d, 15, 20, 21, 22b).

5. Conclusions

The magnitude of the landforming processes can be associated with the spatial distribution of planetary landforms and with their temporal evolution. Landform hierarchy, as well as correlation among diverse mechanisms and processes can elucidate the evolution of landforms inside these basins. This paper challenges the traditional interpretation that surface terrains evolved mainly during a period that followed the moment of impact bombardment (late Noachian- early Hesperian). Instead, three major periods of landscape evolution can be depicted, which correlate to the magnitude of geologic and landforming events. These periods extend throughout the entire Martian history. Landform evolution is revealed here at different scales of study. We have outlined a mechanism of evolution based on interpretation of processes that is explained by watershed delineation due to impact cratering, tectonic control over the base levels, effects of Tharsis-related tectonism of upper weathered strata, and the role of atmospheric control on defining the past and actual landform assemblages in Gorgonum and Atlantis basins. Because there is no conclusive proof that Eridania’s shorelines have been
preserved on the younger structures that surround the chaotic morphologies, and because there are no major channels that could deliver the volume of water suggested by Irwin et al. (2004), the hypothesis proposed here is that the runoff water created small, short-lived (at geologic scale) landforms. The existence of lakes in the depressional areas or crater structures may also have a short existence due to continuous depletion of atmosphere and water-cycle instability after the Noachian magnetic shutdown (Acuña et al. 1999).

There is a hierarchy of forms in the Martian landscape that developed over different time spans in response to different sets of conditions. Throughout time, impact cratering brought into the planetary system infrequent but highly effective energy and material inputs. It created temporary base levels for external processes and disrupted the upper lithosphere. It also created the main watersheds inside which the cascade of energy and materials were distributed. Base level played an important role in distributing the available geomorphic work through the system, and associated with the endogenetic forces (volcanism and tectonism) set the conditions for further evolution of exogenetic forces. Volcanism and associated tectonism acted as triggering factors for external paleo-processes, subordinating them. The response of Martian upper weathered crust to the combined action of geologic and landforming processes was complex. Climate imprinted specific signatures on landform assemblages, as seen on upper weathered crust. As consequence, fluvial and lacustrine paleo-landforms are sparsely distributed along disrupted watersheds, being threshold generated, and highly subordinated to the four processes and mechanisms described above.

In summary, the evaluation of landform disposition based on high-resolution satellite
images and DEM interpretation depicts the inter-dependence between different types of processes, the most important of them remaining the correlation between the formation of fluvial landforms and tectonic modifications in Gorgonum and Atlantis basins. The chapter also presents a different approach of analyzing the extraterrestrial planetary surfaces, in which the focus is on regional-scale interpretation of landforms and cross-cutting relationships between them, instead of on the interpretation of geologic sequences.
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Figure captions:

**Figure 1** Scale variation in planetary image interpretation (Source images from planetary and regional-scale geologic interpretation of Viking mosaic and THEMIS imagery, to local scale of landform description on HRSC H0538_0000_ND3 and MOC M20-00286 imagery).

**Figure 2** Geologic map of Gorgonum and Atlantis basins centered at 171° W, 34° S (Scott and Tanaka 1986).

**Figure 3** THEMIS mosaic context image of Gorgonum and Atlantis basins. Location of following figures is indicated by rectangles.

**Figure 4** Different types of surface morphologies seen on THEMIS mosaic imagery of Atlantis and Gorgonum basins (Ch.= channel; E/D= craters and plains affected by erosion/deposition; HCT= highland cratered terrain; M= mass movements; Sub.= subsidence zones (=tectono-structural basins); T= tectonic trenches; V= volcano).

**Figure 5** Types of crater morphology in northern Gorgonum basin: medium-size craters modified by fluvial erosion and deposition (craters 1-3) or heavily eroded and affected by sedimentation (craters 4-6); rampart ejecta craters (dark arrows) vs. craters without ejecta blankets (dotted arrows). Note that modified craters are medium in size (less than 20 km) and superposed on larger craters or intercrater depressions.

**Figure 6** Tectonism in Gorgonum and Atlantis basins. a. The context image is a composite of DEM/slope/shade rasters. The figure shows the disposition of a regional pattern of tectonic faults in Gorgonum and Atlantis basins. Dark arrows indicate parallel fractures to Sirenum Fossae. A major tectonic trench is indicated in southern Mariner crater (white arrow); Dashed boxes b and c. represent the zoom-in on the THEMIS images that show the *en echelon* type of faulted structures in Gorgonum basin (dotted arrows); White arrows indicate the position of Sirenum faults at the entrance in Gorgonum basin; dark solid arrows indicate the position of an erosional pattern (probably the lower end of an outflow channel) cross-cutting the northern fault. Fault numbers are shown in the context image.

**Figure 7** Topographic profile in western Gorgonum showing the gradient of different surface structures and the possible role of Sirenum Fossae emplacement in increasing the slope of surface deposits toward the centre of the basins. Numbers indicate the location of faults.

**Figure 8** Tectonic modifications of Atlantis basin in the form of (a) transversal (solid arrows) and (b)
longitudinal fault that have continuity in Gorgonum (dashed arrows) and affect a possible intrusive (dike) structure (see text).

**Figure 9** Gravitational slides in western Gorgonum basin (1 to 3 from the youngest to the oldest). MOC R22-01047 image (right) shows the displacement of slide scarp after the emplacement of Sirenum Fossae fault. Transects a, b, and c are shown in Figure 10.

**Figure 10** Topographic profiles of the gravitational slides in western Gorgonum basin. Profiles are oriented from the flank of Gorgonum (higher elevations) to the bottom of Gorgonum basin. See Figure 9 for locations of the transects.

**Figure 11** Volcanic structure in western Gorgonum just north of Sirenum Fossae. A THEMIS mosaic image (left) shows crater pits (collapsed lava tubes) oriented toward volcanic crater (dark arrow). A possible lahar developed toward Gorgonum (white arrow); THEMIS visible V26703011 image (right) show a possible volcanic flow (arrow) and a sharp transition between different lava flows.

**Figure 12** THEMIS mosaic image superposed on shaded relief shows the continuity of fluvial resurfacing process in northern Gorgonum area. Arrows indicate the channel continuity across three geologic deposits (Npl1, Npl2, and Hr). The box indicates the location of Figure 13. Elevation range is between 3152 m (pink) and 1249 m (blue).

**Figure 13** Valley and channel (arrows) development in intercrater depression in northern Gorgonum area (source image THEMIS mosaic). MOC high-resolution image M22-02379 shows the meandering channel at the bottom of the floodplain (valley). See Figure 12 for location.

**Figure 14 a** Outflow channel development in northern Gorgonum basin. Left image (MOC FHA-01368 2.88 km wide) shows meandering channels on the floodplain just before entering Gorgonum basin. Dashed boxes represent the location of the next figures. A-B is the long profile along the channel (see Figure 15).

**Figure 14 (continued)** b) possible tectonic dam at the entrance in northern Gorgonum diverted the flow eastward; CTX image caption P06_003504_1449 shows channel position in front and along a possible tectonic trench. Black arrow indicates subsequent channeling on one valley; c) temporary paleo-lake formation behind a structural remnant; CTX image caption B05_011613_1439 shows channel development along main valley. Black arrows show the main channel emplacement. Source images: THEMIS mosaic. Transects CD and EF are shown in Figure 15.
Figure 14 (continued) d) crater lake filled with water and spilling over along different locations until confined along the median channel caption 1; multiple phases of structural control over consequent channels- shown here with black arrows and permanent retreat of collecting subsequent main channel (1-3)- shown here with white arrows (CTX images P06_003438_1430 and P14_006629_1425); C indicates the location where a reconsecvent channel captures the main channel 2 in a subsequent phase of erosion, after the initial flow was diverted west due to structural tilting. Caption 2 shows the crosscutting relationship of the subsequent collecting channel 2 in the second phase of development with the northern Sirenum trench (CTX image P07_003860_1423); e) the contact with Sirenum Fossae reveals that the development of the central tectonic trench occurred prior to the period of main outflow channel formation, where the main subsequent channel 2 collected the flow. Source images: HRSC H0538_0000_ND3 draped on HRSC DEM.

Figure 15 Long profile along the outflow channel in northern Gorgonum basin (A-B, see Figure 14a); transversal profiles across the main valley before the contact with a presumptive tectonic displacement (C-D, see Figure 14b for location) and then across the rills developed beyond that structure (E-F, see Figure 14b for location).

Figure 16 HiRISE images PSP001816-1410 (38.7° S, 166° W) and PSP001684-1410 (38.9° S, 164° W) showing recent gully development within craters in eastern Gorgonum basin.

Figure 17 Trellis channels on the eastern flank of Atlantis basin resemble gully development. Basal slides (black arrows) develop in continuity of gullies. The material deposited by gullies has continuity at the bottom of the basin (dotted arrows) and embay the desiccated morphology. Diagrams show the topographic profiles of slides developed at the base of the gullies.

Figure 18 a. A three-dimensional oblique perspective in northeastern Atlantis basin shows the two local base-levels, which had a major role in defining flow directions (see text). b. The topographic profile between Atlantis and Magellan shows local base level difference. Two stages of aquifer migrations and runoff develop.

Figure 19 Channel and valley development in south-eastern Atlantis basin (source image is THEMIS mosaic). The white rectangle area is shown in detail in the lower figure, which is a THEMIS high-resolution mosaic (V26441005 and V26728010) that shows in detail the valley development: white arrow
indicates the elbow of capture; black arrows indicate the scarp position of subsequent gravitational sliding.

**Figure 20** Recent gullies and fans development in south-eastern Atlantis basin MOC E0201674 image centered at 174.69°W 38.69°S in eastern Atlantis basin.

**Figure 21** Mudflow in western Atlantis basin originates from chaotic (desiccated mud) structure (see figure 7 for context) Context images THEMIS mosaic (left) and MOC M15-00229 (right) centered at 179.54°W, 36.44°S.

**Figure 22** THEMIS mosaic showing the contact (arrows) between northern slopes of northern Gorgonum basin and the chaotic terrain morphology. Channels developed in two stages (first is indicated by meandering channels in the upper right part of the image, and the second by a quasi-linear channels developed on the lower tilted area emerging from a pitted morphology. Straight channels indicate that in the second phase of fluvial evolution, gradients steepened significantly, indicating a possible sunk of base levels). Channels end just north of the “chaotic” terrain’s edge. Image width is 90 km. Image is centered at S 36° 02′, W 171° 41′ (see location on context figure 3).

**Figure 23** a Mud/ice mixture forms at the bottom of Gorgonum and Atlantis due to accumulation of water and aquifer saturation. Climatic control determined the formation of polygonal structures that were desiccated by continuous sublimation. Eolian or mass wasting erosion could move out finer sediments from troughs. Context image: DEM with altitudes that range between 1000 m and -500 m for both basins b. HiRISE image PSP_001948_1425 shows smooth lobate aspect of polygons and erosion of polygonal flanks/eolian deposition in troughs.

**Figure 24** Magnitude of upper crust modification by impact craters in Gorgonum and Atlantis basins. Solid circles indicate primary major craters. Dashed circles indicate eroded medium-size craters that are superposed on intercrater depressions and structural basins. Transect graphs a, b and c show the magnitude of cratering. Arrows indicate the position of several impact craters.

**Figure 25** Arsia Mons volcanism and its role in triggering the development of marginal displacements of surface deposits in eastern Memnonia and Phaethontis areas. Radial fracture development (Memnonia Fossae (M.F.) and Sirenum Fossae (S.F.) - dotted lines) associated with Hesperian dike intrusions complements the sinking of depressions located behind these deformational structures. Continuous concentric lines represent reverse (thrust) faults generated by compression due to Tharsis bulge extension
over the adjacent crust. Context image: Mars digital elevation model. Numbers indicate the position of the next figures.

**Figure 26** a. Thrust-faults and graben development (marked by the letter G) in eastern Atlantis and b. on Arsia flank contact with cratered region. White arrows indicate the front of thrust-faulted blocks. Source images: THEMIS mosaic.

**Figure 27** Mechanism of thrust-fault generation in south-western Tharsis area.

**Figure 28.** Channels crosscutting different geologic deposits prove that they formed long after the formation of individual large-scale geologic assemblages (blue arrows represent the direction of runoff; the arrow at the western edge of Atlantis basin indicates a channel emerging from an younger geologic sequence (Hcht) and ending in an older one (Hpl3)- see also Figure 21). Dotted lines represent the position of tectonic fractures. Black arrows represent direction of gravitational slides on the flank of both basins.

**Figure 29** a. Regional map of landform distribution and the relative structural position of upper geologic strata: I. basal impact structures; II. basin structures: 2. tectonic trenches, 3. inter-crater depressions, 4. tectono-structural basins; III. recent resurfaced deposits: 5. fluvio-lacustrine deposits, 7. inner-crater deposits, 8. knobby "chaotic" materials. b. Summary of landform hierarchy and evolution. Shadowed areas indicate regions not affected in the correspondent stage of evolution. In upper image (c), black vertical arrows indicate fluvial processes, white arrows indicate "chaos" resurfacing. In middle image (b), white arrows indicate the direction of upper strata movement, white circle indicates the location of volcano, and dotted lines the presence of major fractures. Scale bars are 5 km long.
2) Figure
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Figure 2: Profile showing:

a) intercrater depression 1 - slope $\approx 0.5^\circ$
   intercrater depression 2 - slope $\approx 1.07^\circ$
   contact depression - slope $\approx 1.3^\circ$

b) Western Gorgonum basin

- slope 2.1°
- slope 1.8°
- chaos slope 3.9°

Vertical exaggeration x10
2) Figure
A-A'- profile

Slide scarp

Continuity of gully

Deposition within Atlantis basin
2) Figure
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2) Figure

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2) Figure

Chaos terrain

50 Km

1 km
Figure

Topographic profile A-B

Arsia Mons
17,600 m
Figure

![Image of Martian surface features with scale bars and north arrows.]

Scale: 50 km

G

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LANDFORM HIERARCHY

FLUVIAL LANDFORMS AND KNOBBY TERRAINS

TECTONO-STRUCTURAL BASINS

LARGE IMPACT CRATERS

LANDFORM EVOLUTION

3. FORMATION OF FLUVIAL SYSTEMS FORMATION OF KNOBBY TERRAINS AT BOTTOM OF BASINS

2. FORMATION ON TECTONO-STRUCTURAL BASINS ALONG LINES OF FRACTURES ON TOP AND AT PERIPHERY OF MAJOR CRATERS HEAVY EROSION OF MEDIUM IMPACT CRATERS WITHIN THE BASINS AND INTERCRATER DEPRESSIONS FORMATION OF VOLCANO

1. EMLACEMENT OF LARGE CRATERS DURING THE HEAVY METEORITE BOMBARDMENT FORMATION OF INTERCRATER DEPRESSIONS