EPSC Abstracts
Vol. 7 EPSC2012-390 2012
European Planetary Science Congress 2012


# Fluvioglacial Formation Scenario for Valleys and Ridges at the Deuteronilus Contact of the Isidis Basin, Mars.

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## Introduction

Numerous small valleys are incised into the plains of the southern Isidis basin rim between 82˚/90˚E and 3˚/6˚N and trend tens of kilometers to the north following the topographic gradient toward the center of the basin. The valleys originate exclusively north of the mountainous terrain of the Libya Montes (Fig. 1A, red unit) [e.g.,1-4] and are indicative of Late Hesperian fluvial activity [1,4,6], which was spatially and temporarily distinct from intense and repeated Noachian fluvial activity in the Libya Montes [1-4,6]. Most of the valleys terminate on the smooth Isidis exterior plains (hereafter IEP; Fig. 1A, green unit). A few of them continue across the boundary between the IEP and the knobby Isidis interior plains (hereafter IIP; Fig. 1A, blue unit) and occur then as sinuous ridges in the IIP. This boundary has been discussed as a part of the Deuteronilus contact [e.g.,7,8] and is characterised by an onlap of the IIP onto the IEP, i.e., the IIP are superposed on the IEP. Therefore, the ridges occur stratigraphically higher than the valleys. Because the valleys transition to ridges into less-eroded terrain, their formation is difficult to explain by relief inversion scenarios proposed for sinuous ridges common on Mars [e.g.,9-11] and Earth [e.g.,12,13].

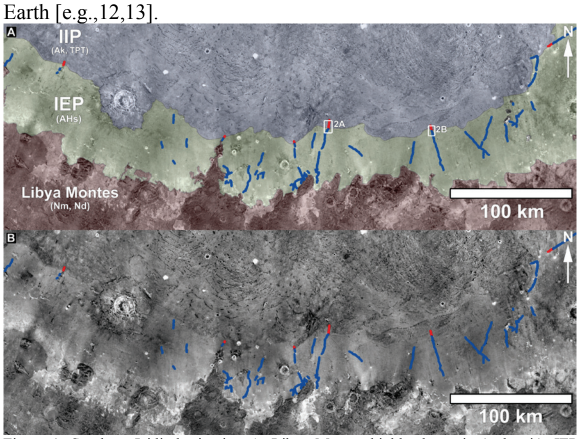


Figure 1: Southern Isidis basin rim. A. Libya Montes highland terrain (red unit), IEP (green unit) and IIP (blue unit). Valleys (blue lines) trend toward the center of the Isidis basin and appear as ridges (red lines) within the IIP. B. Thermal Emission Infrared Spectrometer (THEMIS) IR-Night mosaic.

Based on our investigations we propose an alternative fluvioglacial formation scenario for the morphologic-geologic setting at the Deuteronilus contact. We suggest that the ridges could be glacial meltwater or subglacial streams (eskers) similar to possible eskers identified elsewhere on Mars and Earth [e.g.,14-17] and that their formation is associated with a stationary ice sheet of a proposed Late Hesperian Isidis sea that readily froze and sublimed and resulted in the formation of the IIP [4,6]. The proposed formation scenario has also implications for the formation of the Isidis thumbprint terrain (hereafter TPT) [e.g.,5,6] that is located in the IIP.

## Morphology and Stratigraphy

Most of the valleys incised into the smooth IEP occur along the southern Isidis basin rim. Only a few valleys have been identified on smooth plains elsewhere in the Isidis region [6]. The valleys, typically between ~50 and ~250 meters in width, originate near the boundary between the IEP and the Libya Montes. Although the source of most valleys is difficult to trace, the valleys do not cross distinct topographic breaks in slope at the boundary between the Libya Montes and the IEP, such as the cliffs of the Arabia contact [4], indicating that they are not connected with the Libya Montes valley networks. In addition, model ages show that the valleys were formed between ~3.3. and ~2.7 Ga [4,6] and therefore significantly later than dendritic valley networks identified in the Libya Montes, which ceased to form at the Late Noachian/Early Hesperian boundary [2]. The upstream section of the valleys is characterised by a network of valley segments tens of meters wide and kilometers long. Possible main valleys and associated tributaries are difficult to distinguish. The midstream section mostly shows individual and elongated valleys that trend tens of kilometers toward the center of the basin, associated tributaries are absent. Some valleys become faint, shallow and segmented throughout the IEP. A few kilometers south of the Deuteronilus contact [7,8], which represents the lower end of the IEP [4], the general slope toward the center of the Isidis basin flattens. Here some of the valleys show sinuous sections (sinuosity index of 1.1 – 1.35).

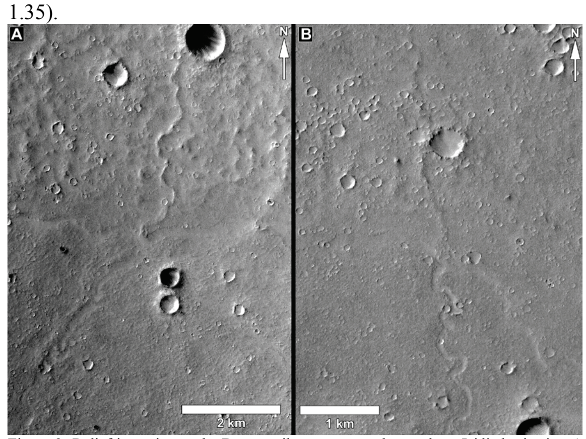


Figure 2: Relief inversion at the Deuteronilus contact at the southern Isidis basin rim. A valleys trend to the north toward the Deuteronilus contact. Across the contact, the morphology changes and a sinuous ridge represents the continuation of the valley.

The downstream sections of the valleys are either characterized by valleys getting progressively shallower and terminating on smooth IEP or by the continuation of the valleys as ridges across the Deuteronilus contact through the IIP (Fig. 2). Ridges continue only for a few kilometers toward the basin center, have widths typically in the same range of the valleys, show variations heights, typically less than 20 meters, and have rounded crests but also show the similar sinuosity of the valleys (sinuosity index of 1.1 – 1.4)

## Formation scenario

Based on our observations and results, we consider a fluvioglacial scenario, which is based on melting and sublimation of a stationary ice sheet that possibly filled the Isidis basin and which is comparable to the formation of terrestrial (subaqueous) eskers [15-17]. However, we also recognize alternative volcanic formation scenarios, because each explanation requires its consistency with both the knobby morphologies of the IIP and possibly also with the cones of the TPT, which have been previously interpreted by some authors as results of volcanic processes [18-20].

After the emplacement of the IEP in the Hesperian between ~3.3 and ~2.7 Ga [4,6] but before the emplacement of the IIP (~<2.7Ga) [4,6], the small valleys have been incised (Fig. 3A) by late stage fluvial activity [4]. Valley erosion must have been short-term, because tributaries and morphologies, which would suggest intense and repeated incision are absent. As the valleys originate exclusively on the smooth IEP they do not represent a continuation of fluvial transport from the highlands to the floor of the Isidis basin. Absolute model ages indicate a formation significantly later than the Late Noachian / Early Hesperian Libya Montes fluvial activity. However, based on the morphologic characteristics of the valleys and the absence of (local) volcanic sources in the upstream region near the Libya Montes, we exclude that flowing lava was involved in the formation of the valleys.

Some of the valleys become faint on the IEP and terminate south of the Deuteronilus contact. Consequently, they were not superposed by the younger IIP and did not continue as ridges. However, valleys, which extended farther toward the basin center were superposed by the IIP and occur now as ridges. Because ridges occur always as a continuation of the valleys and are absent elsewhere at the Deuteronilus contact at the southern Isidis basin rim, their formation is closely linked with the formation of the valleys. In addition, the ridges start directly at the boundary between the IEP and IIP and indicate that ridge formation is attributed also to the formation and extent of the IIP.

On Earth, initial processes for relief inversion from a valley to a ridge include either the filling and cementation by lava flows that possibly drained into the pre-existing valleys or the deposition of coarse-grained fluvial sediments during valley formation [e.g.,9,12,13]. The valley floor becomes more erosion-resistant than the surrounding terrain after a diverse range of processes, including degassing, cooling and sublimation. The valley remains as a ridge or a series of hills after subsequent erosion and exhumation by water and wind [e.g.,9]. However, the ridges near the Deuteronilus contact are difficult to explain by erosion, because the ridges occur in the IIP, which are superposed onto the IEP and into which the valleys are incised. In addition, fluvial landforms, in particular typical twin lateral streams [9] that could have resulted in erosion of surrounding materials are absent within the IIP [1,4,6]. As wind is the dominant process on Mars to remove less resistant surrounding materials [21,22] it may have played a role in the exhumation of the ridges to its present state. Wind erosion might be inconsistent with the inversion of relief along a sharp boundary such as the Deuteronilus contact.

Although the IIP are discussed by multiple authors as the result of volcanic formation processes [e.g.,18-20], the continuation of valleys as ridges across the Deuteronilus contact into less eroded terrain is inconsistent with the common formation of inverted valleys elsewhere on Mars, which transition into more eroded terrain [9-11]. The morphologic-geologic setting at the Deuteronilus contact more likely suggests that the ridges may represent eskers that formed in the Early Amazonian, when a stationary ice sheet (Fig. 3B) possibly filled the Isidis basin, similar to the one proposed that might have filled the northern lowlands and resulted in the formation of the Vastitas Borealis Formation (VBF) [23]. The maximum extent of the possible Isidis glacier may correspond to the location of the Deuteronilus contact at which the valleys continue as ridges (Fig. 3B,C). In a geological short period, the glacier could be covered by a sedimentary veneer due to sublimation and deposition of wind blown materials [23]. Subglacial melting resulted in preferential transport along the pre-existing valleys, which may have served as paths for the transport of materials. Because the pressure increased toward the basin center, water and materials were transported toward the glacier margin. The drainage of water should have resulted in the formation of a proglacial lake [15], although we could not identify any lacustrine deposits along the boundary between the IIP and the IEP. However, during melting and retreat of the glacier toward the basin center (Fig. 3C), materials were deposited along the pre-existing valley course and may have resulted in the formation of a ridge that reflects the course of the pre-existing valley (Fig. 3D). Complete sublimation of the possible glacier finally resulted in the deposition of the rough IIP [23].

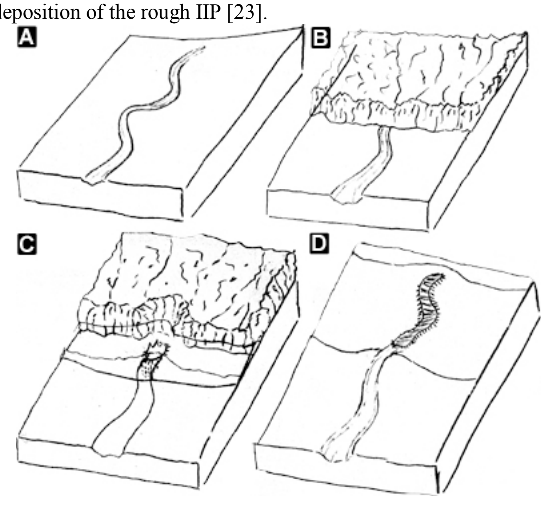


Figure 3: Relief inversion at the Deuteronilus contact is explained by fluvio-glacial scenario. A. Valley incision. B. Formation of stationary ice sheet. C. Retreat of glacier and deposition on materials due to subglacial melting and subaqueous deposition. D. Formation of Deuteronilus contact and ridges.

## Conclusions

Our observations suggest that (1) small valleys were formed later than Late Noachian Libya Montes valley networks and earlier than the IIP, (2) the ridges represent the continuation of the small valleys and are associated with the extent and formation of the IIP, (3) the ridges show similar morphologies to terrestrial eskers, i.e., rounded crests and variations in width and height [9,16,17]. Although the scenario we propose could perhaps better explain how the valleys and ridges were formed than an alternative volcanic formation scenario can do, in particular when compared with terrestrial analogs [12,13,15-17], significant parts remain uncertain and speculative, including, i.e., the lack of sources of the frozen sea [4,24], the thickness of the possible glacier (esker heights relate to about 1/20 of the ice cover) [15], the absence of glacial landforms in the vicinity of the eskers [10] and the direction of the drainage of water and materials.

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