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Valleys and Ridges at the Deuteronilus Contact in Isidis Planitia, Mars: Implications for an Isidis Sea

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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 Isidis Planitia. The valleys originate exclusively north of the Libya Montes highlands (Fig. 1) [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]. The majority of the valleys terminate on the smooth Isidis exterior plains (hereafter IEP; Fig. 1). A few of them continue across the boundary between the IEP and the knobby Isidis interior plains (hereafter IIP; Fig. 1) and occur 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 scenarios based on relief inversion proposed for sinuous ridges on Mars [e.g., 9-11] and Earth [e.g., 12,13].

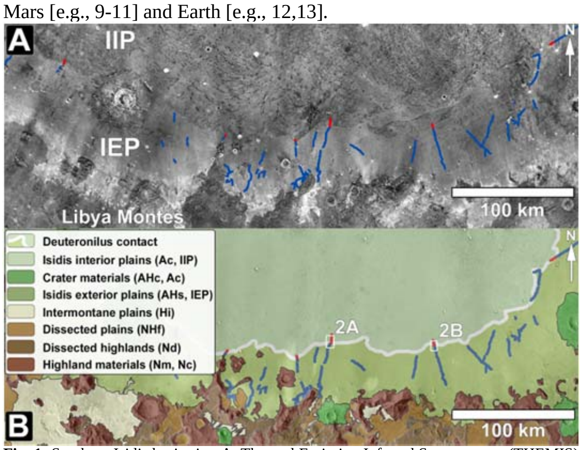

Fig. 1: Southern Isidis basin rim. A. Thermal Emission Infrared Spectrometer (THEMIS) IR-Night mosaic of the Libya Montes highland terrain, the Isidis Exterior Plains (IEP) and the Isidis Interior Plains (IIP). Valleys (blue lines) trend toward the center of the Isidis basin and appear as ridges (red lines) within the IIP. B. Morphologic map of the southern Isidis Planitia.

Based on our investigations we propose an alternative fluvio-glacial 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 sublimated 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, this study], thus significantly later than the dendritic valley networks of 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 of 1.1 – 1.35).

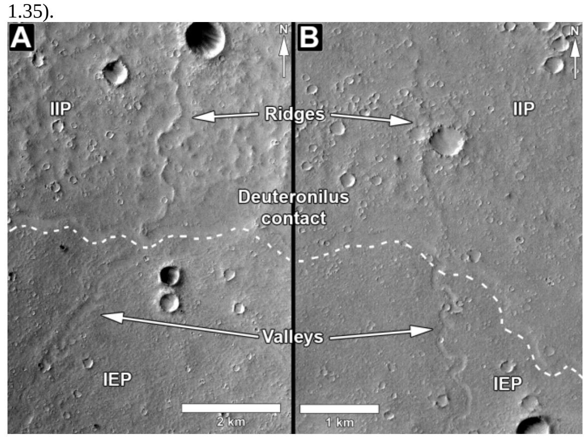

Fig. 2: Deuteronilus contact at the southern Isidis basin rim. Valleys trend to the north toward the Deuteronilus contact. Across the contact, the valleys (negative relief) transition into sinuous ridges (positive relief).

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 as the valleys, show variations in heights, typically less than 20 meters, have rounded crests, and show similar sinuosity as the valleys (sinuosity index of 1.1 – 1.4).

Formation scenario

Based on our observations and results, we consider a fluvio-glacial 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 eskers [15-17]. However, we also recognize alternative volcanic formation scenarios suitable to explain both the knobby morphologies of the IIP and possibly also 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 (>3.3 Ga) but before the emplacement of the IIP (~<2.7 Ga) [4,6], the small valleys have been incised between ~3.3 and ~2.7 Ga [4,6] 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 (Libya Montes), we propose that flowing lava was not 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 appear and/or continue as ridges. However, valleys, which extended farther toward the basin center were superposed by the IIP and occur as ridges within the IIP. Because ridges occur always as a continuation of the valleys and are absent elsewhere along 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 are difficult to explain by exhumation processes, because they occur in the IIP, which do not show any morphologies indicative of erosion. 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. However, wind erosion is 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 along the Deuteronilus contact more likely suggests that the valleys already existed (Fig. 3A) during formation of the ridges that formed significantly later. The ridges may represent eskers that formed in the Early Amazonian, when a short-lived [23] standing body of water filled the Isidis basin and froze to a stationary ice sheet (Fig. 3B). This stationary glacier is 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 proposed Isidis Sea and the possible Isidis glacier that formed subsequently may correspond to the location of the Deuteronilus contact (Fig. 3B). As the Isidis basin represents a region of high eolian deposition [23], the proposed glacier could be covered by a sedimentary veneer of wind-blown materials. Subglacial melting resulted in transport of the water and the deposits toward the glacier margin and toward the upstream direction, respectively. This scenario is based on the assumption that the pressure of the glacier is high in the center of the basin and decreased toward the glacier margin. The drainage of water should have resulted also in the formation of a proglacial lake [15, Fig. 3C], although we could not identify any lacustrine deposits along the boundary between the IIP and the IEP. Furthermore, preferential transport of the water and materials appeared along the courses of the pre-existing valleys. They may have served as paths for the transport of materials because they represented the lowest erosional level on the flat Isidis plains. After filling of the valleys, the courses of the subglacial streams have retained unchanged because of the barely moving, stationary ice sheet [23]. The continuation of material deposition during melting, sublimation and retreat of the glacier led to the formation of the eskers that reflect the course of the pre-existing valleys (Fig. 3C). Finally, the glacier completely sublimated and eolian materials accumulated on the glacier surface and within the glacier were deposited and represent the rough IIP (Fig. 3D).

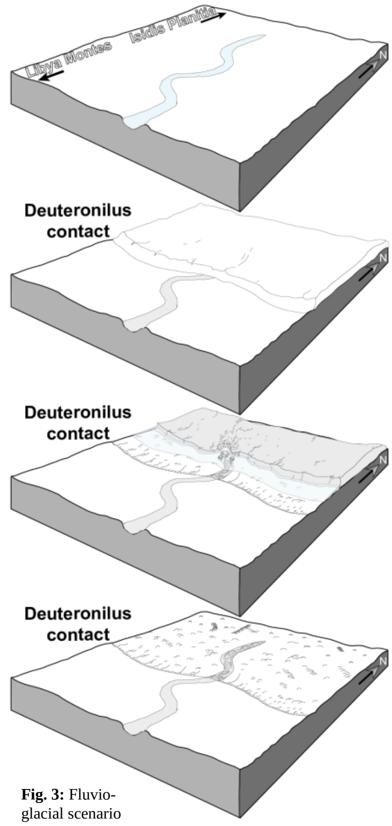

Fig. 3: Fluvio-glacial scenario

Conclusions

Our observations suggest that (1) small valleys postdate the Late Noachian Libya Montes dendritic valley networks and predate the IIP, (2) the ridges represent a morphologic continuation of the small valleys, but are formed later and 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 widths and heights [9,16,17]. Although the proposed scenario can better explain the formation of the valleys and ridges than an alternative volcanic formation scenario, 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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