DID FLUVIAL LANDFORMS FORM UNDER A WARMER EARLY MARS?

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Background: Fluvial landforms on Mars provide fundamental evidences of the physical state of water and the climatic conditions throughout the history of Mars. Topographic data show that fluvial valleys were incised by fluids that followed surface topography confirming early morphological interpretations as past rivers [e.g.,1,2,3]. Recent observations also highlight the presence of tens of alluvial fans and delta fans, the latter suggesting past standing bodies of water. Fluvial landforms and their deposits could imply that Mars had a warmer and wetter climate early in its history because liquid water is unstable on the Martian surface under the present-day climate [e.g.,2]. Nevertheless, present climate models have not been able to reach the conditions necessary for these processes to have occurred perennially, in the past [e.g.,4]; thus, questioning the formation mechanism of these landforms, i.e., whether they could form under a cold climate in association with processes such as volcanism or impacts [e.g., 5,6].

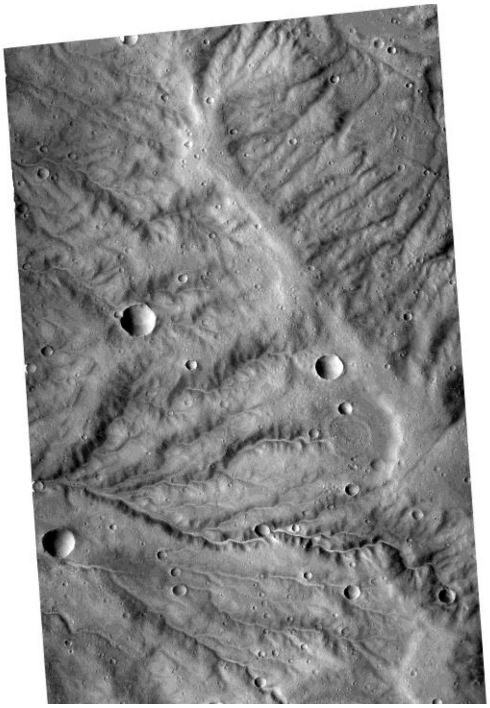

Fig. 1 : Noachian valley network close to Newcomb Crater (Image NASA/CTX/MSSS). Sunlight from the left. Image 25 km in width.

Age and morphology of fluvial valleys: Most valley networks date from the Middle Noachian to the beginning of the Early Hesperian [e.g.,3,7,5,8,9,10]. However, prolonged activity and/or reactivations of ancient valleys has occurred as late as Late Hesperian in several regions such as Eberwalde-Holden crater or the Valles Marineris' interior and plateau [9,10,11]. Early Amazonian valleys have even been observed on volcanoes [12, 13], and mid-latitude ice-rich landforms [14, 15], but these smaller younger valley networks are sparsely localized, suggesting that they could have formed by transient wet climatic episodes and/or regional activity (e.g., water ice sources, impact crater, or volcanic heat melting of ice/snow).

Well-developed (>100 km long) fluvial valleys include various landforms, from wide valleys with single heads to dendritic valley networks with multiple heads. Various erosional processes have been suggested for the formation of valley networks, including erosion by groundwater sapping, and/or surface runoff (see [2] for a detailed discussion). The occurrence of various geometries suggests that formation processes may not be unique. However, the observation of dendritic patterns with multiple heads close to watershed divides is clear evidence for precipitation-fed valleys (Fig. 1) [e.g., 2,3,8,9,10,11]. In the case of large sapping valleys, it was shown that precipitations were needed to explain the high eroded volumes [e.g.,2]. In overall, no doubt exists on the need on precipitation, but no constrain exists on the nature of these precipitations: rainfall or snow deposition and subsequent melting can equally explain the geometry of valleys, providing poor information on the actual climatic conditions. Meanwhile, the eroded volume is by one order of magnitude higher on Noachian valley networks compared to the younger Late Hesperian valleys [26]. This likely signs much long term erosional processes in the Late Noachian.

Fluvial and lacustrine deposition: Delta fans are identified thanks to their specific frontal slopes and/or their internal architecture. Proposed delta fans on Mars include large well-developed structures such as in Terby crater or Ismenius Cavus (>100 km^3), smaller well-preserved structures (from 1 to 10s km^3, including Eberswalde or Jezero crater landforms), and less prominent delta-fans or stepped-deltas (<1 km^3) [e.g,17-24]. Lakes involved by these deposits vary from a few meters to >1 km for Terby crater. In parallel, fluvial deposits that do not involve paleolakes are often found as alluvial fans in several tens of craters of the Noachian highlands [e.g.,25-28].

Well-known delta deposits such as Eberswalde crater delta fan and Gale crater alluvial fans sign late episodes. Indeed, stratigraphic relationships have shown that they form in the Hesperian, and they do not belong to the Late Noachian period of activity. In contrast, ancient deposits at the toe of Noachian valleys are not preserved; they may be buried below the widespread Hesperian lava flow episodes and only locally preserved (e.g., Terby crater). Indeed, the widespread volcanic episodes of the Early Hesperian has covered many depressions including old craters, and buried most of the Noachian erosional products. Thus, a major problem of studying well-preserved deltaic landforms is that most of them formed during the last episodes of fluvial activity, mainly in the Hesperian or later, and for this reason, they do not characterize deposits from the most intense fluvial activity in the Noachian. In addition, recent studies show that some of the smallest deltas were actually formed by the deposition of eroded material during a short-lived event, probably in the Late Hesperian or Early Amazonian [e.g.,22,24]. Lastly, alluvial fans also represent a type of deposits typical of the Hesperian period [27,28]. Indeed, most alluvial fans are found in large craters that have preserved ejecta blanket and only limited fluvial activity [27].

The rover Curiosity has observed conglomerates deposited by fluvial activity at the foot of the Peace Vallis valley system in Gale crater [28,30]. Mudstones were found at the base of alluvial sandstones: they indicate a shallow lacustrine depositional system that formed likely at the base of the fan [31]. Both observations represent a late system of deposition, probably in the Hesperian [32], that nevertheless display diagenetic smectites and veins of calcium sulfates showing that alteration conditions with fluid circulation close to the surface was possible even in a relatively late period.

Conclusions and future challenges: Precipitations, either as snowmelt or rainfall, were necessary to create many of the dendritic valley networks, implying a climate significantly distinct than the present one in the Noachian period, even its exact nature is unknown [e.g.,2,3,7,9,19,28,30]. The well-preserved Hesperian landforms have distracted geologists from the much more developed ancient valleys. Fundamental parameters are missing for a better understanding of the climatic conditions implied by fluvial landforms of the Late Noachian: (1) Identification of deposits from Noachian valleys and source-to-sink study of this period. (2) Better knowledge of the lithology in which valley networks formed; a factor of 10,000 exists between the duration needed to erode valleys inside ash deposits and that needed inside lava flows. (3) Better knowledge of the role of snowmelt versus rainfall. (4) Better knowledge of the role of fluvial/lacustrine activity in the alteration processes observed at the surface. Hesperian valleys, in contrast, show us wonderful examples of fluvial activity, including assemblages of fluvial and lacustrine deposits at the Curiosity rover site. Climatic conditions were never favorable to the presence of paleolakes, in which numerous fan-deltas and alluvial fans settled at the outlet of fluvial valleys [e.g.,18-26]. However, the episodic and patchy distribution of Hesperian valleys at a global scale questions the exact nature of the climate, as being warmer over long term or due to regionally warmer conditions: (5) Have these late fluvial landforms formed under the last gasps of the globally warmer early Mars or under more localized conditions, perhaps related to past obliquity cycle or regional heat sources? (6) Future missions should also weight the fact that focusing on well-preserved Hesperian landforms may only link to late climatic episodes not representative of the actual early Mars conditions.

Lastly, with extent and erosional volumes much lower, the scarce Amazonian valleys (< 3 Ga) appear to have been formed under cold and hyperarid [29]. They are much less developed even when close to volcanic heat sources so large than Alba Patera. A clear implication of their small distribution is that pre-Amazonian valleys were not able to form under same Amazonian cold/icy conditions, or those scarce Amazonian valleys on impact or volcanoes would not be that distinct from their predecessors.

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