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from the earth to the sun, the world is one family

Can Sedimentary Basins Form Without Tectonics? Lessons from Mars for Earth's Future

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Abstract

The formation of sedimentary basins on Earth is primarily controlled by tectonic and structural deformation processes that have operated since the planet's early history. Recent advances in planetary science have opened new perspectives by integrating extraterrestrial analogues to better understand Earth's evolution and anticipate its potential future dynamics. In this context, comparative studies with Mars have gained increasing attention in recent years.

Mars and Earth formed at broadly similar times, approximately 4.603 and 4.543 billion years ago, respectively, and experienced comparable early evolutionary stages (Bultel, 2016). However, Mars underwent a major divergence when its internal geodynamic activity ceased relatively early. This shutdown is evidenced by the decline of core activity and paleomagnetic signatures, indicating the loss of a global magnetic field (Lammer et al., 2013; Mittelholz et al., 2020). As a result, tectonic processes on Mars became extremely limited, with the most prominent Earth-like deformation being extensional tectonics, exemplified by the Valles Marineris rift system (Davis et al., 2021).

In contrast to Earth, where sedimentary basins are predominantly formed through tectonic mechanisms such as rifting and orogeny, Mars exhibits a different dominant process: impact cratering. Several studies have documented sedimentary deposits within impact basins, demonstrating that these structures can act as major depocenters independent of tectonic activity (Fassett and Head, 2007; Cabrol and Grin, 2010; Irwin et al., 2015).

These deposits are often clastic in nature, analogous to those formed on Earth through the erosion of uplifted mountain belts following orogenesis, suggesting that sedimentary basins can develop through non-tectonic processes.

The aim of this study is to compare the formation and evolution of sedimentary basins on Earth and Mars, with a focus on non-tectonic origins, and to evaluate whether similar processes could occur on Earth if tectonic activity significantly diminishes.

Objectives

General Objective:

To investigate whether sedimentary basins can form and evolve without active tectonics by using Mars as a natural analogue to better understand the future evolution of sedimentary systems on Earth.

Specific Objectives:

1-Compare sedimentary basin formation processes on Earth and Mars. Assess the role of impact craters as sedimentary basins in the absence of tectonic activity.

2-Identify and characterize Martian alluvial, deltaic, and lacustrine depositional systems.

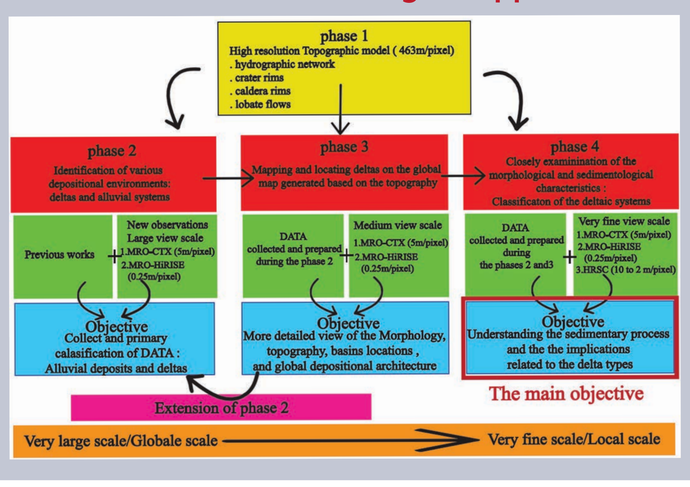
3-Distinguish sedimentary processes related to impacts, hydrology, and volcanism.

4-Reconstruct the hydrological and climatic history of Mars from sedimentary records.

5-Develop a conceptual model for sedimentary basin formation under non-tectonic conditions.

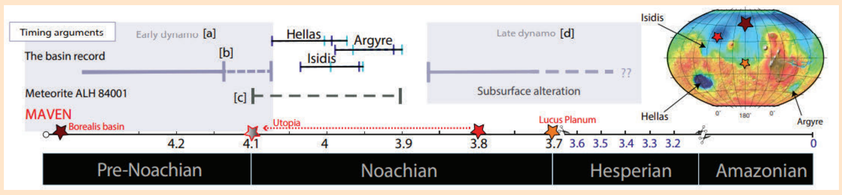
6-Evaluate the implications of Martian sedimentary systems for Earth's future and for comparative planetary geology.

Data and Methodological Approach



Resultats

Martian Dynamo Activity: internal geodynamics of Mars



Dynamo timing scenarios (Mittelholz et al., 2020).

1-Early Active Dynamo (≈ 4.5–4.1 Ga)

Mars had a hot, convecting core generating a global magnetic field. This period likely coincided with strong mantle convection and a more active, deformable lithosphere with early tectonic activity.

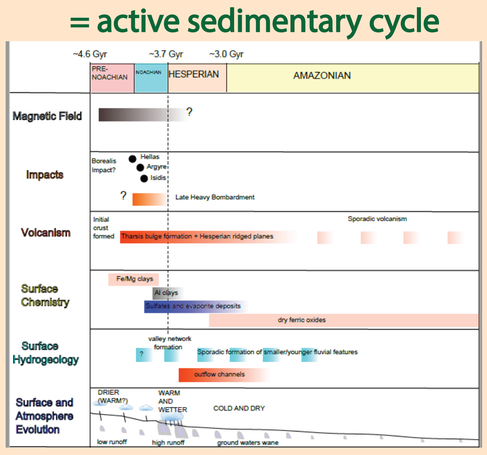
2-Dynamo Decline (≈ 4.1–3.8 Ga)

Rapid planetary cooling reduced core and mantle convection. Magnetic field strength decreased while tectonic activity became less widespread and more localized.

3-Dynamo Shutdown (≈ 3.8–3.7 Ga)

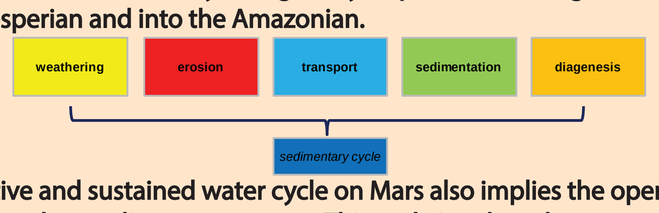
Core convection stopped, ending the global magnetic field. Mars transitioned to a stagnant-lid regime with limited tectonic deformation and mainly localized volcanic activity.

Hydological activity independet to dynamo = active sedimentary cycle



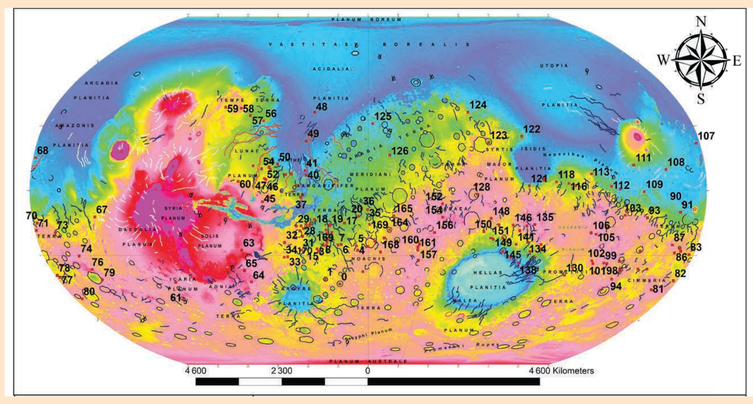
A synthesis of the hydroclimatic evolution on Mars (Ramirez and Craddock, 2018).

Although Martian tectonic activity largely ceased around ~3.7 Ga at the end of the Noachian and the beginning of the Hesperian, evidence indicates that an active hydrological cycle persisted throughout the Hesperian and into the Amazonian.



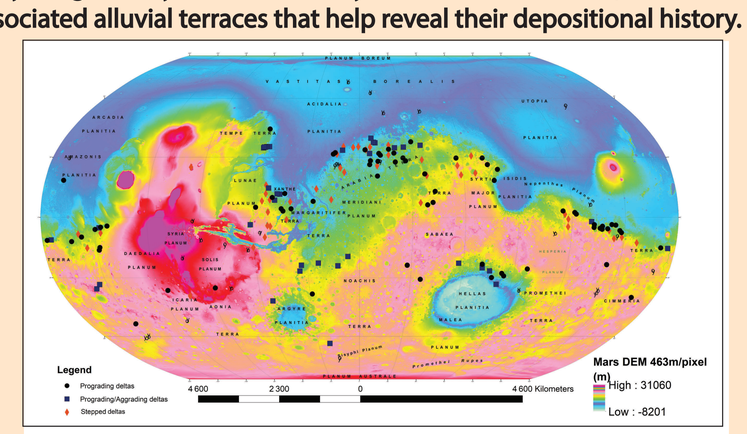
An active and sustained water cycle on Mars also implies the operation of a complete sedimentary system. This cycle involves the progressive breakdown of source rocks through weathering, followed by erosion and sediment transport, subsequent deposition within sedimentary basins, and ultimately diagenesis, which transforms these deposits into coherent stratigraphic units.

Sedimentary Systems on Mars Investigated in This Study



Location of the alluvial deposits identified in this study

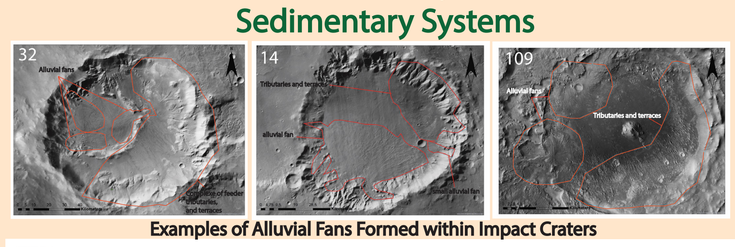
A total of 170 alluvial systems based on their lobate morphology, their location within impact craters, and their connection to drainagenetworks. They are generally characterized by braided channels and, in some cases, associated alluvial terraces that help reveal their depositional history.



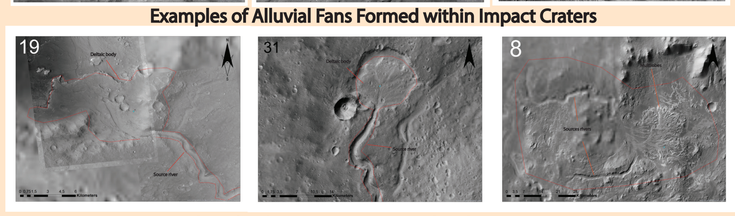
Map of the Global Distribution of the Studied deltaic Systems

Deltaic systems were identified using morphological and stratigraphic criteria such as meandering channels, depositional geometries, and their position within impact-crater basins. More than 143 deltaic systems were recognized and classified according to their formation processes and evolutionary characteristics.

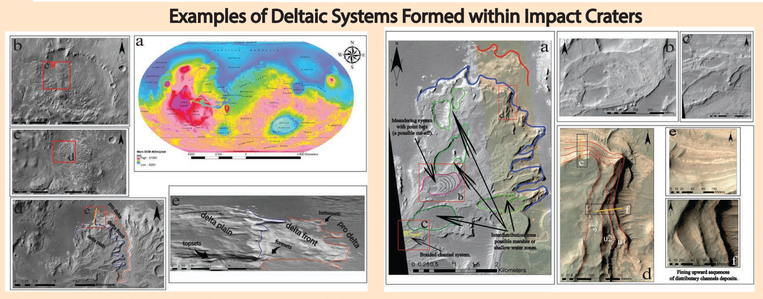
Impact Craters: The Primary Hosts of Martian Sedimentary Systems



Examples of Alluvial Fans Formed within Impact Craters



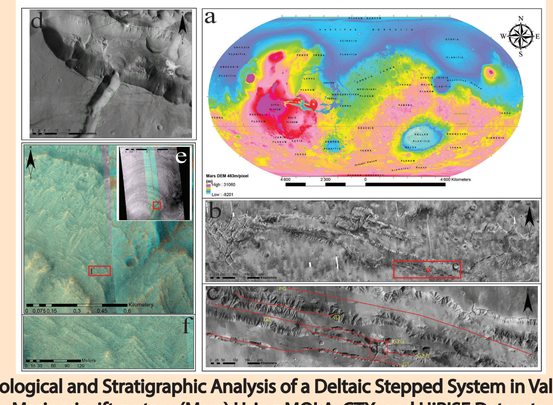
Examples of Deltaic Systems Formed within Impact Craters



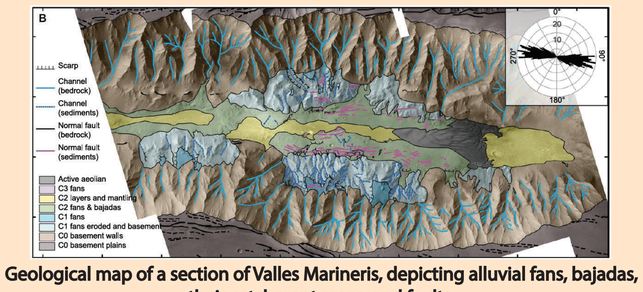
Overview and Stratigraphic Zonation of the Eberswalde Delta System from MOLA and CTX Data

Sedimentological Characterization of the Eberswalde Delta System from HiRISE Data

Valles Marineris: A Rift-Type Sedimentary Basin Analogous to Earth's Rift Systems



Geological and Stratigraphic Analysis of a Deltaic Stepped System in Valles Marineris rift system (Mars) Using MOLA, CTX, and HiRISE Datasets



Geological map of a section of Valles Marineris, depicting alluvial fans, bajadas, their catchment areas, and faults.
The rose diagram shows the orientations of normal faults (Davis et al., 2021).

Conclusion

Mars shows that sedimentary basins can develop and persist even after the shutdown of global tectonic and dynamo activity. Despite the loss of active geodynamics, a long-lived hydrological cycle continued, producing complete sedimentary processes from erosion to diagenesis. The dominance of alluvial and deltaic systems within impact craters highlights their role as the main sedimentary depocenters on Mars. These results demonstrate that sedimentary basins can form under non-tectonic conditions, mainly controlled by impact structures and surface hydrology.

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