What do the fluvio-lacustrine sedimentary records at Gale and Jezero craters tell us about the past climate of Mars?

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Introduction: Rovers on Mars are well-equipped vehicles able to explore Mars surface and analyze rocks with several instruments such as cameras and spectrometers, enabling an assessment of the facies, texture, chemistry and mineralogy of rocks exposed along their traverse. Curiosity landed in Gale crater in 2012 and, so far, explored a ~880 m thick sedimentary sequence along a 35 km long traverse. Perseverance landed in 2021, and, so far, crossed igneous plains, a sedimentary fan, and an enigmatic ultramafic unit, and is currently exploring the rim of Jezero crater, with 37 km of traverse. In this abstract, we summarize some of the findings of both rovers made in the sedimentary sequences analyzed, showing especially that the sedimentary records at Gale and Jezero are notably different, suggesting substantially different aqueous environments related either to distinct climatic periods or to regional climatic differences.

Jezero crater delta and paleolake: Jezero crater is a 45 km diameter crater with two inlet valleys and one outlet valley, which suggested the presence of a lake in the past [e.g., 1, 2]. The age of the fan has been estimated to be Late Noachian [3] or Hesperian [4].

Texture and geometry of sedimentary rocks: Observations of the fan front and the Kodiak remnant butte highlight a systematic stratigraphy [5-9]: (i) The bottoms of hillslopes display recessive, light-toned deposits that are best explained as lacustrine deposits at the delta toe (bottomsets and toesets), part of the Shenadoah fm. [6]. (ii) The central part of the fan front hillslopes corresponds to dipping foreset beds usually developed over 20 to 25 m of vertical extension. They display sigmoidal geometry with steeply dipping sandstones and some conglomerates. (iii) Above the foresets various types of fluvial deposits (sandstones and conglomerates) are present, with frequent cross-beddings interpreted as topset beds deposited from rivers feeding Jezero Lake. (iv) Above these bedded sedimentary rocks lie massive, poorly-sorted boulder conglomerates that truncate the underlying strata. They represent an energetic last stage of fluvial floods for which the relationships to the Jezero Lake is unclear (i.e., the lake may have already disappeared when these conglomerates were emplaced). The transition between topsets and foresets varies from -2410 m close to the fan apex to -2500 m at Kodiak and at the Eastern Cape [9], showing that the lake level dropped significantly during the emplacement of the delta (forced regression) [9]. Older deposits may exist within Jezero craters, below the volcanic floor, but are not accessible.

Composition of sedimentary rocks: The composition of beds inferred as foresets and topsets are generally ultra-mafic with high FeO and MgO abundances, and are dominated by olivine and a substantial presence of carbonates with locally phyllosilicates [10, 11]. The composition of the recessive lower unit (bottomset and lake deposits) is distinct, dominated by phyllosilicates and sulfates. While the imprint of liquid water is obvious for these sediments, the partial preservation of olivine, suggests that the alteration was not as extensive compared to what such ultramafic rocks would have been altered on Earth.

Implications for the climate environment: While the past presence of a lake in Jezero is clear from both morphological and sedimentological observations, proof of its persistence over a geologically long period of time is lacking. Most of the delta seems to have been built below the level of the breach, by progressive downstepping, within a closed system [5, 9]. This result is in agreement with the interpretation that the outlet channel seems to have been working as an overflow during a limited duration [12]. The alteration of ultramafic sediments into carbonates has been strong, but the preservation of some olivine suggests a limited time and/or a low temperature close to 0°C, not fully altering the olivine. Estimations of the lake duration is very variable within the literature (from few tens of years to millions, 13-15); the scenario of a down-stepping delta suggests a duration closer to thousands of years [16], at least for the stage of the lake deposits observed by Perseverance. Hence, Jezero paleolake could have been developed within a relatively cold climate, enabling liquid water at least seasonally, although no direct evidence for actual glacial or periglacial activity was observed directly within the sedimentary sequence. With a probable formation in the Hesperian [4], Jezero crater landforms observed by Perseverance should not be taken as a landform typical of Early Mars activity, but rather as a late-stage deposit after which most of the activity stalled, with exception of the episodic floods that deposited boulders at the top of the delta.

Gale crater fluvial and lacustrine deposits: Gale crater is a 150 km diameter crater that is filled by a 4.5 km thick pile of sedimentary rocks informally named Mt. Sharp. Its selection was made thanks to the presence of these sediments that are known to contain phyllosilicates and sulfates from orbital data, and due to the vicinity of an alluvial fan at the base of the crater's inner rim. The age of the crater is estimated to be close to the Late Noachian-Early Hesperian boundary [17, 18], and the presence of sulfates above phyllosilicates was taken as representing the transition observed globally on Mars [17]. We limit the description hereafter to the lower 300 m of the observable sedimentary pile, below the sulfate-bearing sediments further described in this meeting [19].

Texture and geometry of sedimentary rocks: The sedimentary rocks located on the Aeolis Palus plain close to the landing site, and in the basal section of Mt. Sharp contain fluvial strata ranging from medium sandstones to pebble conglomerates, with local cross-beddings [20-22]. Finer-grained beds (down to mudstones) have been observed at a location named Yellowknife Bay, and much more extensively within the Mt. Sharp group, from its base at Pahrump Hills to the Glen Torridon member that corresponds to the clay-bearing unit identified from orbit. Local drying out has been observed through the presence of desiccation cracks [23], as well as transitions to shore deposits, especially within the Glen Torridon unit [24-25]. However, no sign of meter-scale polygonal cracks related to permafrost or to freeze-thaw cycles have ever been observed, except in very recent (Late Amazonian) time after exposure of the rocks to the current atmosphere [26].

Composition of sedimentary rocks: The coarsest fraction of the rocks, sandstones to conglomerates, bears a chemistry that is basaltic to trachytic, with local high alkali abundances. No or poor alteration was observed in these rocks from their chemistry, as expected for fluvially transported material. In contrast, mudstones display a substantial alteration tracked by the chemical index of alteration (CIA, estimated from the ChemCam chemistry of major elements) that reaches values up to 65, suggesting an open-system alteration within either the lake system or the watershed upstream [27, 28]. While these values are far from those of warm areas on Earth where they can reach 100, they are above those recorded in Arctic zones in which phyllosilicates tend to be in limited amount due to the low temperatures. The presence of 10 to 30 wt.% of phyllosilicates in a dozen of the drill samples analyzed by the CheMin instrument, fits with their identification from orbital spectroscopy at Glen Torridon, and fits with the alterations measured by the CIA [29]. Local enrichments in salts have been detected locally either from sulfur-enhanced or chlorine-enhanced bedrocks [30, 31], and overall oxidized (hematite-rich) rocks, suggesting that the lake underwent evaporative cycles, and may not have been deep (in agreement with the presence of mud cracks), perhaps with exception of the few locations where magnetite is present and may indicate a deeper, stratified lake body [32].

Implications for climate environment: While Mt Sharp deposits do not bear clear evidence for deltaic deposition, either due to a lack of preservation or a limited depth of water, the huge package of lacustrine beds (up to 300 m) dominated by fine-grained sediments requiring quiet settling suggests a prolonged period of time during which a lacustrine environment was present, possibly 100 ky-1 My [21].

Discussion: Gale and Jezero craters share the presence of fluvial and lake deposits, but they display strong differences in sedimentary structures and compositions, highlighting differences between their formation and evolution. Mt Sharp deposits display a huge package of lacustrine beds (up to 300 m) dominated by fine-grained sediments containing substantial phyllosilicate abundance, requiring a prolonged period of time for the fluvial and lacustrine deposition. The recent finding of lake deposits perched 600 m higher than the basal lacustrine mudstones also demonstrates a prolonged and complex history [33], with likely several episodes of lakes, under variable aqueous chemistry. By comparison, the Jezero delta was a more dynamic system of deposition in which relatively coarse fraction (sandstones and conglomerates) were deposited relatively quickly at the geological timescale [4].

Gale and Jezero craters sedimentary rocks were sourced from two distinct protoliths: an ultramafic source in the olivine-rich area of Nili Planum, and a basaltic to trachytic source within the highlands around Gale crater. This difference makes a direct comparison of their evolution more difficult. Nevertheless, the substantial alteration observed at Gale crater with the lack of olivine and the limited preservation of pyroxene, suggests a stronger alteration there than at Jezero crater.

Conclusion: Jezero crater presents a remarkable preservation of a delta-lake system on Mars, but its preservation is actually a sign of a relatively late-stage formation. Its small volume (3-5 km^3) and limited alteration suggest an environment with low temperatures and/or short-timescale of formation. In contrast, Gale crater's huge package of sediments dominated by mudstones in its lower 300 m of stratigraphy requires geologically long-term periods with a relatively stable lake system in which no evidence of glacial or periglacial environments were recorded despite of the large number of facies observed. An older age of Gale crater's Mt Sharp deposits compared to Jezero western fan deposits may explain the difference in both their environment of deposition and their alteration, but a regional climate difference with colder conditions at Jezero crater cannot be ruled out, given that the age of each sequence cannot be determined with sufficient precision.

The analysis of these two locations adds to what was discovered at Meridiani Planum by the Opportunity rover, namely rocks formed under an acidic environment with a low water:rock ratio [34]. Hence, these three rovers have analyzed three distinct aqueous depositional environments that cannot be summarized by a unique Early Mars environment. Yet, Gale crater records in a single location a diversity of aqueous environments [e.g., 14, 15, 33]. More in-situ data in other contexts of deposition or other periods (e.g., ExoMars at Oxia Planum) would be necessary to get a more comprehensive view of the sedimentary record from Early Mars, and enable a decent reconstitution of what is frequently referred to as the "warm and wet" Mars climate, an expression that hides a large diversity of environments.

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