Article Type (REVIEW)

Reconstructing Jezero Crater's Paleoenvironment: Insights from Perseverance Rover and Orbital Data

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ABSTRACT

Jezero Crater on Mars is a critical site for investigating ancient aqueous environments due to its preserved delta and lacustrine features. Reconstructing its paleoenvironmental history is essential for understanding Mars' climate evolution and assessing its past habitability. This study integrates in-situ data from the Perseverance rover, including review for high-resolution imaging, mineralogical analyses, and subsurface radar, with orbital imagery from Mars Reconnaissance Orbiter and Mars Express. Terrestrial analogues aid in interpreting sedimentary structures and depositional processes. The integrated analysis reveals that Jezero Crater's floor consists of igneous rocks with minimal aqueous alteration, overlain by deltaic sediments rich in clays and carbonates, indicative of a lacustrine setting. Orbital data confirm extensive fluvial networks and mineralogical diversity, while subsurface radar indicates stratified deposits consistent with episodic sedimentation. Sulfate-rich deposits suggest post-depositional diagenetic processes. The findings depict a complex history of initial igneous activity, followed by prolonged water-related sedimentation forming the delta, and subsequent aeolian modification, highlighting the dynamic nature of Mars' early environment. By synthesizing rover and orbital data, this review work provides a comprehensive model of Jezero Crater's paleoenvironment, offering valuable insights for future Mars exploration and the search for biosignatures.

Keywords: Jezero Crater, Paleoenvironment; Martian Geology; Perseverance Rover; Orbital Imagery.

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1. Introduction

Martian paleodepositional settings provide critical insights into the planet's ancient environmental conditions[1], offering a window into its geological evolution, past climate, and potential habitability. These settings, characterized by sedimentary deposits formed in ancient lakes, rivers, and deltas, preserve evidence of surface processes that shaped Mars during its wetter past. Among these, Jezero Crater, a 45-km-diameter impact crater located on the western margin of Isidis Planitia, stands out due to its well-preserved fluvial delta, inlet and outlet valleys, and mineralogical signatures indicative of prolonged water activity. Selected as the landing site for NASA's Mars 2020 Perseverance rover, which touched down on February 18, 2021, Jezero Crater is a focal point for investigating Mars' hydrological history and its implications for past habitability. The crater's geological features[2], including a fan-shaped delta and evidence of a paleo-lake, suggest it once hosted a dynamic aqueous environment, making it an ideal target for studying the planet's early environmental conditions.

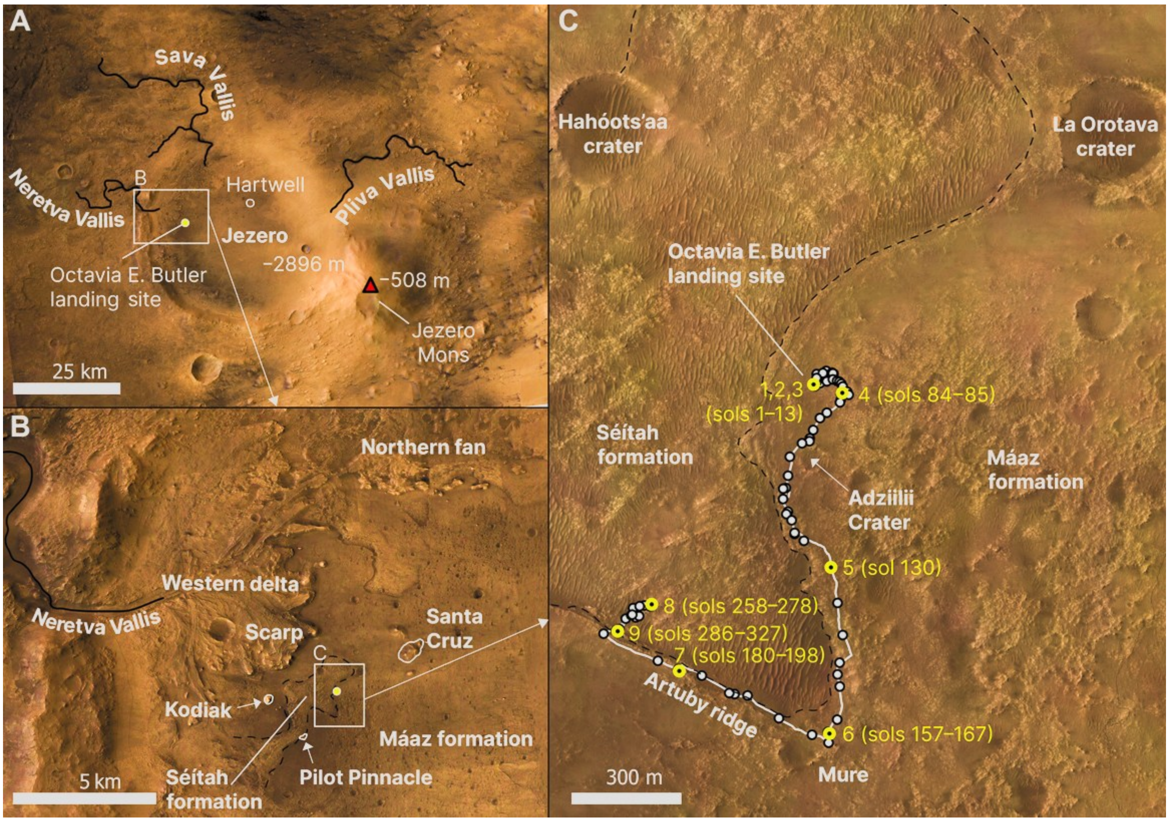

*Figure 1. Context Map of Jezero Crater[31]. highlighting the Perseverance rover's landing site, inlet/outlet channels, and key geological features. This provides a spatial context for the study. North is up, and illumination is from the left. (**A**) Context map showing Jezero crater, the inlet/outlet channels (outlined in black), and the edifice Jezero Mons in the southeast. (**B**) Close-up of the western delta with its associated features as mentioned in the text. (**C**) Detail view of the rover landing and traverse site, through mission sol 327 (20 January 2022). White circles represent the sol-by-sol locations of the rover starting from the OEB landing site, and yellow circles represent the different site locations defined so far in the mission. Base images: MRO/HiRISE, MRO/CTX, MEx/HRSC.*

Water and wind processes have been instrumental in shaping Martian landscapes, particularly in Jezero Crater. Fluvial processes, such as river flow and sediment transport, are evident in the crater's inlet valleys and deltaic deposits, which indicate a lake system that persisted for a minimum of 90–550 years, as estimated through sedimentological and hydrological analyses[2]. These findings build on broader research into Martian paleolakes, such as the work by Grotzinger et al. (2015)[1], which documented a fluvio-lacustrine system in Gale Crater, highlighting the role of water in sediment deposition and alteration. In Jezero, orbital observations reveal carbonate and clay minerals, further supporting the presence of a long-lived lake[4]. Aeolian processes, driven by wind, have also modified Jezero's surface, contributing to the erosion of exposed rocks and the formation of dunes and regolith, particularly after the cessation of widespread aqueous activity. These processes are critical for understanding the temporal evolution of the crater's landscape and its current morphology.

Despite significant advances in Martian exploration, a comprehensive understanding of Jezero Crater's paleoenvironmental history remains incomplete. Previous studies have primarily relied on either orbital imagery, such as data from the Mars Reconnaissance Orbiter's HiRISE and CRISM instruments, or initial in-situ observations from Perseverance's instruments, including Mastcam-Z, PIXL, and SHERLOC. However, there is a notable lack of integrated analyses that combine these datasets to provide a holistic reconstruction of the crater's geological evolution. This gap limits our ability to fully elucidate the sequence of depositional and erosional events that shaped Jezero, as well as their implications for Mars' climatic history. For instance, while Salese et al. (2020)[2] constrained the minimum lifespan of Jezero's paleo-lake, and Mangold et al. (2021)[5] detailed deltaic stratigraphy, these studies have not fully synthesized rover and orbital data to model the interplay of fluvial, lacustrine, and aeolian processes over time.

This study addresses this research gap by integrating review studies on high-resolution in-situ data from the Perseverance rover with orbital imagery from Mars Reconnaissance Orbiter and Mars Express to reconstruct Jezero Crater's paleoenvironmental history. The objectives are to: (1) characterize the geological and mineralogical features of Jezero Crater using rover data, including sedimentological and subsurface analyses; (2) contextualize these findings within the regional geology using orbital datasets; (3) reconstruct the paleoenvironmental conditions, focusing on the nature and duration of water-related processes; and (4) assess the implications for Mars' climate evolution and past habitability. By synthesizing these datasets, this paper aims to provide a comprehensive model of Jezero Crater's geological history, from its formation as an impact crater through periods of fluvial and lacustrine activity to subsequent aeolian modification. This integrated approach will enhance our understanding of Mars' early environmental conditions and inform future exploration efforts, including the Mars Sample Return mission, by identifying key geological contexts for sample analysis.

2. Materials and Methods

2.1 Data Sources

2.1.1 Perseverance Rover Data

The Perseverance rover, part of NASA's Mars 2020 mission, landed in Jezero Crater on February 18, 2021, and is equipped with a suite of instruments designed to investigate the crater's geology and paleoenvironmental history. The following instruments provide the primary datasets for this study:

- **Mastcam-Z (Multispectral, Stereoscopic Imaging System)**: The rover's mast has two zoomable cameras called Mastcam-Z. They take high-resolution stereo pictures (up to 1600 × 1200 pixels) and multispectral data across 11 visible and near-infrared bands (400–1000 nm). These data make it possible to make accurate geological maps, find sedimentary formations, and study surface textures, which are all important for figuring out how deposits formed[8].
- **PIXL (Planetary Instrument for X-ray Lithochemistry)**: The rover's robotic arm has an X-ray fluorescence spectrometer called PIXL that can look at the elemental compositions of things with a spatial resolution of 120 μm. It finds major, minor, and trace elements (such Si, Fe, Mg, and S) in rocks and soils, which helps us learn more about how minerals originate and how geochemical processes work. PIXL's hyperspectral mapping creates thousands of data points over small areas, making it easier to do fine-scale geochemical analysis[12].
- **SHERLOC (Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals)**: SHERLOC, which is also aboard the robotic arm, uses a deep ultraviolet (UV) laser (248.6 nm) for Raman and fluorescence spectroscopy. It can find mineral phases and organic compounds with a spatial resolution of 100 μm. The Wide-Angle Topographic Sensor for Operations and eNgineering (WATSON) camera adds context to the images. SHERLOC's data are very important for finding water-altered compounds and possible biosignatures.
- **RIMFAX (Radar Imager for Mars' Subsurface Experiment)**: RIMFAX is a ground-penetrating radar that works between 150 and 1200 MHz. It can see structures below the surface up to around 10 m deep with a vertical resolution of 15 to 30 cm. It gives radargrams that show stratigraphic layering, unconformities, and

geological structures below the surface, which are important for figuring out the history of Jezero Crater's deposits.

2.1.2 Orbital Imagery

Orbital datasets provide regional context for the in-situ observations, enabling a comprehensive analysis of Jezero Crater's geology. The primary orbital instruments used are:

- **Mars Reconnaissance Orbiter (MRO)**:
  - **HiRISE (High Resolution Imaging Science Experiment)**: The HiRISE camera has a 0.5 m main mirror and can see in the visible spectrum. It can see things as small as 0.25–0.3 m/pixel at a height of 300 km. It takes detailed pictures of the surface's shape, including deltaic structures, channels, and aeolian features. It also makes digital elevation models (DEMs) from stereo pairs with a vertical precision of about 0.2 m.
  - **CRISM (Compact Reconnaissance Imaging Spectrometer for Mars)**: CRISM is a hyperspectral imager that works in the range of 362 to 3920 nm and has 544 spectral bands with a resolution of 6.55 nm. In targeted mode, it can map mineral distributions (such clays, carbonates, and sulfates) that show where water used to be, with spatial resolutions of 18–36 m/pixel. The multispectral mode (72 bands, 100–200 m/pixel) covers a wider area for the regional mineralogical environment.

- **Mars Express**:
  - **HRSC (High Resolution Stereo Camera)**: HRSC is a push-broom stereo camera with nine CCD line sensors. It can take color and stereo pictures with resolutions of 10–30 m/pixel (nadir) and up to 2 m/pixel with its Super Resolution Channel (SRC). HRSC makes DEMs with a grid spacing of 50 to 100 m and a vertical precision of about 10 m. This lets us look examine Jezero's delta, valleys, and crater floor in terms of topography.

2.1.3 Additional Datasets

We use digital elevation models (DEMs) made from stereo pairs from HiRISE and HRSC for morphometric and topographic studies. The Virtual Hiking Map combines data from HiRISE, MRO's Context Camera (CTX), and HRSC to create an interactive platform for seeing rover trails and geological features. NASA's Planetary Data System (PDS) (https://pds.nasa.gov) and ESA's Planetary Science Archive (PSA) (https://www.cosmos.esa.int/web/psa) are the places where you can find all the datasets.

2.2 Analytical Methods

2.2.1 Sedimentological Analysis

Sedimentological analysis focuses on characterizing depositional environments through the study of sedimentary structures, textures, and stratigraphy. Key methods include:

- **Image-Based Analysis**: Photogrammetric methods are used to interpret Mastcam-Z stereo images and create 3D surface models that show features like cross-bedding, ripple markings, and polygonal cracks. HiRISE pictures add to these observations by showing deltaic morphology, channel networks, and aeolian bedforms in greater details. Image textures are used to estimate grain size distributions, which are then compared to those found on Earth.
- **Subsurface Stratigraphy**: We use RIMFAX radargrams to find bedding planes, unconformities, and sediment thickness by mapping subsurface reflectors. Standard geophysical methods, like time-depth conversion and clutter suppression, are used to interpret radar data and recreate the stratigraphic structure of the delta and crater floor.

2.2.2 Mineralogical Mapping

Mineralogical mapping integrates in-situ and orbital data to characterize Jezero Crater's mineral composition:

- **In-Situ Mineralogy**: SHERLOC's Raman and fluorescence spectra can find mineral phases (such carbonates, clays, and sulfates) and organic substances down to less than a millimeter. PIXL's X-ray fluorescence measurements show the elemental compositions of minerals, which lets us use stoichiometric analysis to figure out how much of each mineral is present. Both sets of data are related to each other in order to show where minerals are found at rover sampling sites.

- **Orbital Mineralogy**: Radiative transfer models are used to process CRISM hyperspectral data to get rid of atmospheric effects and find out how many minerals are present. We use spectral indices, like band depth at 1.9 µm for hydrated minerals, to map clays, carbonates, and sulfates across Jezero Crater. This gives us a better idea of what the rover is seeing in the area.

2.2.3 Terrestrial Analog Comparisons

Scientists use similar features on Earth to figure out what Martian sedimentary features are. The Oligocene-Miocene Guadalope-Matarranya Fan in Spain, as studied by Cardenas et al. (2021)[7], serves as one of the key analogues for Jezero's deltaic deposits. This fan has ridge-bearing megafan structures that are similar to those seen in Martian rivers, and it has sedimentological traits that are also similar, such as inverted channels and point-bar strata. Comparative study helps us understand how sediments were deposited and what the environment was like by comparing Martian sedimentary formations and mineral assemblages to those found in the Guadalope-Matarranya Fan.

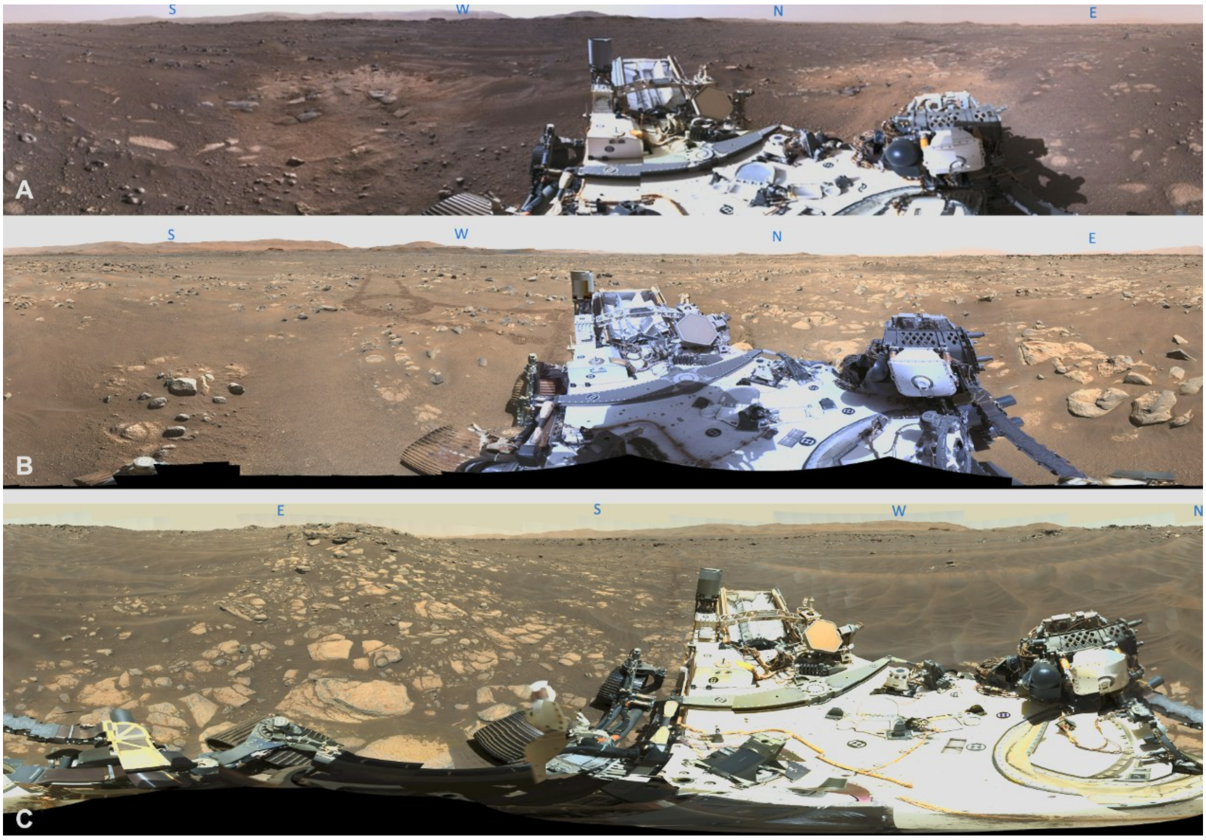

*Figure 2. Perseverance Rover in Action[31]. Example 360° mosaics. Mastcam-Z enhanced color RGB 360° panorama from the Perseverance rover. (**A**) OEB landing site, 34-mm focal length, sol 3. (**B**) Van Zyl Overlook, 110-mm focal length, sols 53 to 64. (**C**) Village outcrop, within Séítah, 110-mm focal length, sols 214 to 215. Cylindrical projection views with local azimuth cardinal points indicated and extending from −60° local elevation angle out to the horizon.*

2.2.4 Modeling Depositional Timelines

We use sediment transport and hydrological models to figure for how long rivers and lakes were active in Jezero Crater[6-7]. The method uses both experimental and numerical methods from Kleinhans et al. (2013)[6] and Salese et al. (2020)[2]:

- **Sediment Transport Models**: Using real-world examples of bedload and suspended load transfer under Martian gravity (0.38g), we can figure out how fast sediment moves. The input parameters include the width and depth of the channel (50–190 m and 5 m), the size of the grains (D50: 0.25–20 mm), and the water discharge rates that come from the shape of the delta. These models figure out how much sediment there is and how fast it is deposited. They limit the time it takes for a delta to form to tens to hundreds of years for single-event scenarios or longer for persistent flows.

- **Hydrological Modeling**: We used Salese et al. (2020)[2] to create hydrological models that show how lake levels and inflow rates change based on the shape of the valley network and the amount of delta sediment. The models employ Manning's equation to figure out how fast the water is flowing and consider evaporation and infiltration losses to make better guesses about how long the lake will last (90–550 years minimum)[9–11].
- **Numerical Simulations**: The Delft3D software, which is used in studies of terrestrial deltas, has been changed to model the growth of Martian deltas with different lake levels and sediment inputs. This gives us time limits on the sequences of deposition[12–15].

2.2.5 Data Integration

Geographic information systems (GIS) and image processing software (ArcGIS) are used to combine data. We georeference rover traverse tracks and sampling locations onto HiRISE and HRSC orthoimages and DEMs to make sure they are all in the right place. We use mineralogical maps from CRISM and in-situ data to connect observations made in different places and regions. This combined method lets us fully piece together Jezero Crater's paleoenvironmental history by connecting surface and subsurface characteristics with mineralogical and chronological data.

3. Results

The Perseverance rover and the Mars Reconnaissance Orbiter (MRO) and Mars Express have combined their in-situ data and orbital images to give a detailed description of Jezero Crater's stratigraphic framework, mineralogical composition, and signs of paleoenvironmental changes. The purpose of this study was to learn more about the crater. These new findings have helped us understand the geological history of this impact crater, which is 45 kilometers wide and located on the western side of Isidis Planitia on Mars.

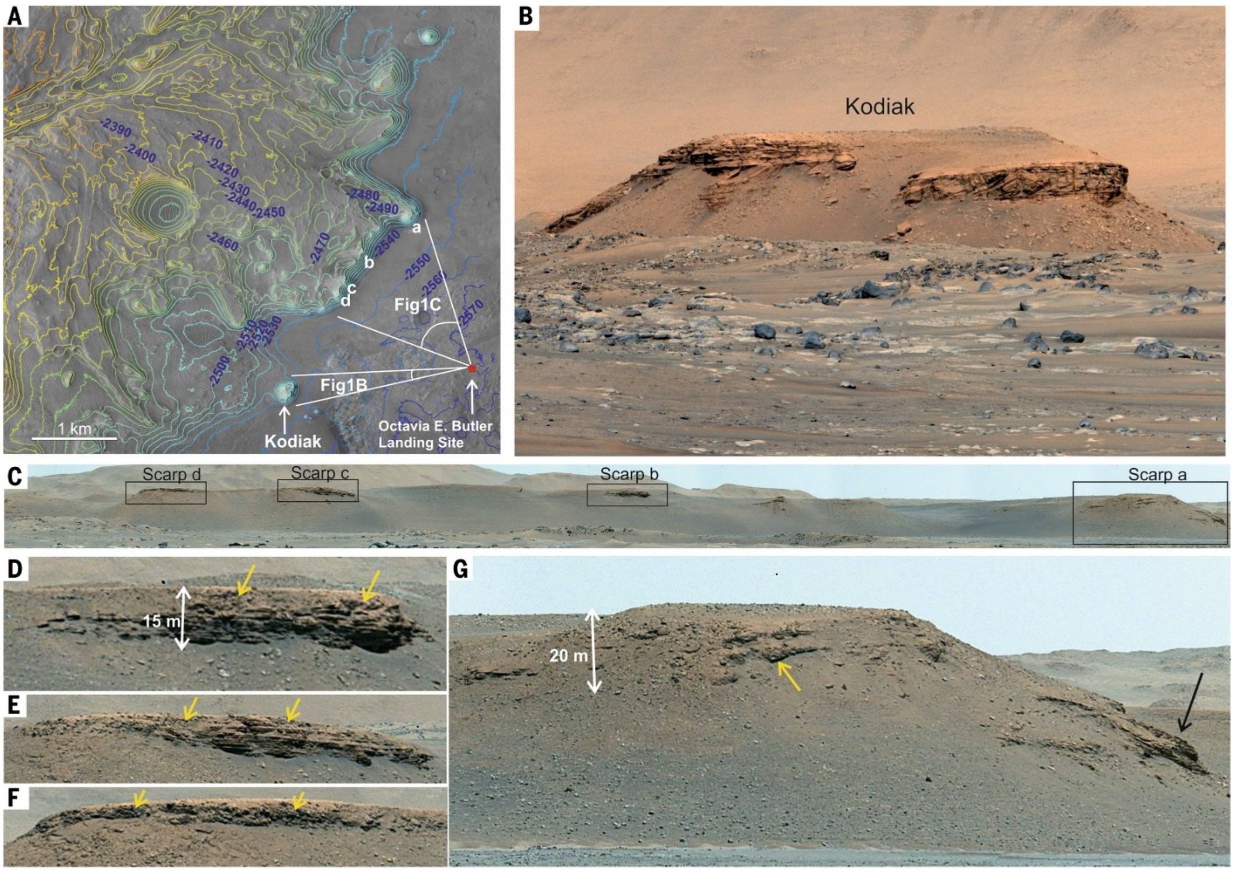

*Figure 3. High-Resolution Image of Deltaic Deposits[10]. (**A**) High Resolution Imaging Science Experiment (HiRISE) mosaic ([14]) with 10-m elevation contours from a digital elevation model (DEM) ([14]) showing the western fan inside Jezero crater and the landing site, informally named Octavia E. Butler (red dot). White arcs represent the fields of view of (B) and (C). (**B**) The butte informally named Kodiak, imaged from a distance of ~2.24 km by Mastcam-Z. (**C**)*

*Mastcam-Z enhanced color mosaic of the delta front, taken from a ~2.20-km distance with black boxes indicating scarps of interest. (**D** to **G**) Each scarp viewed in the corresponding 110-mm focal length Mastcam-Z images. The black arrow in (G) indicates an exposure with dipping strata.*

3.1 Stratigraphic Sequences

The stratigraphic record of Jezero Crater reveals a sequence of igneous and sedimentary units, reflecting a complex geological history. The key units identified are:

1. **Séítah Formation**: This particular unit is the oldest one that can be observed on the floor of the crater. There is a high concentration of olivine in this cumulate, which most likely originated as a lava flow or laccolith. Based on the observations made by the Mastcam-Z and RIMFAX equipment of the Perseverance, it has been determined that the surface possesses a coarse-grained texture and ridges that range from northeast to southwest. It appears from this that the surface was produced prior to the presence of a significant amount of water activity. The formation is considered to be several tens of meters thick and appears to have very little water alteration, according to the data obtained from subsurface radar research.
2. **Máaz Formation**: The Máaz Formation is made up of lava flows that are rich in pyroxene and are located on top of the Séítah Formation. PIXL and SHERLOC investigations can be used to find these flows. The upper part of this unit has a rougher, more substantial, and cratered shape, while the lower part has a smoother shape. Using rover observations and HiRISE digital elevation models (DEMs), scientists have seen that the Máaz Formation has changed the amount of water in different ways. They estimate that it is between 20 and 30 meters thick.

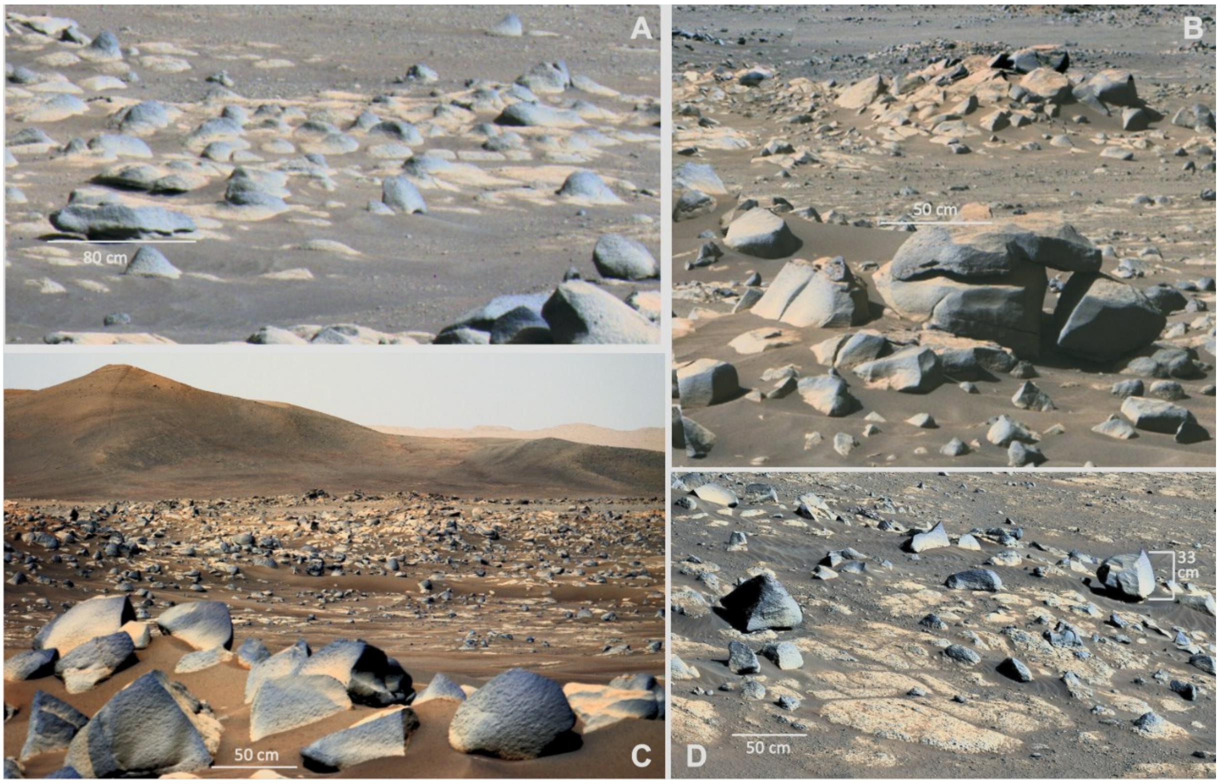

*Figure 4. Examples of typical Máaz formation rocks[31]. (A) Naat'áanii pavers and associated higher-standing Ch'ał member rocks. Sol 22, sequence zcam07000. (B) Ch'ał member rocks. Sol 63, zcam08108. (**C**) Field of typical Ch'ał member boulders, looking northeast toward Santa Cruz hill. Sol 68, zcam8028. (**D**) Roubion member pavers and Ch'ał member rocks. Sol 135, zcam08139.*

3. **Fan Front Sediments**: These deltaic deposits have a thickness of around 65 meters and demonstrate a significant shift in the way sedimentary processes operate. Photos taken by Mastcam-Z and HiRISE demonstrate that the bedrock at the base of the mountain is composed of fine-grained clay, and that it becomes coarser as one ascends the mountain. There are inclined strata in the sediments, which is an indication of deltaic progradation, and boulder conglomerates, which are an indication of high-energy floods that occur on occasion. Both of these features are present in the sediments.

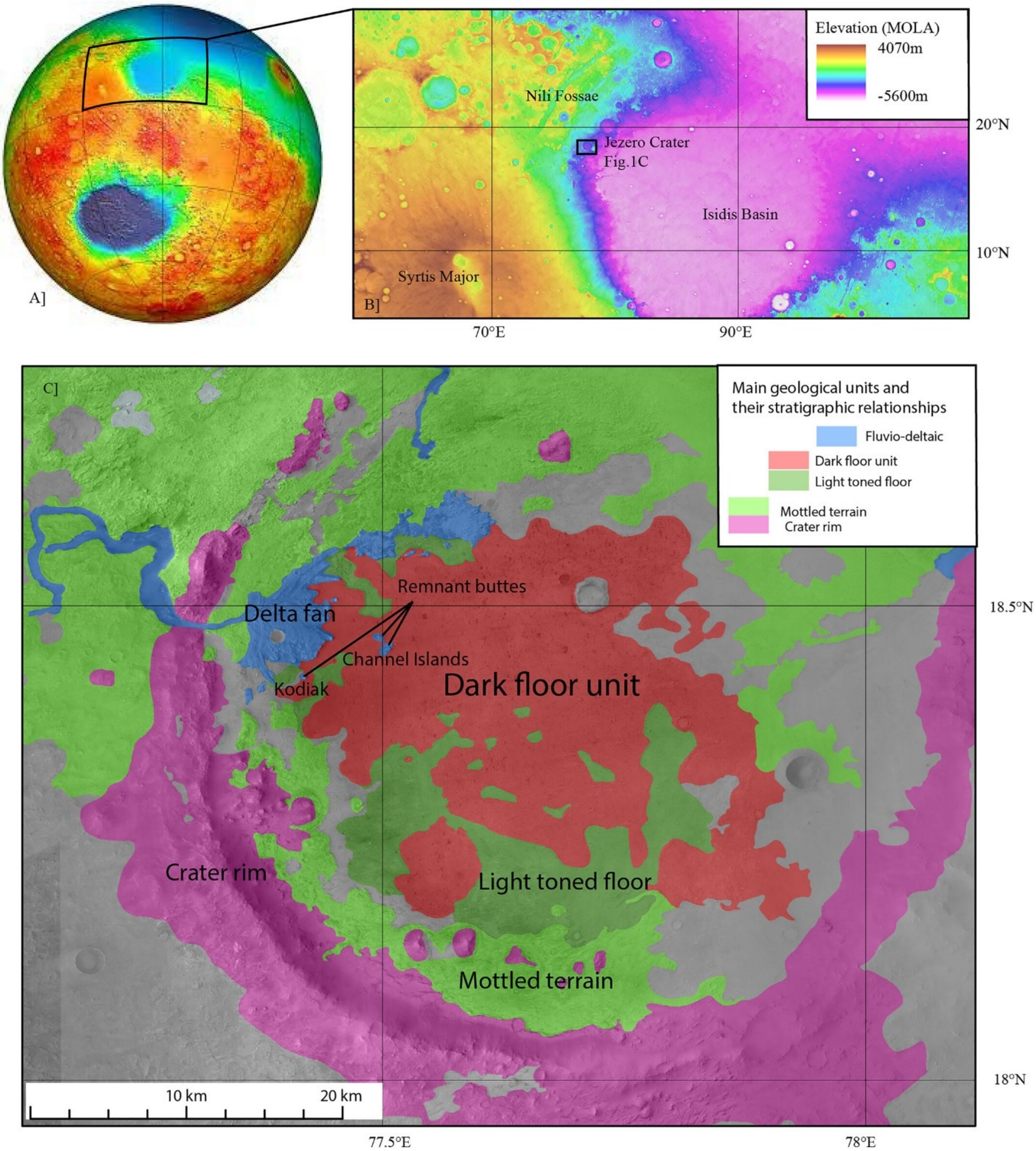

*Figure 5. Stratigraphic Column of Jezero Crater Floor. (a) Mola Hemispheric view of Mars with the location of (b). (b) Regional context of (c) MOLA topography is displayed in transparency over Themis Day-time mosaic (Smith et al., **2003**). (c) Simplified geological context of the Jezero dark crater floor unit (here in red). The geological unit contours are from Goudge et al. (**2015**). The interpretation of the remnant deposit is from Stack et al. (**2020**) and Mangold et al. (**2021**). The stratigraphic relationships displayed in the legend are from Holm-Alwmark et al. (**2021**) who argued for a dark floor unit pre-dating the deltaic deposits.*

4. **Upper Fan Deposits**: These coarse-grained sediments from the Hesperian period are the newest ones in the sequence and are found on top of the fan front formation. They are made up of delta truncated curvilinear (D-tcl) and delta blocky (D-bl) units, which may be seen using HiRISE and Mastcam-Z images. These units are different because they have smaller grains and minerals that come from the Nili Planum watershed[16–18].

3.2 Mineral Distributions

Mineralogical analyses, combining in-situ data from PIXL and SHERLOC with orbital CRISM hyperspectral data, reveal a diverse mineral assemblage across Jezero Crater's stratigraphic units:

- **Séítah Formation**: The main minerals include coarse-grained olivine (Fo 55–70, 60–70 vol%), augite, and Al-rich mesostasis. There are also small amounts of Na/K-feldspars, Fe-Cr-Ti oxides, and Ca-phosphates. Secondary phases include hydrated Mg-sulfates, anhydrite, and carbonates[19–22], which shows that there was not much water alteration. SHERLOC's Raman spectroscopy shows that carbonate phases are there, and PIXL finds small amounts of sulfate minerals.

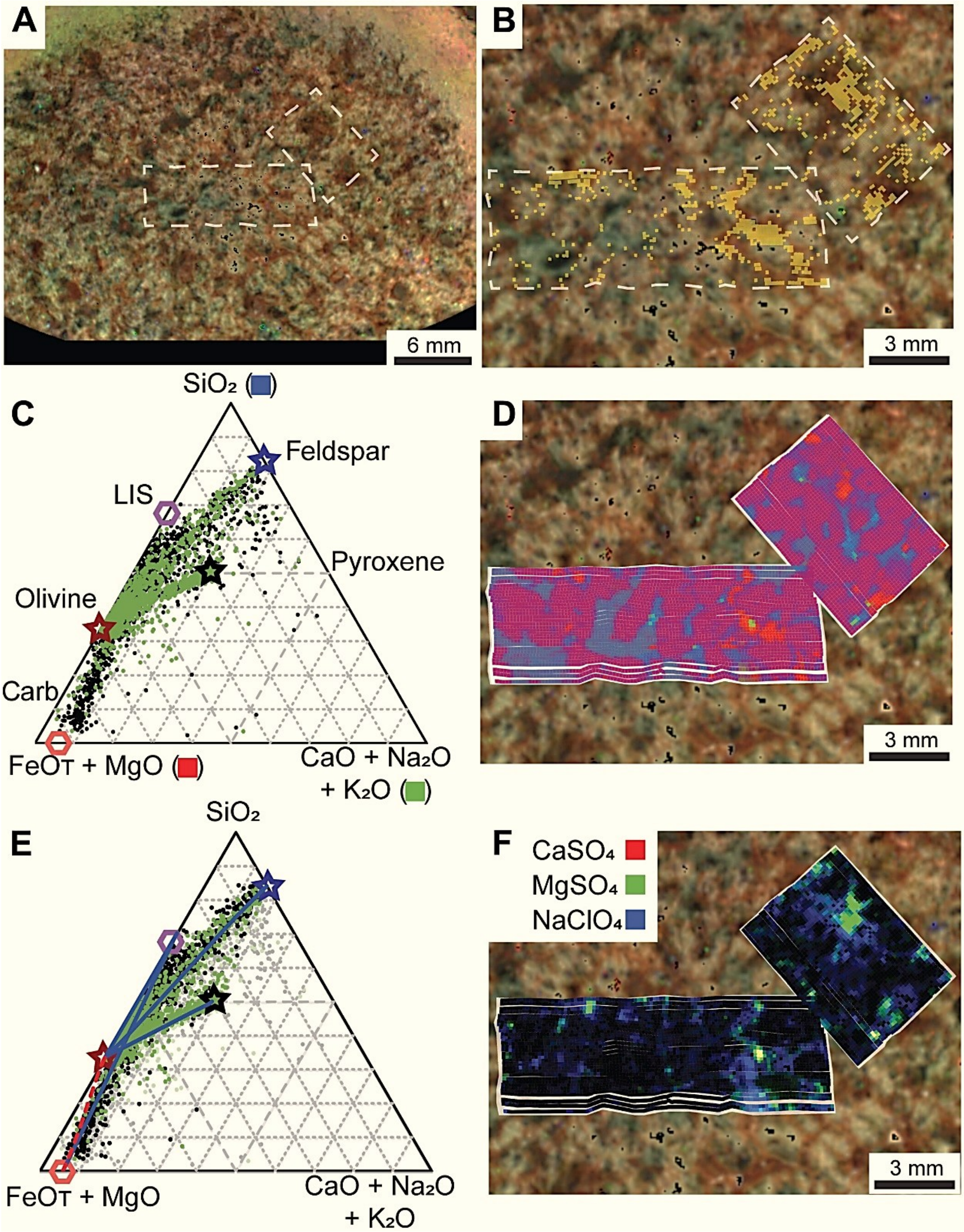

Figure 6. Minerals and how they form crystals[32]. (A) A color stack that has been put back together with red = 735 nm (near infrared), green (G) = 530 nm, and blue (B) = 450 nm. Take note of the many tan grains that are about a millimeter wide and have dark brown and green patches on them. The dashed white boxes show the PIXL x-ray map areas B, D, and F. (B) Areas where no diffraction was seen are covered with a pale yellow color. Nondiffracting materials both cut into grains and line up visible grain boundaries. (C) A mineral categorization ternary diagram that

uses molar abundances and shows the principal (stars) and secondary (hexagons) mineral endmembers. Green spots that diffract. Black spots that do not diffract. Carb is a (Fe,Mg)-carbonate, and LIS is a low-(Fe,Mg) silicate. There are red, green, and blue channels in (D) next to each pole. (D) A false color map of PIXL measurement patches that shows where different minerals are. The colors come from the ternary diagram in (C). The intensity of each color channel shows how close it is to one of the poles: red, FeO-T + MgO; green, CaO + Na2O + K2O; and blue, SiO2. (E) This is a mineral classification ternary diagram like the one in (C), but it has simple accessory minerals (merrillite, calcium sulfate, magnesium sulfate, and Fe,Cr,Ti-spinels) taken out to make it easier to find more common minerals. Gray shows the locations before they were subtracted for comparison. The blue lines represent modeled mixing relationships that happen when minerals partially overlap under the PIXL measuring location. The dashed red line indicates the mixing relationship that should happen when olivine and (Fe,Mg)-carbonate grains touch, however this does not happen. (F) A false-color map of PIXL measurement patches that shows where salty minerals are found. CaSO4 is red, MgSO4 is green, and NaClO4 is blue. When both sulfate minerals are present, the hue is yellow. Sulfate minerals are found in the middle of patches that also have other secondary minerals. Perchlorate runs along certain olivine grains and cuts through others.

- **Máaz Formation**: It is mostly made up of Fe-rich pyroxene and plagioclase, with hydrated Mg-sulfate, anhydrite, perchlorate, and uncommon carbonates as secondary minerals. PIXL's X-ray fluorescence results show that there is little Mg and varying amounts of Fe, which suggests that the area has been changed by water. CRISM results confirm that sulfates are present in the higher Máaz members[22–24].
- **Fan Front Sediments**: Have detrital igneous minerals including olivine and pyroxene, as well as authigenic phases such clays (smectites), carbonates, sulfates, and ferric iron sulfates. There are veins of anhydrite and sulfate minerals that contain cerium. SHERLOC can see UV light coming from phosphates. CRISM hyperspectral data show that there are a lot of clay and carbonate deposits, especially in the deltaic deposits. There are also small amounts of hydrated silica in some places.
- **Upper Fan Deposits**: They have detrital mafic minerals (such olivine, feldspar, pyroxene, Fe/Cr/Ti-oxides, phosphate), hydrated sulfates, carbonates, phyllosilicates, and silica. There is clear cementation by silica, sulfate, and carbonate, and CRISM confirms regional phyllosilicate and carbonate signals.
- **Margin Units**: These units lie near the western crater rim and may be the oldest sedimentary deposits, possibly coming from the coastline or a lake. They have olivine, pyroxene, altered silicates (serpentine), Mg-Fe carbonates, high-silica phases, Mg-sulfates, oxides, feldspar, chlorides, and hydrated silica, but not a lot of organic matter (<0.1 wt%).

Table 1: Mineralogical Composition of Key Rock Samples

Sample	Formation	Key Minerals	Alteration Phases
Sample A	Séítah	Olivine, pyroxene	Carbonates, sulfates
Sample B	Máaz	Pyroxene, plagioclase	Hydrated Mg-sulfates
Sample C	Fan Front	Clays, carbonates, detrital minerals	Sulfates, silica

3.3 Evidence of Fluvial-Lacustrine Transitions

The transition from igneous to sedimentary units in Jezero Crater indicates a shift from volcanic to aqueous-dominated processes. Key evidence includes:

- **Stratified Layers and Deltaic Features**: The pictures from Mastcam-Z and HiRISE show slanted layers in the fan front deposits, which are a sign of deltaic progradation. These layers are made up of fine-grained clay-rich beds at the bottom, which change to coarser sandstones and conglomerates as you go up. This is similar to a Gilbert-type delta[25–28].
- **Boulder Conglomerates**: Mastcam-Z found boulder conglomerates in the fan front sediments, which shows that there were high-energy floods on Mars that happened from time to time. These floods are probably related to the fact that Mars' environment dried out and there was less water activity.
- **Aqueous Alteration Minerals**: The fact that there are a lot of clays, carbonates, and sulfates in the fan front and upper fan deposits, but not so many in the igneous Séítah and Máaz formations[14–15], shows that there have been a lot of interactions between water and rock. CRISM data show that clay and carbonate are spread out in a regional way, especially in the deltaic and periphery units. This supports the idea that the environment is lacustrine.
- **Subsurface Continuity**: RIMFAX radargrams show that the subsurface layers match up with the layers on the surface. The radargrams also reveal that there are slanted reflectors under the fan front that line up with distinct kinds of deposits. According to this information, there is a continuous depositional history that goes from the bottom of the crater to the delta, with thicknesses of up to 65 meters.

Table 2: Stratigraphic Units in Jezero Crater

This table summarizes the stratigraphic units, their descriptions, key minerals, and inferred depositional environments, providing a concise overview of Jezero Crater's geological framework.

Unit	Description	Key Minerals	Depositional Environment
Upper Fan	Coarse-grained sediments, Hesperian age	Detrital mafic minerals, sulfates, carbonates, phyllosilicates	Fluvial-deltaic
Fan Front	Deltaic sediments, ~65 m thick	Clays, carbonates, sulfates, detrital minerals	Fluvial-lacustrine
Máaz Formation	Pyroxene-rich lava flows, variable alteration	Pyroxene, plagioclase, hydrated Mg-sulfates, anhydrite	Volcanic
Séítah Formation	Olivine-rich cumulate, minimal alteration	Olivine (Fo 55–70), augite, carbonates, sulfates	Volcanic

4. Discussion

The combined study of Jezero Crater's mineralogy and stratigraphy, using data from the Perseverance rover and orbiting satellites, gives us a strong basis for piecing together its paleoenvironmental history and gives us important information about Mars' past climate and water flow. The data show a series of igneous units (Séítah and Máaz formations) covered by sedimentary deposits (fan front and upper fan). The mineral assemblages include clays, carbonates, and sulfates, which suggest that the area changed from rivers to lakes. This part looks at these results in light of Martian climate and hydrology, compares them to the geological record of Meridiani Planum as described by Squyres et al. (2006)[3], looks at how groundwater affects things based on Salese et al. (2019)[2,8], and talks about problems with the data's resolution and time frame.

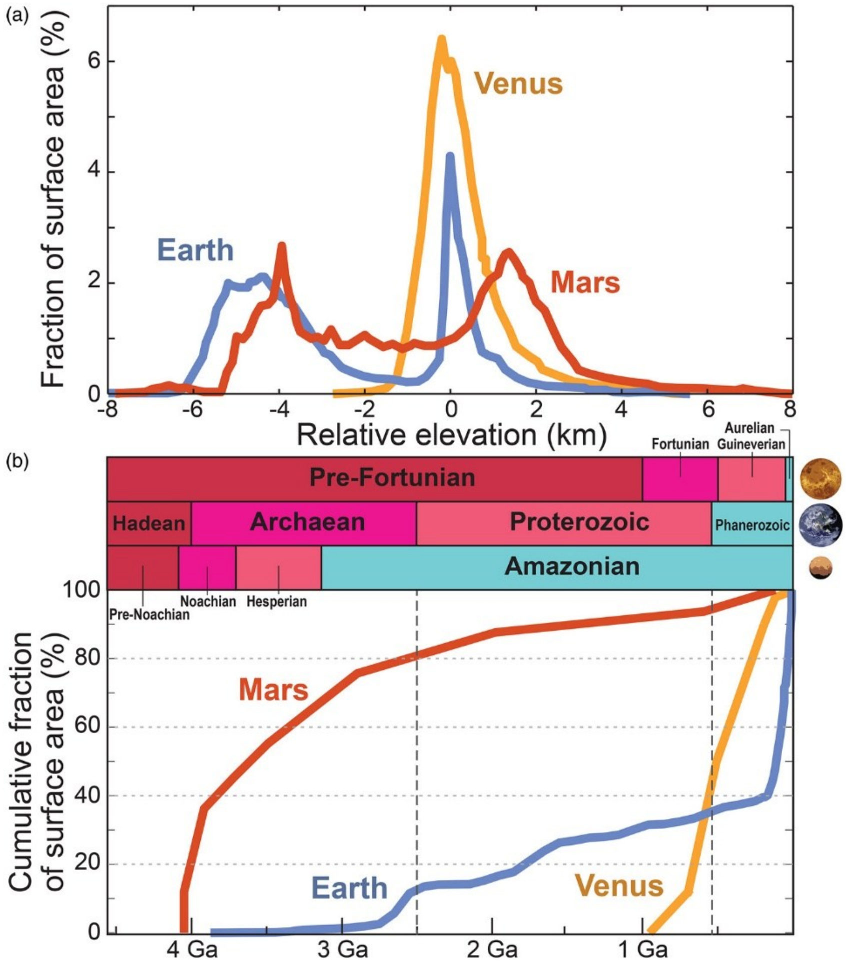

*Figure 7. Terrestrial Analog Comparison. (**a**) Hypsometric curves of Earth, Mars and Venus (Stoddard and Jurdy 2012; Venus hypsometry was re-centred around 0 km elevation for a clearer comparison). (**b**) Comparison between the distributions of terrestrial crustal ages and martian and venusian crater-retention ages. Terrestrial crustal ages were*

compiled from [Condie and Aster (2010)] for continental crust and [Seton et al. (2020)] for oceanic crust (assuming continents represent c. 41% of Earth's surface). Martian crater-retention ages were compiled from [Tanaka et al. (2014a, b)], whereas a mean surface age of c. 500 ± 200 Ma was used for Venus ([McKinnon et al. 1997]) although venusian surface ages could be more narrowly distributed if catastrophic resurfacing occurred.

4.1 Martian Climate and Hydrology

The stratigraphic sequence in Jezero Crater shows a complicated geological history that starts with volcanic activity and continues with long-lasting river and lake processes. The Séítah and Máaz formations, which have cumulates rich in olivine and lava flows rich in pyroxene, show that there was early igneous activity, perhaps during the Noachian period (around 3.7 to 4.1 Ga). The sediments above the fan front, which are about 65 m thick, have sloping layers and boulder conglomerates, which is what you would expect from a Gilbert-type delta that originated in a lake. The presence of clays, carbonates, and sulfates in these sediments implies that water and rocks interacted for a long time, which supports the idea that early Mars had a wetter climate that might have supported stable bodies of water on the surface. According to hydrological modeling, the lake will last at least 90 to 550 years (Salese et al., 2020)[2,8], which suggests that there was episodic but important water action.

The Opportunity rover examined Meridiani Planum, which has sulfate-rich sandstones with hematite spherules ("blueberries"). This suggests that it was a playa-like environment with acidic water activity that happened from time to time (Squyres et al., 2006)[3]. The Burns formation in Meridiani is made up of fine-grained siliciclastics and sulfates. It formed when basaltic predecessors were reworked by wind and water, and hematite spherules imply that the minerals formed in a wet, oxidizing environment. Meridiani's mineralogy is different from Jezero's in that it has a lot of sulfates (like jarosite) and very few clays. This suggests that it was a very acidic and short-lived water system, probably caused by seasonal or episodic groundwater upwelling instead of a permanent lake. The festoon cross-lamination and polygonal cracks in Meridiani's rocks also support the idea that there were short-lived, evaporative conditions (Squyres et al., 2006)[3].

The difference between Jezero and Meridiani shows how Martian hydrology changes from place to place. The clay and carbonate-rich sediments in Jezero suggest that the area is less acidic and maybe even neutral to alkaline, which would make it more stable for water throughout time and maybe even habitable. Meridiani's acidic, sulfate-rich circumstances suggest a more unstable hydrological regime, perhaps caused by volcanic or impact-driven events (Niles & Michalski, 2009)[16]. These discrepancies show that Mars had a variety of watery environments in its early climate. For example, Jezero had a stable lake basin, whereas Meridiani was a playa system with changing water tables. This range of values shows how complicated Mars' hydrological evolution is, which has consequences for world climate models that suggest a shift from a wetter Noachian phase to a drier Hesperian period.

4.2 Groundwater Influence

Salese et al. (2019)[2,8] provide geological proof of a planet-wide groundwater system, showing that groundwater is becoming more and more important in Martian sedimentary processes. Their research found deep craters (more than 4000 m below Martian datum) with flat floors and valleys inside them. This suggests that lakes formed through sapping and upwelling. Groundwater probably had a big effect on the minerals and strata that we see in Jezero Crater. The fact that authigenic clays and carbonates are present in the fan front and upper fan deposits shows that groundwater intrusion helped water and rocks interact. These minerals may have formed when groundwater with a lot of dissolved ions came into contact with the igneous basement rocks (Séítah and Máaz formations) or detrital deposits.

Sulfate minerals, such as hydrated Mg-sulfates and anhydrite, can be found in both sedimentary and igneous units. They may also be connected to evaporative processes that happen when groundwater flows out. Salese et al. (2019)[2,8] say that deep basins like Jezero cut through a zone full of water, which led to the creation of lakes that are nourished by groundwater. This hypothesis fits with Jezero's deltaic deposits, which show that water has been flowing in steadily, maybe with the help of groundwater rising. The underlying continuity seen in RIMFAX radargrams, which reveal layered reflectors below the fan front, supports the idea that groundwater helped sediment deposition and diagenesis. These results are in line with other indications of groundwater activity in places like Arabia Terra and Meridiani Planum, where groundwater processes have been linked to similar mineralogical signatures (Andrews-Hanna et al., 2010)[17].

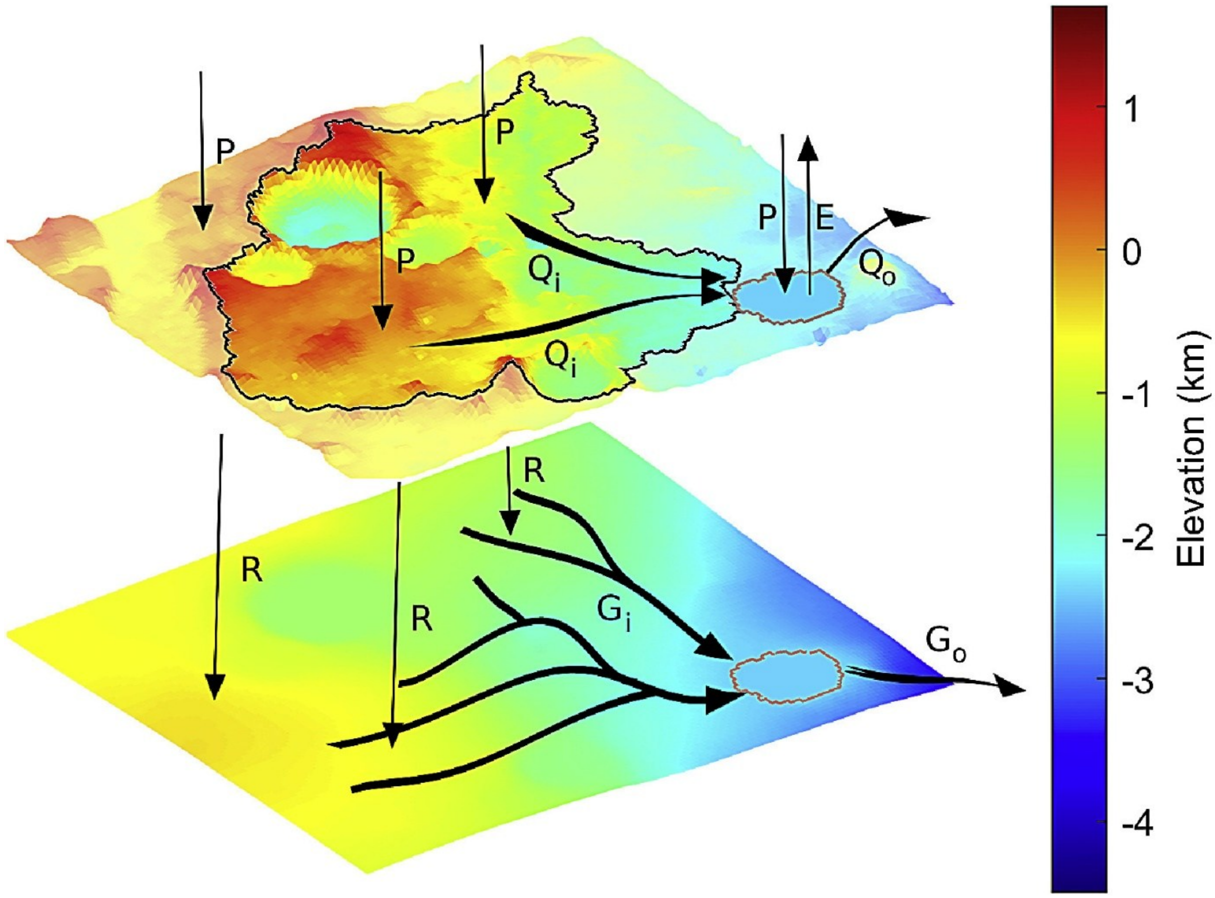

Figure 8. Jazero crater catchment model domain showing the surface (top layer) and subsurface (bottom layer) inflows and outflows into the Jezero lake and regional aquifer overlain on the regional elevation and hydraulic head maps respectively. Arrows indicate fluxes from precipitation (P), aquifer recharge (R), surface runoff (Q_i), groundwater inflow (G_i), surface outflow (Q_o), groundwater outflow (G_o), and evaporation (E). The catchment area (black outline) and lake area (gray outline) are based on the estimates of Goudge et al. (2018) and Fassett and Head (2005) respectively.

The groundwater influence[17] at Jezero Crater probably went beyond mineral precipitation and changed the paleo-lake's hydrological equilibrium. Groundwater might have kept the lake alive longer by supplying a consistent supply of water and dissolved minerals. This would have made it easier for the 65-m-thick sedimentary succession to form. This is different from Meridiani Planum, where groundwater upwelling is assumed to have happened more often, which helped to make evaporites in a playa context (Squyres et al., 2006)[2.] The way that surface and groundwater interact in Jezero shows how complicated Martian hydrological systems are. It suggests that there is a network of water on the planet that varies in strength and length from one place to another[28–29].

4.3 Limitations

Despite the robust dataset, several limitations impact the interpretation of Jezero Crater's paleoenvironmental history:

- **Data Resolution**: The Perseverance rover's instruments (e.g., Mastcam-Z, PIXL, SHERLOC) provide high-resolution in-situ data (down to 100–120 μm), but orbital imagery from HiRISE (0.25–0.3 m/pixel) and CRISM (18–36 m/pixel in targeted mode) has lower spatial resolution. This discrepancy complicates the correlation of local rover observations with regional geological features, particularly for fine-scale sedimentary structures or mineral distributions. Additionally, RIMFAX's ground-penetrating radar, while effective to ~10 m depth, has a vertical resolution of 15–30 cm, limiting the detection of thin subsurface layers or small-scale unconformities[10,15,20].
- **Temporal Uncertainties**: The lack of in-situ absolute age dating hinders precise temporal constraints on Jezero's depositional events. While relative stratigraphy establishes a sequence from igneous to sedimentary units, the exact timing and duration of fluvial-lacustrine activity remain uncertain. Hydrological models estimate a minimum lake lifespan of 90–550 years (Salese et al., 2020)[2,8], but these are based on assumptions about sediment transport rates and water availability, which may not fully capture episodic or variable

hydrological conditions. This limits correlations with global Martian chronologies, such as the Noachian-Hesperian transition.

- **Data Integration Challenges**: Integrating rover and orbital datasets requires careful georeferencing and calibration, which can introduce uncertainties. Differences in spatial scales and data acquisition conditions (e.g., atmospheric interference in CRISM spectra) may affect the accuracy of mineralogical and stratigraphic correlations. These challenges necessitate assumptions about data consistency, potentially impacting the reliability of regional interpretations.

5. Conclusions

Using data from the Perseverance rover and images from the Mars Reconnaissance Orbiter and Mars Express, we have put together a full paleoenvironmental history of Jezero Crater, a 45-km-diameter impact crater on Mars' western edge of Isidis Planitia. The geological record shows that there was a period of volcanic activity at first, as seen in the olivine-rich Séítah and pyroxene-rich Máaz formations, which formed during the Noachian period (around 3.7–4.1 Ga). There are sedimentary deposits on top of these igneous units. These include the ~65-m-thick fan front and upper fan units, which have delta-like characteristics and a lot of clays, carbonates, and sulfates. This series of rock layers shows a change from a dry, volcanic terrain to a long-lasting fluvial-lacustrine ecosystem, perhaps because of both surface water flowing in and groundwater rising. The boulder conglomerates and inclined strata in the fan front sediments imply that there were short bursts of high-energy flooding. The authigenic minerals, on the other hand, suggest that the water and rock interacted for a long time, possibly in a stable lake system. Recent findings, including a composite volcano on the southeastern rim of Jezero, imply that volcanic elements may have helped form the crater's floor, making its geology even more complicated.

When you compare Jezero's clay- and carbonate-rich sediments to Meridiani's sulfate-dominated, ephemeral playa system, you can see that Martian hydrology changes from place to place. Jezero's sediments show that the water was less acidic and lasted longer than Meridiani's. The mineral distributions and subsurface layering show how groundwater affects Jezero's paleoenvironment. This shows how a planet-wide hydrological system shapes the environment.

These results have major effects on future Mars exploration. Jezero Crater's well-preserved record of past water activity is an important model for figuring out how the climate on Mars has changed over time and helping to choose future landing sites with similar fluvio-lacustrine features. Perseverance's instruments (including Mastcam-Z, PIXL, SHERLOC, and RIMFAX) and orbital datasets (like HiRISE, CRISM, and HRSC) have helped us get a better picture of its geology and mineralogy. This gives us a strong starting point for figuring out what similar geological units on Mars are like. For astrobiology, Jezero is a great place to look for signs of previous habitability since it has clays and carbonates that are known to preserve organic molecules. Researchers should focus on the environmental conditions that could have supported life rather than biological evidence itself. The Mars Sample Return (MSR) mission, which is still going on, will help us learn more about the early environmental conditions on Mars by allowing for high-precision laboratory investigations. This could help us narrow down the time frame of the samples and improve our understanding of Mars' early conditions.

To sum up, this work adds to what we know about Jezero Crater's paleoenvironment by showing how volcanic, fluvial, and lacustrine processes interact with each other. These findings help shape plans for future Mars exploration, stressing the need for more research into the planet's varied geological past and what it means for finding places that can support life.

Author Contributions

AKM Eahsanul Haque: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Not applicable.

Data Availability Statement

Most of the analytical data are provided in the main text or in the **Supplementary Material**. Additional data are available from the author upon reasonable request.

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Conflicts of Interest

The authors have no conflicts of interest to declare.

References

1. Grotzinger JP, Gupta S, Malin MC, Rubin DM, Schieber J, Siebach K, et al. Deposition, exhumation, and paleoclimate of an ancient lake deposit, Gale crater, Mars. Science. 2015;350(6257):aac7575. doi:10.1126/science.aac7575.
2. Salese F, Pondrelli M, Neesemann A, Schmidt G, Ori GG. The hydrology of the Jezero crater paleolake: implications for the climate and limnology of the lake system from hydrological modeling. Earth Planet Sci Lett. 2020;628:118573. doi:10.1016/j.epsl.2024.118573.
3. Squyres SW, Arvidson RE, Bell JF, Brückner J, Cabrol NA, Calvin W, et al. Two years at Meridiani Planum: results from the Opportunity Rover. Science. 2006;313(5792):1403-7. doi:10.1126/science.1130890.
4. Horgan BHN, Anderson RB, Dromart G, Amador ES, Rice MS. The mineral diversity of Jezero crater: evidence for possible lacustrine carbonates on Mars. Icarus. 2020;338:113520. doi:10.1016/j.icarus.2019.113520.
5. Mangold N, Dromart G, Ansan V, Salese F, Kleinhans MG, Massé M, et al. Fluvial regimes, morphometry, and age of Jezero crater paleolake inlet valleys and their exobiological significance for the 2020 rover mission landing site. Astrobiology. 2020;20(8):994-1013. doi:10.1089/ast.2019.2132.
6. Kleinhans MG, Bussettini M, van de Lageweg WI. The effects of sediment supply and concentrations on the formation timescale of Martian deltas. Icarus. 2013;226(1):308-23. doi:10.1016/j.icarus.2013.06.008.
7. Cardenas BT, Lamb MP, Ortiz AA, Fairén AG. The Oligocene-Miocene Guadalope-Matarranya Fan, Spain, as an analog for long-lived, ridge-bearing megafans on Mars. J Geophys Res Planets. 2021;126(7):e2021JE006993. doi:10.1029/2021JE006993.
8. Salese F, McMahon WJ, Balme MR, Ansan V, Davis JM, Kleinhans MG. Sustained fluvial deposition recorded in Mars' Noachian stratigraphic record. Nat Commun. 2020;11(1):2067. doi:10.1038/s41467-020-15622.
9. Bell JF, Maki JN, Alwmark S, Ehlmann BL, Fagents SA, Grotzinger JP, et al. Geological, multispectral, and meteorological imaging results from the Mars 2020 Perseverance rover in Jezero crater. Sci Adv. 2022;8(47):eabn3783. doi:10.1126/sciadv.abn3783.
10. Mangold N, Gupta S, Gasnault O, Dromart G, Tarnas JD, Sholes SF, et al. Perseverance rover reveals an ancient delta-lake system and flood deposits at Jezero crater, Mars. Science. 2021;374(6568):711-7. doi:10.1126/science.abl4051.
11. Salese F, Pondrelli M, Neesemann A, Schmidt G, Ori GG. Geological evidence of planet-wide groundwater system on Mars. J Geophys Res Planets. 2019;124(2):374-95. doi:10.1029/2018JE005802.
12. Squyres SW, Knoll AH. Sedimentary geology at Meridiani Planum, Mars. Earth Planet Sci Lett. 2005;240(1):1-10. doi:10.1016/j.epsl.2005.09.038.
13. Farley KA, Stack KM, Shuster DL, Horgan BHN, Hurowitz JA, Tarnas JD, et al. Aqueously altered igneous rocks sampled on the floor of Jezero crater, Mars. Science. 2022;377(6614):eabp5204. doi:10.1126/science.abp5204.
14. Tarnas JD, Mustard JF, Lin H, Goudge TA, Amador ES, Bramble MS, et al. Orbital identification of hydrated silica in Jezero crater, Mars. Geophys Res Lett. 2019;46(22):12771-82. doi:10.1029/2019GL085584.

15. Stack KM, Grotzinger JP, Gupta S, Kah LC, Lewis KW, McBride MJ, et al. Sedimentology and stratigraphy of the Murray formation, Gale crater, Mars. J Geophys Res Planets. 2019;124(6):1522-55. doi:10.1029/2018JE005895.
16. Niles PB, Michalski JR. Meridiani Planum sediments on Mars formed through weathering in massive ice deposits. Nat Geosci. 2009;2(3):215-20. doi:10.1038/ngeo438.
17. Andrews-Hanna JC, Phillips RJ, Zuber MT. Meridiani Planum and the global hydrology of Mars. Nature. 2007;446(7132):163-6. doi:10.1038/nature05594.
18. Ehlmann BL, Mustard JF, Murchie SL, Bibring JP, Meunier A, Fraeman AA, et al. Subsurface water and clay mineral formation during the early history of Mars. Nature. 2011;479(7371):53-60. doi:10.1038/nature10582.
19. McLennan SM, Bell JF, Calvin WM, Christensen PR, Clark BC, de Souza PA, et al. Provenance and diagenesis of the evaporite-bearing Burns formation, Meridiani Planum, Mars. Earth Planet Sci Lett. 2005;240(1):95-121. doi:10.1016/j.epsl.2005.09.041.
20. Hamran SE, Paige DA, Amundsen HEF, Berger T, Brovoll S, Damsgård L, et al. Ground penetrating radar observations of subsurface structures in the floor of Jezero crater, Mars. Sci Adv. 2022;8(28):eabp8564. doi:10.1126/sciadv.abp8564.
21. Scheller EL, Ehlmann BL, Hu R, Adams DJ, Yung YL. Long-term drying of Mars by sequestration of ocean-scale volumes of water in the crust. Science. 2021;372(6537):56-62. doi:10.1126/science.abc7717.
22. Rampe EB, Ming DW, Blake DF, Bristow TF, Chipera SJ, Grotzinger JP, et al. Mineralogy of an ancient lacustrine mudstone succession from the Murray formation, Gale crater, Mars. Earth Planet Sci Lett. 2017;471:172-85. doi:10.1016/j.epsl.2017.04.021.
23. Sun VZ, Stack KM, Kah LC, Thompson L, Fischer W, Williams AJ, et al. Geologic map of the Perseverance field site in Jezero crater constructed by the Mars 2020 Science Team. J Geophys Res Planets. 2023;128(4):e2022JE007461. doi:10.1029/2022JE007461.
24. Poulet F, Carter J, Bishop JL, Loizeau D, Murchie SM. Mineral abundances at the final four curiosity study sites and implications for their formation. Icarus. 2020;339:113561. doi:10.1016/j.icarus.2019.113561.
25. Vasavada AR. Mission overview and scientific contributions from the Mars Science Laboratory Curiosity rover after eight years of surface operations. Space Sci Rev. 2022;218(3):14. doi:10.1007/s11214-022-00882-7.
26. Goudge TA, Milliken RE, Head JW, Mustard JF, Fassett CI. Sedimentological evidence for a deltaic origin of the western fan deposit in Jezero crater, Mars and implications for future exploration. Earth Planet Sci Lett. 2017;458:357-65. doi:10.1016/j.epsl.2016.10.056.
27. Rivera-Hernández F, Sumner DY, Mangold N, Stack KM, Forwick M, Heydari E, et al. Grain size variations in the Murray formation: implications for grain size fining mechanisms and aqueous history at Gale crater, Mars. J Geophys Res Planets. 2020;125(3):e2019JE006156. doi:10.1029/2019JE006156.
28. Salvatore MR, Mustard JF, Head JW, Cooper RF, Marchant DR, Wyatt MB. Development of alteration rinds by oxidative weathering processes in Beacon Valley, Antarctica, and implications for Mars. Geochim Cosmochim Acta. 2013;115:137-61. doi:10.1016/j.gca.2013.04.002.
29. Quantin-Nataf C, Carter J, Mandon L, Thollot P, Balme M, Volat M, et al. Oxia Planum: the landing site for the ExoMars "Rosalind Franklin" rover mission: geological context and prelanding interpretation. Astrobiology. 2021;21(3):345-66. doi:10.1089/ast.2019.2191.
30. Murchie SL, Seelos FP, Hash CD, Humm DC, Malaret E, McGovern JA, et al. Compact Reconnaissance Imaging Spectrometer for Mars investigation and data set from the Mars Reconnaissance Orbiter's primary science phase. J Geophys Res Planets. 2009;114(E2):E00D07. doi:10.1029/2009JE003344.
31. James F. Bell, III et al. Geological, multispectral, and meteorological imaging results from the Mars 2020 Perseverance rover in Jezero crater.Sci. Adv.8,eabo4856(2022).DOI:10.1126/sciadv.abo4856.
32. Michael M. Tice et al. ,Alteration history of Séítah formation rocks inferred by PIXL x-ray fluorescence, x-ray diffraction, and multispectral imaging on Mars.Sci. Adv.8,eabp9084(2022).DOI:10.1126/sciadv.abp9084.