

RESEARCH ARTICLE SUMMARY

MARTIAN GEOLOGY

Aqueously altered igneous rocks sampled on the floor of Jezero crater, Mars

K. A. Farley *et al.*

INTRODUCTION: The Perseverance rover landed in Jezero crater on Mars on 18 February 2021 with three scientific objectives: to explore the geologic setting of the crater, to identify ancient habitable environments and assess the possibility of past martian life, and to collect samples for potential transport to Earth for analysis in laboratories. In the 290 martian days (sols) after landing, Perseverance explored rocks of the Jezero crater floor.

RATIONALE: Jezero, a 45-km-diameter crater, was selected for investigation by Perseverance because orbital observations had shown that it previously contained an open-system lake, prior to ~3.5 billion years ago. Major climate change then left Mars in its current cold and dry state. On Earth, broadly similar environments of similar age to Jezero contain evidence of microbial life. Jezero crater contains a well-preserved delta, identified as a target for astrobiological investigation by the rover. Perseverance landed ~2 km away from the delta, on rocks of the crater floor. Previously pro-

posed origins for these rocks have ranged from lake (or river) sediments to lava flows. Olivine-rich rocks identified on the crater floor, as well as in the area surrounding Jezero, have previously been attributed to a widely distributed impact melt or volcanic deposit, variably altered to carbonate. We used Perseverance to investigate the origin of the crater floor rocks and to acquire samples of them.

RESULTS: The Jezero crater floor consists of two geologic units: the informally named Mááz formation covers much of the crater floor and surrounds the other unit, which is informally named the Séítah formation. Mááz rocks display a range of morphologies: structureless boulders, flagstone-like outcrops, and ridges that are several meters high. The ridges expose prominent layers, ranging in thickness from a few centimeters to a few tens of centimeters. Rocks of Séítah are often tabular and strongly layered, with layer thicknesses ranging from centimeters to meters. Mááz and Séítah rocks display no outcrop

or grain-scale evidence for transport by wind or water.

Perseverance observations show that the Mááz rocks consist of 0.5- to 1-mm interlocking crystals of pyroxene and plagioclase. Combined with bulk chemical composition measurements, this suggests Mááz is an igneous unit that cooled slowly. In contrast, most Séítah rocks are very rich in magnesium and are dominated by densely packed 2- to 3-mm-diameter crystals of olivine, surrounded by pyroxene. These properties indicate settling and accumulation of olivine near the base of a thick magma body, such as an intrusion, lava lake, or thick lava flow. Ground-penetrating radar indicates that Séítah rocks dip beneath the Mááz formation. We hypothesize that Mááz could be the magmatic complement to the Séítah olivine-rich rocks or, alternatively, Mááz could be a series of basaltic lavas that flowed over and around the older Séítah formation.

The olivines in the Séítah formation are rimmed with magnesium-iron carbonate, likely produced by interaction with CO₂-rich water. Mááz formation rocks contain an aqueously deposited iron oxide or iron silicate alteration product. Both units commonly contain patches of bright-white salts, including sodium perchlorate and various sulfate minerals. Although both rock units have been altered by water, preservation of the original igneous minerals and the absence of aluminous clay minerals indicate that the alteration occurred under low water/rock ratio and that there was little loss of soluble species to the surroundings. It remains unclear when these aqueous processes occurred and whether they relate to the lake that once filled Jezero.

The exposure of the olivine-rich Séítah rocks at the surface, the absence of lake or river sediment in the exploration area, and several nearby erosional remnant hills of delta sediment indicate that substantial crater floor erosion occurred after formation of these igneous units.

Samples of both of these geologic units were collected as drill cores. The drill cores were stored in ultraclean sample tubes, for potential transport to Earth by future missions in the early 2030s.

CONCLUSION: The floor of Jezero crater explored by Perseverance consists of two distinct igneous units that have both experienced reactions with liquid water. Multiple rock cores were collected from these units for potential transport to Earth and analysis in terrestrial laboratories. ■

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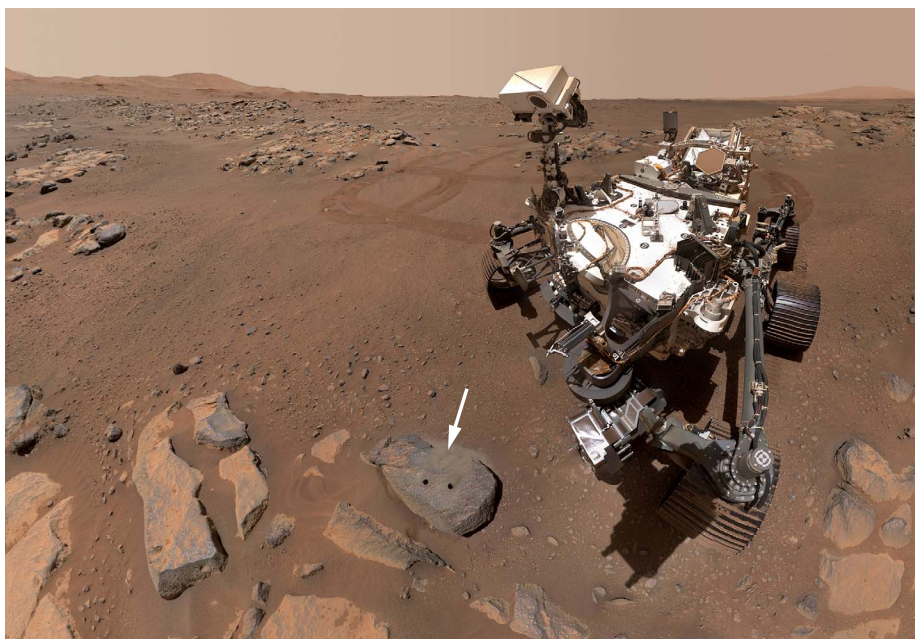
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Sample collection by Perseverance on Mars. This image mosaic was acquired by the WATSON camera on the rover's robot arm. Rock cores were drilled from the two holes (arrow) in an igneous rock of the Mááz formation. The 6-cm-long, 1.3-cm-diameter cores were sealed into individual sample tubes and are now stored inside the rover.

RESEARCH ARTICLE

MARTIAN GEOLOGY

Aqueously altered igneous rocks sampled on the floor of Jezero crater, Mars

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The Perseverance rover landed in Jezero crater, Mars, to investigate ancient lake and river deposits. We report observations of the crater floor, below the crater's sedimentary delta, finding that the floor consists of igneous rocks altered by water. The lowest exposed unit, informally named Séítah, is a coarsely crystalline olivine-rich rock, which accumulated at the base of a magma body. Magnesium-iron carbonates along grain boundaries indicate reactions with carbon dioxide-rich water under water-poor conditions. Overlying Séítah is a unit informally named Mááz, which we interpret as lava flows or the chemical complement to Séítah in a layered igneous body. Voids in these rocks contain sulfates and perchlorates, likely introduced by later near-surface brine evaporation. Core samples of these rocks have been stored aboard Perseverance for potential return to Earth.

The Perseverance rover, part of the Mars 2020 mission, landed on the floor of Jezero crater on 18 February 2021. Perseverance was designed to characterize the geology, investigate records of past climate, and seek evidence of possible ancient life contained in rocks laid down when martian surface conditions were more habitable than they are today (1). The multiyear mission is intended to select, collect, and document ~35 rock and soil samples for potential transport to Earth by future missions for laboratory analysis (1). We report results from the science campaign that ran until mission sol (martian day) 290, exploring the geology and geochemistry of geological units on the Jezero crater floor. These rocks, which form part of a regional stratigraphy, record an ancient period when impact cratering, volcanism, and water were actively shaping the surface of the planet.

Jezero crater, with a diameter of 45 km, lies on the western flank of Isidis, a giant impact basin of Noachian age [~4.0 billion years ago (Ga)] (2) and northeast of Syrtis Major, a younger shield volcano (3). Jezero was formed

by an impact onto an early Noachian basement unit that includes Isidis impact deposits (3–6). The crater later hosted an open-basin lake, fed by a large system of river valleys that were active in the late Noachian (~3.6 to 3.8 Ga) (7) to early Hesperian (>3.2 Ga) (8). Sediments delivered by those rivers into the crater lake produced a clay and carbonate-bearing delta, which appears to be well preserved (4, 8–10). The valleys that fed Jezero pass through a regional stratigraphy that includes an olivine-bearing unit, partially altered to carbonate (11, 12), that overlies the Noachian basement. The olivine unit is in turn overlain by a low-albedo crater-retaining unit, with spectral signatures of pyroxene (5, 13). Mars' three largest impact basins are each surrounded by such olivine-bearing rocks (14). The olivine unit on the southern and western margins of the Isidis basin is the largest contiguous olivine-rich unit on Mars, with several hypothesized origins: impact melt (3, 5), extrusive or intrusive magmatism (15–17), volcanic ash fall (18), pyroclastic surge deposition (19), and detrital sedimentation (20).

Rock units potentially equivalent to this regional stratigraphy occur on the floor of Jezero crater (9, 21). Orbital mapping of the Jezero crater interior (21) before landing delineated a pyroxene-bearing unit, with a high density of superposed impact craters, named Crater Floor Fractured Rough (hereafter Cf-fr), and an olivine-bearing unit named Crater Floor Fractured 1 (Cf-f-1). Perseverance directly accessed these two geologic units (Fig. 1B). The rocks of Cf-fr, informally named the Mááz formation (see supplementary text in the supplementary materials), have been interpreted to be lava flows (9, 22) or sandstones deposited by flowing water or wind (21, 23). Crater counting on this unit constrains the ages of Jezero crater floor rocks, but studies have yielded inconsistent age estimates ranging from 1.4 to 3.45 Ga (9, 22, 24). The spatially heterogeneous crater density on this unit (Fig. 1B) is likely the source of this age discrepancy and indicates that the Mááz formation experienced a complex history of surface exposure. Olivine-bearing rocks occur outside Jezero crater, draping across the rim, and within the crater (9). The olivine-bearing rocks of the Cf-f-1 unit, informally named the Séítah formation, have previously been proposed to share an origin with the regional olivine-bearing unit (9, 21, 25), possibly reworked or chemically modified by water within Jezero crater (21, 23). Although the Séítah formation has been interpreted as older than the delta and its associated lake (21, 23, 26), the age of the Mááz formation relative to the delta is debated. The Mááz formation has been interpreted as one of the youngest units in the crater, postdating all delta deposition (27), or as substantially older, predating the delta (21, 23, 28). Much of the Séítah formation is topographically higher than the Mááz formation, but previous studies agree that it is nonetheless older (23, 28).

During atmospheric entry, the Mars 2020 spacecraft's Terrain Relative Navigation system (27) autonomously selected the highest-probability safe landing site available, which was at 18.4447°N, 77.4508°E, between the heavily cratered Mááz terrain to the east and the abundant aeolian bedforms of the Séítah terrain to the west (Fig. 1). This location has been informally named the Octavia E. Butler landing site (OEB); it lies on a narrow strip of smooth topography, ~2 km southeast of the delta scarp and within tens of meters of the Séítah-Mááz geologic contact. Neither the cratered terrain of the Mááz formation nor the rugged sandy terrain of the Séítah formation is suitable for rover operations, but a narrow smooth strip of Mááz rocks near their contact provided a traversable pathway for the mission's first science campaign. In June 2021, after completion of hardware commissioning and demonstration flights of the

Ingenuity helicopter, the rover embarked on an out-and-back-again journey to the south and then west, with the goal of documenting the two formations. This route provided access to abundant surface exposure of Mááz rocks and more-limited exposures of Séítah bedrock, along with a scarp informally named Artuby ridge, which delimits the two units (Fig. 1C).

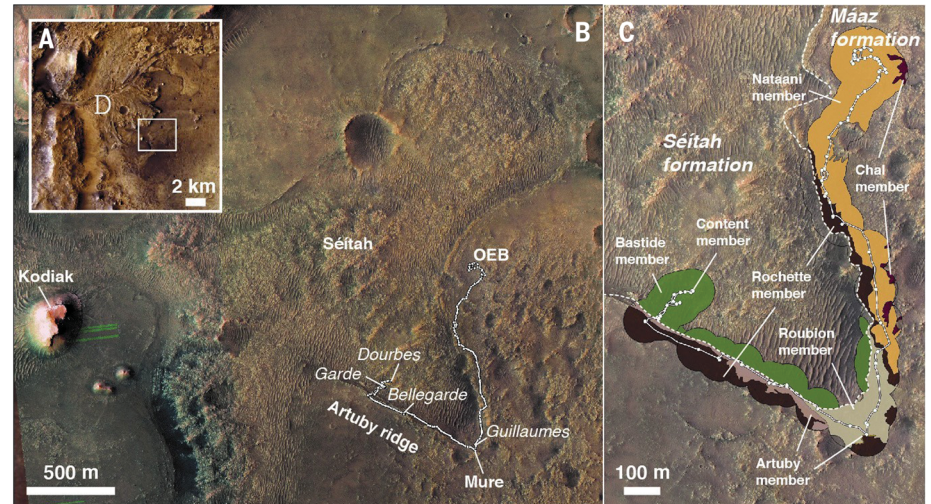
Fig. 1. Orbital images of the Jezero crater floor study area.

(A) Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) base map overlain by Mars Express High Resolution Stereo Camera color images. The study area is on the western side of Jezero crater, a few kilometers east of the delta (indicated by the letter D). (B) High Resolution Imaging Science Experiment (HiRISE) color image of the rover's landing site at the Octavia E. Butler landing site (OEB), and its traverse up to sol 290 (white path; each circle on the path is the end of a sol). The locations of the four abrasion patches are labeled in italics, and four landforms, Séítah, Artuby ridge, the Kodiak delta remnant (60), and the Mure outcrop, are labeled in roman. Séítah is characterized by abundant aeolian bedforms and northeast-southwest striking ridges. The region east and southeast of OEB is part of the Mááz formation, which exhibits high but variable impact crater density. (C) Enlarged portion of (B), overlain with a geologic map showing our interpreted distribution of the Séítah and Mááz formations. Colors indicate mapped distribution of formation members (labeled), and the formation contact is indicated by the dashed white line. The Content member is only visible at the point indicated. Figure S5 shows stratigraphic columns associated with this map.

Rover observations

We used Perseverance to acquire collocated textural, compositional, and mineralogical maps, at both the microscopic and outcrop scale, along a 2.4-km traverse of the Jezero crater floor. Subsurface structure was imaged with a ground-penetrating radar (29). We characterized the natural surfaces of rock outcrops along the rover traverse using the Mastcam-Z

multispectral stereo camera (30), the WATSON [Wide Angle Topographic Sensor for Operations and eNginEering (31)] microscopic camera, and the SuperCam laser-induced breakdown and visual-infrared spectrometers (32). These instruments are most effective when there is minimal coating of rock surfaces by dust and other materials. Removal of dust is also required for the proximity science instruments



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SHERLOC (Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals), a Raman and fluorescence spectrometer (31), and PIXL (Planetary Instrument for X-ray Lithochemistry), an x-ray fluorescence spectrometer (33). To remove the dust coating, rocks were studied after abrading a circular pit of ~5 cm diameter and ~1 cm depth into each target. Debris was removed from the resulting abrasion patch using compressed N₂ gas (34). Proximity observations were taken at four abrasion sites (informally named Guillaumes, Bellegarde, Garde, and Dourbes; Fig. 1B); sample collection was attempted at each of these sites except Garde.

Descriptions of Mááz and Séítah formations

Mááz

The Mááz formation consists of blocky, massive, and layered bedrock (Fig. 2 and fig. S1). Natural surfaces of Mááz formation rocks contain occasional millimeter-sized grains and millimeter-to-centimeter-sized voids or pits. Many Mááz formation outcrops appear polished and grooved by aeolian abrasion. Others appear to be failing along concentric fractures, consistent with spheroidal weathering (fig. S1C). Mááz rocks are often partially covered by regolith, dust, and sometimes a discontinuous purple coating or rind (Fig. 3A); rock

textures are more clearly observed on mechanically abraded surfaces. Sedimentary structures formed by grain transport, such as migrating ripples and dunes, were not observed within this formation.

The Roubion member is exposed at the lowest elevation along the traverse, and we therefore infer it to be the oldest interval of the Mááz sequence (fig. S5). This member is composed of meter-scale low-lying (<5 cm of relief) rock surfaces, which are polygonally fractured. The Guillaumes abrasion patch was performed on such an outcrop of the Roubion member; it reveals light and dark grains with a pervasive but heterogeneously distributed brown tint (Fig. 3A). In the least-brownish regions, we observed millimeter-sized interlocking dark gray or green and light-toned prismatic grains, with no evidence of intergranular porosity or visible cement. Although sometimes elongated, grains show no preferred orientation. If this rock is igneous, the coarse grains suggest a moderately slow cooling rate (i.e., it is a holocrystalline or microgabbroic rock). Irregularly shaped voids or pits, up to 5 mm in diameter, are present within the abrasion patch, which also contains elongated crevices. The edges of these features, and several other areas on the abrasion surface, appear to be coated by a smooth

red-brown or black mantle that partially or completely obscures the underlying grains. Many of the lighter-toned grains are variably stained reddish brown. Millimeter-sized irregularly shaped patches of bright-white material, some also stained brown, occur between grains

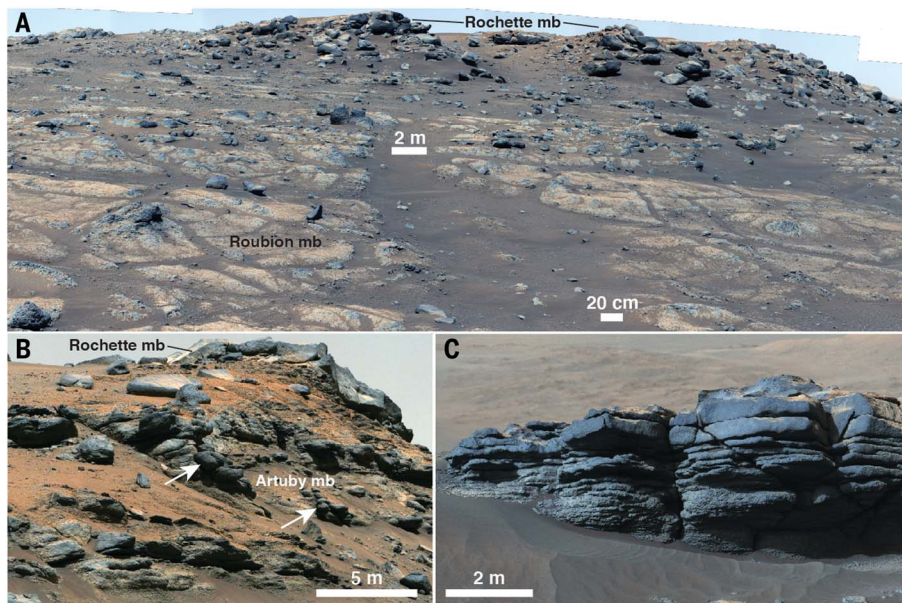


Fig. 2. Rover images of igneous rocks of the Mááz formation. All panels show enhanced-color Mastcam-Z images. (A) Image acquired on sol 138, showing low-relief, friable outcrops of the Roubion member (mb; foreground) overlain upslope by resistant caprocks of the Rochette member. (B) Image acquired on sol 175, showing layered rocks of the Artuby member, which are capped by the resistant rocks of the Rochette member. Artuby member layers range in thickness from <1 cm up to several decimeters and are generally planar. White arrows point to rounded outcrop protrusions. (C) Image acquired on sol 282, showing layered caprock of the Rochette member. Layers range in thickness from several centimeters to several decimeters and show an apparent thickening-upward trend. Layers are planar and dip ~10° to the south (into the page). Source images (39) in this figure and shown below have been white-balanced, contrast-stretched, and gamma-corrected to improve viewability and contrast.

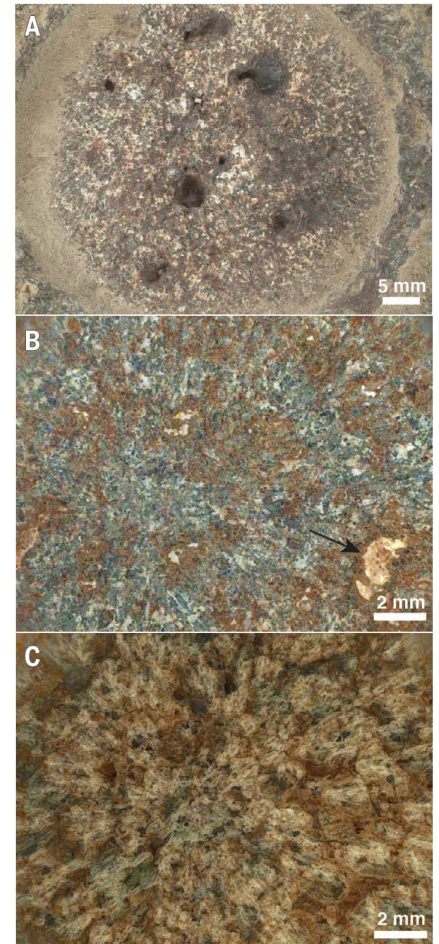


Fig. 3. Microscope images of abrasion patches. (A) WATSON image of the Guillaumes abrasion patch, on the Roubion member of the Mááz formation, acquired on sol 160. Millimeter-sized light- and dark-toned minerals interlock, bright-white and brown-to-black material coats surfaces and fills interstices, and several holes and crevices penetrate into the rock. (B) Combined SHERLOC and WATSON images of the Bellegarde abrasion patch, on the Rochette member of the Mááz formation, acquired on sol 186. Light and dark minerals ranging from 0.5 to 1 mm in size are present, coated or stained with brown material, but less extensively than in Guillaumes. The black arrow points to bright-white material, also stained brown, likely filling a void in the rock. (C) Combined SHERLOC and WATSON images of the Dourbes abrasion patch, on the Bastide member of the Séítah formation, acquired on sol 257. Light-toned grains ranging from 2 to 3 mm in size are surrounded by a dark-green mineral. Brown material occurs on most grain boundaries, sometimes coating the lighter-toned grains.

(likely in filled voids) and as a surface coating on some of the prismatic grains. Collectively, these observations are consistent with an igneous rock that has experienced aqueous alteration (i.e., modification by reactions with water).

Up-section and westward along Artuby ridge, an ~1-km-long linear scarp that reveals 2 to 3 m of southwest-dipping stratigraphy on its northeastern side (Fig. 2B), the Roubion member transitions into the Artuby member, distinguished by the presence of distinct layering. The Artuby member is composed of decimeter-thick layers with rounded protrusions and an apparently coarse granular surface texture, although this is sometimes obscured by regolith (Fig. 2 and fig. S1). The thick layers are separated by, and sometimes transition laterally into, thin recessive subcentimeter-scale layers. The layered rocks of the Artuby member are typically overlain by a resistant caprock, the Rochette member, that can be traced laterally over hundreds of meters along the crest of Artuby ridge. This caprock also appears to extend southward from the ridge as fragmented blocky flat-lying exposures partially covered by regolith (Fig. 1B). The Rochette member is ~30 to 50 cm thick and sometimes appears structureless but more commonly exhibits centimeter-scale layering. At an outcrop informally named Mure (fig. S1, D and E), the Rochette caprock exhibits thin layers that pinch out below more-massive layers and an ~2-cm-wide chain of pits (possibly vesicles) that for ~75 cm traces the curvature of the layer in which it is enclosed. A second abrasion patch, Bellegarde, was performed on a tabular boulder of the Rochette member, on the crest of Artuby ridge. Bellegarde is characterized by smaller crystals (~0.5 mm) of similar appearance to Guillaumes (Fig. 3). These crystals are occasionally stained by a reddish-brown material that is less pervasive than in Guillaumes but appears otherwise similar. Irregular white patches are also present, but there are no large pits or thick dark coatings in Bellegarde.

Resistant, blocky caprocks, like those of the Rochette member, are also observed in several ~1- to 2-m-high scarps along the eastern edge of Séítah (west and southwest of OEB). Here, the Rochette member appears to be overlain by disaggregating low-relief polygonal outcrops of the Nataani member. Rocks of the Nataani member appear morphologically and lithologically similar to those of the underlying Roubion member but are distinct in their geographic extent, elevation, and inferred local stratigraphic relationships (Fig. 1B and fig. S5). The low-relief Nataani member transitions eastward and up-section into the boulder-forming hills of the Chal member. East of OEB and the southbound rover traverse, massive submeter-to-meter-scale boulders of the Chal member erode from hilly

outcrops, with no signs of internal layering. This rough terrain extends to cover most of the crater floor and is associated with the highest crater densities observed within Jezero (Fig. 1B).

Séítah

Bedrock exposure of the Séítah formation is mostly limited to ~1- to 10-m-tall ridges trending northeast-southwest, with the remainder of the region covered by sand ripples, loose rocks, and boulders (Fig. 4 and fig. S2). The Séítah formation comprises the strongly layered Bastide member and the overlying Content member, which is structureless and characterized by abundant millimeter-to-centimeter-sized pits (fig. S2A). Long-distance imaging shows that the Bastide member is widespread and exposed in outcrops throughout the several square kilometers of observed Séítah formation. Most layers of the Bastide member are 1 to 3 cm thick, but the thickest layers are apparently structureless over thicknesses of 10 to 40 cm. Thinner layers sometimes transition laterally into massive outcrops. There is an apparent thickening-upward trend within the Bastide member, in which thinly layered rocks transition up-section into thicker-layered rocks that cap ridges (fig. S2C). Most layers are generally tabular and even in thickness, with planar layer-bounding surfaces, although some exhibit centimeter-scale undulations.

Individual layers can sometimes be traced laterally over distances of several meters within an individual outcrop, but individual layers and distinctive sets of layers usually cannot be correlated between outcrops. We identified no indicators of transport by wind or water, such as planar lamination and ripple or dune-cross stratification. The pitted rocks of the overlying Content member do not exhibit layering, and they lack olivine (as discussed in the section on Séítah mineralogy). The Content member is observed only locally, exposed over lateral distances no greater than several meters. Its contact relationship with the Bastide member is unknown.

Natural surfaces of Bastide member outcrops show densely packed, clast-supported, homogeneous 2- to 3-mm-diameter dark-gray or green grains (or crystals) with indistinct, lighter-toned material between grains (Fig. 4C). The grain-size distributions do not vary across multiple outcrops, nor did we visually detect grain-scale sorting or grading at apparent layer boundaries. The millimeter-sized grains, when observed in abraded surfaces of Bastide (the Dourbes and Garde abrasion patches), are light toned and mostly equant, but some elongated grains are also present (Fig. 3C) (35); we observed no gradation in grain size in the abrasion patches. Less common than the light-toned grains are slightly

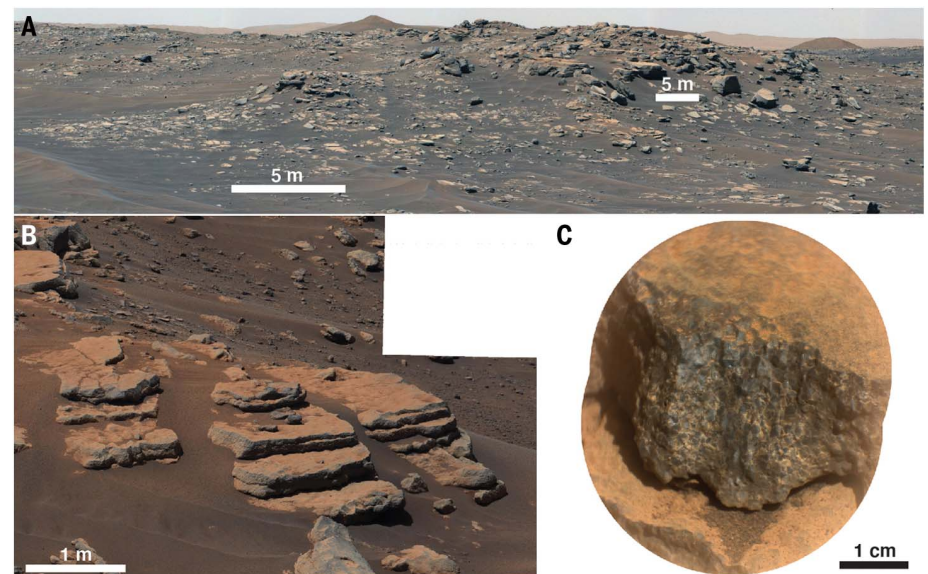


Fig. 4. Layered and coarse-grained appearance of the Bastide member of the Séítah formation.

(A) Enhanced-color Mastcam-Z mosaic of Bastide, acquired on sol 201, showing bedrock exposures eroding into tabular boulders, which occur mostly on ridges. Bastide member bedrock varies from thinly layered to structureless, and individual layers cannot typically be traced more than a few meters. The platy and tabular appearance of the Séítah formation contrasts strongly with the more-rounded boulders of Máaz (Fig. 2A). (B) Enhanced-color Mastcam-Z mosaic, acquired on sol 204, of the Bastide outcrop where the Garde abrasion was performed. Centimeter-scale layering is accentuated by differential erosion. (C) SuperCam mosaic of the Cine abrasion target on the Bastide formation, acquired on sol 206. On surfaces with little dust or coating, the Bastide member rocks reveal abundant 2- to 3-mm angular to rounded gray-green grains, separated by lighter-toned material.

smaller dark-gray or green grains that are sometimes angular but more often appear to fill the space between lighter grains. Light-brown material stains the light-toned grains and is concentrated between grains, in some cases encircling or rimming them. A few submillimeter-scale bright-white patches are also present. Although a few natural surfaces of Bastide member rocks contain millimeter-scale pits, the occasional voids in the two abraded surfaces are much smaller.

Near the base of Artuby ridge, at the transition between the Mááz and Séítah formations, Séítah layering is observed both in outcrop and in the subsurface with ground-penetrating radar. The layering typically dips $\sim 10^\circ$ to 15° to the southwest (fig. S3). These dips are consistent with those of Mááz formation rocks exposed along Artuby ridge. This indicates that Séítah formation bedrock lies stratigraphically below Mááz formation rocks, even though the Mááz formation is topographically lower than some Séítah exposures, confirming a pre-landing hypothesis (23). Thus, the Séítah formation is the lowest exposed stratigraphic unit on the Jezero crater floor, which is overlain by the Mááz formation. The boundary between the Séítah and Mááz formations is obscured by regolith, so it is unknown whether the units are separated by an unconformity. The inferred contact between the two units varies in elevation, by ~ 10 m along Artuby ridge and up to ~ 30 m around the entire Séítah exposure.

Mááz formation geochemistry and mineralogy

Mastcam-Z multispectral observations (30) of Mááz formation rocks along the traverse show broad absorption bands centered near 0.88 to $0.90 \mu\text{m}$, consistent with pyroxene or Fe^{+3} -bearing alteration minerals (fig. S4). These are similar to the weak pyroxene bands observed from orbit across the eastern portion of the crater floor (9, 36). Seventy-seven Mááz formation targets were analyzed with SuperCam infrared (IR) spectroscopy (32); these spectra frequently show a band at 1.92 to $1.93 \mu\text{m}$, which we attribute to hydrated iron oxides, ferric smectites, or hydrated salts (fig. S6) (37). Weaker absorption features observed at 1.42 and $2.28 \mu\text{m}$ are consistent with Fe-OH bands in hydrated silicates (37).

SuperCam laser-induced breakdown spectroscopy (LIBS) (32) was used to characterize the elemental composition of 67 Mááz formation targets. At its typical operating distance of 2.7 m from the rover, the laser beam interrogates a region $\sim 350 \mu\text{m}$ in diameter at each of the 5 to 10 observation points investigated on each rock target. In some cases, individual points had elemental abundances consistent with specific minerals rather than mixtures. From these points we infer the presence of common igneous minerals (augite, plagioclase,

ilmenite, ferrosilite, and unidentified iron oxides), at least some of which are moderately coarse grained ($>350 \mu\text{m}$). No IR spectra or LIBS compositions consistent with olivine were observed in Mááz formation bedrock. Figure S8 shows the average composition of each analyzed rock target, which indicates that the Mááz formation is fairly homogeneous and dominated by varying proportions of plagioclase and augite. The average LIBS-based composition of Mááz (table S1) is broadly basaltic, with 48% SiO_2 , low MgO (3 wt %), and high (20 wt %) FeO_T (defined as total iron as Fe^{+2}).

PIXL x-ray fluorescence mapping (33) shows (Fig. 5) that the Guillaumes (Roubion member) and Bellegarde (Rochette member) abrasion patches are dominated by two distinct 0.5- to 1-mm-scale common igneous phases. The blocky to prismatic white grains (Fig. 3) are chemically consistent with plagioclase (Al-rich regions in Fig. 5A), whereas the darker grains have the composition of pyroxene (specifically augite, Ca-rich regions). Also present are $100\text{-}\mu\text{m}$ -scale regions indicative of FeTi oxides and Ca phosphates. The red-brown to black material consists mostly of Fe and Si, with molar Fe/Si ratios ranging from ~ 0.7 to 1.5 and MgO and Al_2O_3 both $<4\%$. This composition overlaps with some igneous Fe silicate minerals, such as Fe-bearing pyroxene and olivine, but is also consistent with several secondary Al-free Fe silicates, such as greenalite, hisingerite, and cronstedtite. Alternatively, this material may be a mixture of iron oxide and silicates; Mastcam-Z multispectral data indicate the presence of hematite and/or goethite in both Mááz abrasion patches (fig. S4). Coupled with its elemental composition, the color and textural properties of this material (Fig. 3) suggest in situ aqueous alteration of one or more primary igneous minerals.

Raman spectroscopy indicates that the bright-white void-filling material in the Mááz formation abrasion patches is at least partially composed of hydrous Ca sulfate and Na perchlorate, sometimes colocated with each other (fig. S7, A and B). Elemental abundances support these identifications; a phase with molar Na/Cl ratio of ~ 1 is consistent with Na perchlorate, halite, or both.

In the average bulk composition of the Mááz abrasion patches (table S2), the abundances of SO_3 (~ 3.0 wt %) and Cl (~ 2.6 wt %) are both far higher than typical unaltered martian igneous rocks (38). If Mááz consists of igneous rocks, they have experienced addition of S- and Cl-bearing materials. To estimate the primary chemical compositions of Guillaumes and Bellegarde, we computed a subset average of PIXL data by excluding salt-rich bright-white areas (Fig. 3) (39). This alteration-free compositional average (table S2) indicates, on the basis of total alkali metals and silica, that the primary Mááz formation rocks were basal-

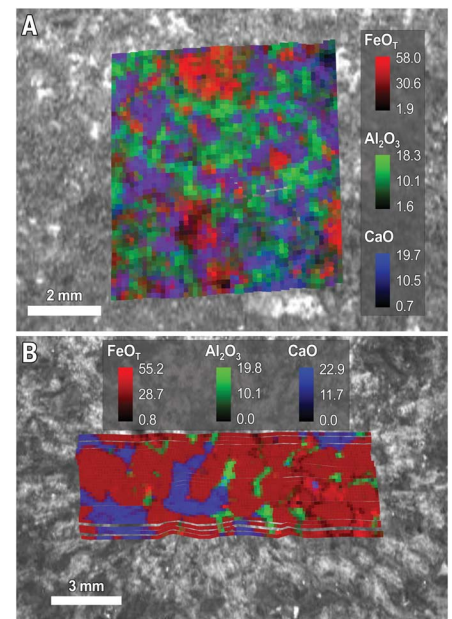


Fig. 5. Compositional maps of Guillaumes and Dourbes abrasion patches. PIXL x-ray fluorescence maps indicating composition are shown in color (as indicated in the legends), with concentrations in weight %. These are overlain on grayscale visual images indicating rock texture. (A) Guillaumes is dominated by grains with compositions consistent with plagioclase (high Al, corresponding to the light grains visible in Fig. 3A) and augite (high Ca and Fe, corresponding to dark grains in Fig. 3A). Fe-rich material appears brown in Fig. 3A; it could be primary or secondary Fe silicates, iron oxides, both, or FeTi oxides and sulfates, as these are indistinguishable in this representation. (B) Dourbes is dominated by euhedral to subhedral olivine of $\sim \text{Fo}_{55}$ composition (Fe-rich, corresponding to light-toned grains in Fig. 3C). Augite (high Ca, corresponding to dark-green grains in Fig. 3C) engulfs olivine, which a companion paper interprets as poikilitic igneous texture indicating an igneous olivine cumulate rock (35). High-Al regions indicate plagioclase. Sulfates and carbonates appear as small areas with the highest Fe. Figure S9 provides individual maps of Ca, Fe, and Al concentrations to aid interpretation of colors in this figure. FeO_T is total iron as Fe^{+2} .

tic in composition. Compared with Earth basalts, Mááz rocks are enriched in FeO_T (22 wt %) and P_2O_5 (2.2 wt %). Compositions estimated by x-ray fluorescence, which represent the analysis of just a few square millimeters of rock, are similar to the average composition of all Mááz formation rocks obtained by LIBS (fig. S8).

Séítah formation geochemistry and mineralogy

Mastcam-Z multispectral images and SuperCam IR spectra of Bastide member rocks of the Séítah formation are dominated by a broad

1- μm absorption feature, indicating olivine (fig. S4). IR spectroscopy also shows a 1.9- μm feature similar to, but weaker than, that observed in Máaz formation rocks, which we attribute to mineral hydration (fig. S6) (37). Individual LIBS points on the prominent 2- to 3-mm gray-green grains observed on natural surfaces (Fig. 3C) commonly have compositions approaching those of pure olivine. The target-averaged LIBS compositions of 25 Bastide member rocks extend from olivine toward mixtures of augite and plagioclase (fig. S8). The Bastide member compositions have only minor overlap with the dominantly plagioclase-augite Máaz formation rocks. The overall mean composition of all Bastide member targets is listed in table S1.

Raman spectra of the Bastide member abrasion patches (Dourbes and Garde) confirm the abundant presence of olivine (fig. S7C). X-ray fluorescence elemental mapping (performed on Dourbes only; Fig. 5B) indicates that 65% of the analyzed surface, associated with the light-toned grains (Fig. 3), is chemically consistent with approximately Fo_{55} olivine (i.e., 55% Mg and 45% Fe on an atom basis) (35). The olivine is partially surrounded with, and sometimes enclosed by, dark-green augite (13% of the analyzed surface). A companion paper (35) interprets this relationship as consistent with poikilitic igneous texture in which late-forming augite grows around density-segregated olivine. Al-rich areas making up 10% of the analyzed surface likely include feldspars; 0.1-mm-scale phosphates and Cr- and Ti-bearing Fe oxides are also present. The reddish-brown material that occurs between grains (Fig. 3C) is chemically complex. It often has Raman peaks consistent with carbonate, frequently associated with olivine peaks (fig. S7). In other instances, Raman spectra consistent with hydrated sulfate (fig. S7) yield Mg/S ratios that indicate the presence of MgSO_4 . In elemental composition maps, the brown areas sometimes contain low SiO_2 , elevated abundances of Fe and Mg, and low analytical oxide totals, consistent with carbonate with an approximate composition of $\text{Fe}_{0.5}\text{Mg}_{0.5}\text{CO}_3$. Raman signatures of the rare white patches indicate the presence of hydrated Ca and Mg sulfates and perchlorate (fig. S7). A broad Raman signature at $\sim 1020\text{ cm}^{-1}$, widely distributed in the abrasion patch, is potentially amorphous silicate (fig. S7G).

Séítah formation rocks, like those of Máaz, appear to consist of primary igneous minerals (e.g., olivine, augite, plagioclase) and secondary aqueous alteration phases (carbonate, sulfates). Excluding material that has likely been transported from elsewhere (39), the mean primary composition obtained by PIXL on Dourbes is ultramafic, with 20 wt % MgO and 40 wt % SiO_2 (table S2). Compared with the Bastide member LIBS average, this composi-

tion has lower SiO_2 and higher FeO but is otherwise similar.

In contrast to the Bastide member targets, LIBS measurements of the Content member appear to be dominated by augite and feldspar, with no olivine. This is consistent with the appearance of this rock, which lacks the coarse gray-green olivine grains characteristic of the Bastide member. Only limited data on this member were acquired.

Interpretations and hypotheses

Origins of Máaz and Séítah formations

We interpret the Bastide member of the Séítah formation as igneous. The grain size and high modal abundance of olivine, coupled with the poikilitic texture, indicate an olivine cumulate in which pyroxene, plagioclase, and primary Fe-Ti-Cr oxides crystallized from residual melt (35). These characteristics indicate slow cooling, differentiation, and crystal settling (40). Therefore, Bastide member rocks likely crystallized in a thick lava flow, a lava lake or impact melt sheet, or an intrusion. On Earth, variations in crystal size or modal mineralogy define layers that often give cumulate rocks a sedimentary appearance in outcrop (40, 41). Imaging, spectroscopic, and LIBS observations revealed no evidence for such differences among Bastide layers or at their interface. The prominently layered appearance of the Séítah formation (Fig. 4) could arise from layer-parallel cooling joints, differential aqueous alteration, or subtle variations in rock composition or texture that enhance near-horizontal fracturing. Such features are likely to have been accentuated by erosional processes, especially wind abrasion. This interpretation implies that the layering in Séítah corresponds to magmatic layering.

Given their mineralogy, texture, and bulk composition, rocks of the Máaz formation are also most consistent with a primary igneous, rather than sedimentary, origin. We exclude the possibility that Máaz consists of basaltic sandstones owing to the lack of sorting among grains of different size and specific gravity, the interlocking grain texture, the lack of evidence for pervasive intergranular porosity or cements in the Guillaumes and Bellegarde abrasion patches, and the apparent absence of sub-aqueous or aeolian transport features.

On Earth, the high abundance of olivine in olivine cumulate rocks is usually complemented by less-mafic (i.e., less Fe and Mg) materials, commonly overlying the cumulate, that, when combined, constitute the parental melt composition (40). Rover observations within Jezero crater, and more spatially extensive orbital spectroscopy (36), indicate that the high olivine abundances characteristic of the Bastide formation are also found throughout Séítah, with olivine-poor rocks (such as the Content member) being rare. If a less-mafic comple-

ment to the Bastide member previously existed in this region, it must have been at least partially removed by erosion. The Máaz formation could be the remnant of such a complement—it has abundant pyroxene and plagioclase and little magnesium, is moderately coarsely crystalline, and lies stratigraphically above the Bastide member, all of which would be expected if the two units originated from a single differentiated igneous melt. The various members of the Máaz formation could be equivalent to layers in the igneous body.

Alternatively, the Máaz formation could be a sequence of younger basaltic lavas that flowed up against, and at least partially overtopped, the Séítah formation after erosional removal of the putative less-mafic complement. The morphologically distinct Máaz members could then be cogenetic lava flows, with variable properties related to composition and/or eruption temperature. An extrusive igneous origin for Máaz would account for some of its morphologies and textures, for example, the lobate structures in the Artuby member (Fig. 2B), possible vesicles in Guillaumes (Fig. 3A), and in the chain of pits in the Rochette member (Fig. 2). Variations in elevation of the Máaz–Séítah contact could reflect underlying topography of the Séítah formation on which the Máaz lavas were erupted. However, other features are less characteristic of lava flows, such as the centimeter-scale layers observed in the Rochette and Artuby members and the lack of flow orientation of elongated grains in the Máaz abrasion patches (Fig. 3).

The limited data on the Content member of the Séítah formation make it difficult to define its origin. It could also be a remnant of a once more-expansive less-mafic complement to Bastide; a remnant of Máaz formation lava flows that overtopped the Bastide member; or remnant sedimentary rocks deposited atop the Bastide member.

Multiple sources of melting are possible for the igneous crater floor units within Jezero; present data are insufficient to discriminate between the possibilities. The impact that produced Jezero could have generated a sufficiently deep melt sheet to differentiate into an olivine cumulate, but we have found no evidence of associated impact breccias on the crater floor, and crater-scaling relationships suggest that the original Jezero floor is buried by $\sim 1\text{ km}$ of postimpact basin-filling materials (4, 22). Although Jezero is close to the Isidis impact basin, and Bastide member petrology is similar to hypothesized olivine-rich cumulates in a melt sheet potentially created by the Isidis impact (3, 5), Isidis cannot be the source because Jezero postdates Isidis. There are no other impact basins of appropriate age, size, and proximity to Jezero to be plausible sources. Alternatively, melting could have occurred without an impact, especially in the early

Hesperian, when the martian mantle was substantially hotter than at present—this is thought to be the origin of the nearby Syrtis Major shield volcano (42).

Magmas could have been introduced into Jezero crater over its rim or from below. Although the Jezero crater rim has been extensively eroded, materials like those in the Bastide member have been interpreted as draping its western side (9), and we suggest that hills on the southeast rim of Jezero could be of volcanic construction. However, these features are not contiguous with the Séítah formation. We consider the most likely scenario to be fissure-fed eruptions occurring both within Jezero and in the surrounding region. By analogy to some volcanically filled craters on the Moon (43) and other craters on Mars (44), magma injection could have occurred directly into the low-density materials of the crater floor at any time after Jezero formation. This process could lead to intrusive and/or extrusive igneous activity (43).

Séítah formation rocks were previously proposed to be part of an ~70,000-km² olivine-rich region associated with the Isidis basin (15, 18, 45, 46). The widespread distribution of this olivine-rich material, apparent draping across topography, poor crater retention, and limited regolith cover have been interpreted as indicating a clastic origin (5, 18–20). That interpretation is difficult to reconcile with our conclusion that the Séítah formation is a slowly cooled magmatic differentiate. Despite their similarities, the regional olivine unit could have an origin distinct from that of Séítah. Alternatively, widespread injection and differentiation of compositionally similar magmas might have occurred throughout the region.

Aqueous processes

After emplacement of the igneous rocks on the crater floor, multiple forms of aqueous interaction modified—but did not destroy—their igneous mineralogy, composition, and texture. Evidence for alteration includes the presence of carbonate in the Séítah abrasion patches, the iron oxides in the Mááz formation abrasion patches (which we presume are due to iron mobilization and precipitation), and the deposition of salts, including sulfates and perchlorate. More broadly, the appearance of possible spheroidal weathering textures (fig. S1C) suggests that aqueous alteration played a role in rock disintegration (47).

The similarity of Fe/Mg ratios in the carbonates and olivine within the Dourbes abrasion patch, rimming of olivine by carbonate, and their possible association with likely amorphous silicate are all consistent with in situ olivine carbonation, in which olivine reacts with CO₂-rich water to produce this phase assemblage in close physical proximity

(48–50). Olivine carbonation often occurs together with conversion of olivine to serpentine group minerals (serpentinization), but in the Séítah formation we have found no evidence for such minerals. The similarity of olivine and carbonate cation compositions, and the survival of substantial abundances of olivine, indicate aqueous alteration under rock-dominated conditions, possibly occurring over a short duration. Olivine carbonation can occur over a wide range of temperatures, from hydrothermal or metamorphic conditions to low-temperature weathering (11). The presence of carbonate places a lower bound on fluid pH that depends on the concentrations of cations and dissolved inorganic carbon (51, 52). For example, if Mg and Fe concentrations ranged from 10⁻⁴ to 10⁻² mol kg⁻¹ and the initial dissolved inorganic carbon equilibrated with 0.1 to 10 bar CO₂(g), the pH would have a lower limit of between 5.5 and 7.5 (at 25°C).

Although we have found no evidence for carbonate in the Mááz formation abrasion patches, the abundant dark mantling material (Fig. 3A) could be a secondary serpentine group mineral produced by aqueous alteration of Fe-rich pyroxene or olivine (53). The presence of secondary Fe silicate without high abundances of carbonate in Mááz formation rocks could indicate a fluid with lower dissolved inorganic carbon concentrations than we inferred for the Séítah formation. These Fe silicates can also form across a wide range of temperatures, from ambient to hydrothermal; we cannot constrain the emplacement conditions without knowing the precise mineral composition. Alternatively, the Fe-rich materials could represent films of Fe oxides or oxyhydroxides coating and penetrating primary silicates, such that our elemental measurements include both phases. On Earth, iron staining of rocks is common when reduced Fe is released from aqueously altered igneous phases and then precipitated under oxidizing conditions. For example, sulfide dissolution by oxidizing solutions commonly yields hematite or goethite, while simultaneously mobilizing sulfate (54).

Sulfate minerals, sodium perchlorate, and possibly other salts (e.g., halite) indicate that other styles of aqueous activity also occurred in the crater-floor igneous formations. These salts fill pore spaces, voids, and cracks that themselves might have resulted from aqueous alteration, for example, from volume expansion accompanying carbonation and serpentinization (55), dissolution of phases such as sulfides, or by chemical and physical erosion processes producing open space (such as the pits in Guillaumes). We have not observed sulfides, but if they were once present, their alteration could have contributed to the production of Ca, Mg, or Fe sulfates or mixtures of them in situ. However, the high sulfate concen-

trations observed in Guillaumes and Bellegarde suggest an external source for at least some of the sulfates. As has been proposed for rocks at Gale crater investigated by the Curiosity rover (56), perchlorate can be introduced into near-surface rocks by downward percolation and evaporation of brines, possibly associated with ephemeral wetting events extending into the Amazonian (<3 Ga). The co-occurrence of perchlorate and sulfate minerals indicates that at least some of the sulfate could have been similarly sourced. The diversity of salt compositions in the analyzed white patches (e.g., their variety of S/Cl and Ca/Mg/Fe ratios) indicates that several different fluids could have been involved, possibly at different times and possibly repeatedly. The extreme solubility of perchlorate salts indicates that they are the youngest alteration materials in these rocks. Salt hydration and dehydration can cause substantial volume expansion (57), weakening the rock and contributing to the mechanical erosion and disaggregation of outcrop by aeolian processes across the floor of Jezero crater.

Although there is evidence for rock-dominated aqueous alteration and a diversity of secondary phases, there is no geochemical or mineralogical indication of extensive open-system aqueous alteration, in which soluble cations (Ca, Na, K) are entirely removed, resulting in enrichments in aluminous phases (i.e., Al-rich clays) (58). The bulk compositions of both the Mááz and Séítah formations are consistent with near-pristine igneous rocks (except in S and Cl; see tables S1 and S2); hydrated aluminosilicates are rare or absent; and there is no textural or chemical evidence for extensive plagioclase alteration or olivine and pyroxene dissolution (59).

Geologic models

We propose two scenarios for the history of the Jezero crater floor, given our inability to distinguish whether the Mááz formation consists of lava flows (hereafter model 1) or an igneous complement to the olivine cumulate of the Séítah formation (model 2).

During or after the formation of Jezero crater, a thick magma body or melt sheet (35) existed within the crater. This could have been emplaced on, or intruded into, a preexisting crater fill. Differentiation and crystal settling formed the olivine cumulate (35) while also producing a less-mafic complement (Fig. 6A). In model 1, erosion removed most (or all) of this less-mafic material, leaving at least tens of meters of topography on the residual olivine cumulate deposit (Fig. 6B), after which lava flows of the Mááz formation flowed around, and at least partially overtopped, the underlying topography (Fig. 6C). Deformation of unknown origin then tilted the originally flat-lying layers of both formations, at least locally, by ~10° to the southwest (Fig. 6D), as observed

along Artuby ridge. In model 2, both Mááz and Séítah were produced by magmatic differentiation similar to a layered igneous body (Fig. 6E). Deformation of unknown origin then uplifted Séítah relative to Mááz, tilting both (Fig. 6F).

In both models, the Mááz and Séítah formations later experienced further erosion that removed overlying Mááz formation rocks from above the Séítah formation (Fig. 6G). We adopt the interpretation (21, 28) that the crater-floor units were then at least partially buried by the delta and associated Jezero lake deposits (Fig. 6H). The late Noachian age (3.6 to 3.8 Ga) (7) of the largest river valley networks feeding Jezero and the assumed Hesperian age of the exposed delta (8) provide a possibly long period of aqueous activity during which lacustrine and igneous processes both occurred, possibly driving hydrothermal interactions. However, we have found no evidence for remnant sedimentary units along Perseverance's traverse up to sol 290. If delta or lake sediments once covered both the Mááz and Séítah formations (Fig. 6H), they appear to have largely eroded away (Fig. 6I), except for delta remnant mounds such as Kodiak (60).

A variety of concurrent and subsequent processes, including rock-dominated alteration and salt deposition, modified the chemistry and mineralogy of these rocks as they interacted with aqueous solutions. Spatially and chemically distinct materials (carbonate, likely amorphous silicate, Fe oxides, perchlorate, sulfates, and possibly Fe silicates) could be the product of multiple distinct aqueous events, differing in chemistry and possibly separated in time. Both hydrothermal waters and groundwater could have played a role.

Habitability and preservation potential

One proposed definition of a habitable environment is one in which liquid water, available energy, nutrients, and other physicochemical conditions are adequate for supporting known forms of life (61). On Earth, reactions of igneous rocks with water produce diverse habitats for microbial life (62, 63). The oxidation and partitioning of iron into secondary phases during alteration processes, such as carbonation and serpentinization, can yield H_2 —a potential energy source—along with methane and other hydrocarbons, which can form raw materials for the synthesis of more-complex organic molecules (62, 63). The chemical reduction of nitrate, sulfate, and metal ions, along with hydrocarbon degradation, is thought to power microbial metabolisms in Earth's deep subsurface (64). Rocks of the Jezero crater floor appear to share the compositional components of these habitable environments. The soluble salts and vein-filling minerals we observe, such as iron oxides, perchlorate, and sulfate salts, could have formed

under habitable low-temperature conditions but could also have formed under nonhabitable conditions (65–67).

The potential for secondary aqueous phases to preserve evidence of life depends on how they formed. On Earth, studies of evaporitic and desert environments demonstrate the presence and preservation of microbial life in association with salts (65, 66, 68, 69). Carbonate veins on Earth, produced through serpentinization and carbonation, can pre-

serve biomarkers such as lipids (70–72) and/or organic structures interpreted as fossilized microbial communities (71). By analogy, we propose that the secondary phases in the altered igneous rocks of the Jezero crater floor might have the potential to record biosignatures, if ancient habitable environments existed.

Sample collection

Laboratories on Earth have measurement capabilities superior to instruments that can

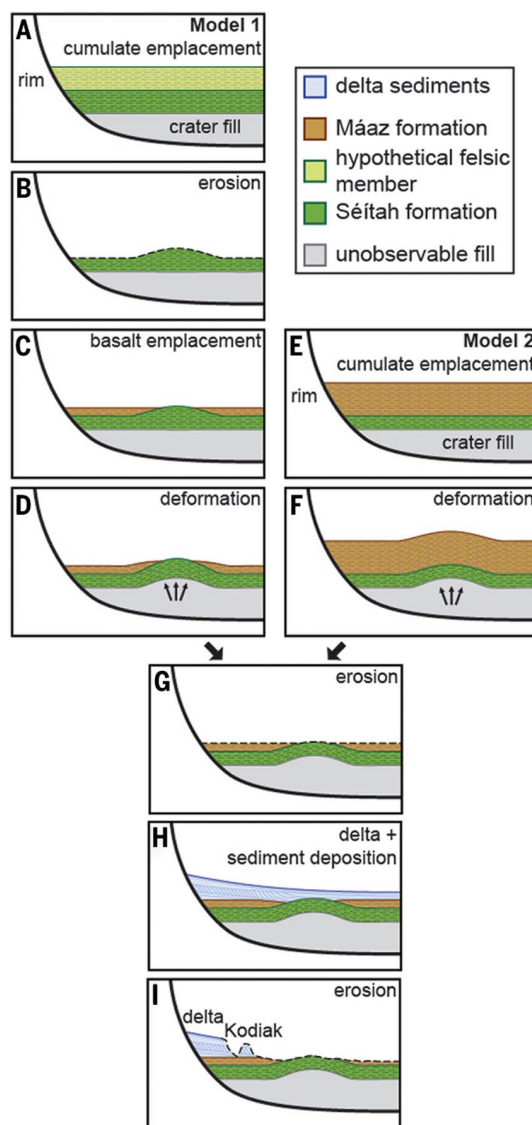


Fig. 6. Two possible models for the evolution of the Jezero crater floor. Proposed geological formations are indicated by the legend. (A) In model 1, the differentiated magma body experienced (B) erosion that removed a less-mafic complement, producing topography on the Séítah formation olivine cumulate. (C) Mááz formation lavas surrounded this underlying topography. (D) Deformation of unknown cause tilted both Séítah and Mááz, as observed along Artuby ridge. (E) In model 2, flat-lying layers of a differentiated magma body (F) deformed in a way that tilted both the olivine cumulate (Séítah formation) and the less-mafic complement (Mááz formation) and also uplifted Séítah relative to Mááz. In (G) and (H), common to both models, erosion occurred and delta and lacustrine sediments were deposited in the lake that filled Jezero. (I) Later, these rock units were eroded to their current surface exposure distribution. Aqueous alteration processes could have occurred during any of these steps.

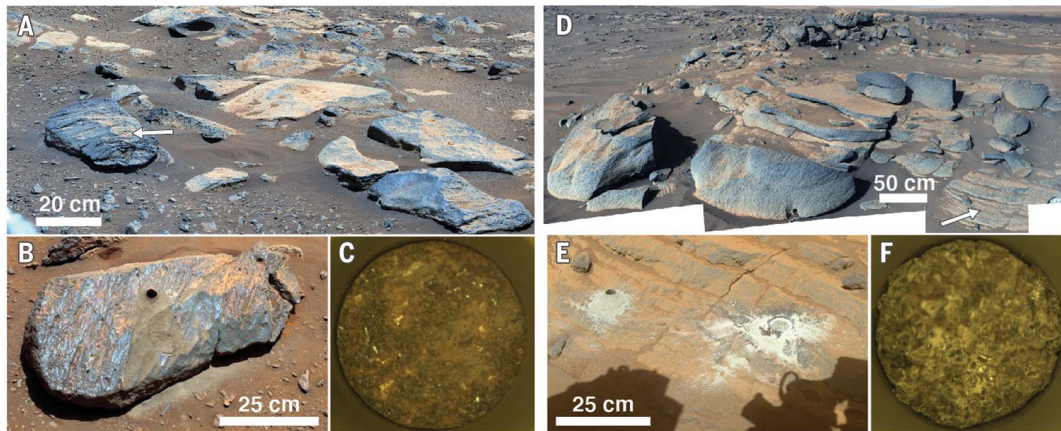


Fig. 7. Core samples collected for potential return to Earth. (A) Máaz formation Rochette member outcrop. The white arrow indicates the sampled rock, part of an apparent degrading layer on the crest of Artuby ridge. Enhanced-color Mastcam-Z mosaic acquired on sol 180. (B) Close-up of the sampled rock, showing the core hole. The Bellegarde abrasion patch is located directly below the hole, partly buried by tailings. Perseverance Navigation Camera (Navcam) (75) image acquired on sol 190, white-balanced with slight color saturation applied. (C) White-balanced Cache Camera (CacheCam) (75) image of the bottom of the core named Montdenier

be mounted on a Mars rover. An objective of the Mars 2020 mission is therefore to collect samples, in the form of drilled rock cores, for potential transport to Earth by another spacecraft in the 2030s (supplementary text). We attempted core acquisition on three different rock targets: two in the Máaz formation and one in the Séítah formation. The first coring attempt occurred near Guillaumes (Fig. 1B), in the low-lying, polygonal pavement of the Roubion member of the Máaz formation. Although the sample collection process appeared to execute as expected, the sample tube was subsequently found to contain no rock or rock fragments. A likely explanation is that this rock disintegrated during drilling, probably as a result of the rock's aqueous alteration (Fig. 3A). The sample tube was sealed and instead provides a sample of ambient martian atmosphere. A second sample acquisition attempt was performed on the Rochette member on the crest of Artuby ridge near Bellegarde, and a third on the Séítah formation Bastide member near Dourbes; these were both successful (Fig. 7).

Aqueously altered igneous rocks have advantages as samples for return to Earth. The formations these samples were taken from likely date from the late Noachian to early Hesperian; only a small fraction of martian meteorites are this old (73). Their crystallization ages, along with the pressures and temperatures during igneous rock formation, could potentially be determined with current laboratory equipment. Because both the Máaz and Séítah formations are thought to extend beneath the delta in Jezero (21, 28), igneous crystallization ages would provide upper bounds

on the age of the lake and the fluvial processes that deposited the delta (60), a lower bound on the age of the Jezero impact, and an upper bound on the age of the smaller craters on the Máaz formation. The igneous lithologies of the samples might be suitable for paleomagnetic analysis of the ancient martian magnetic field (74).

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SUPPLEMENTARY MATERIALS

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Aqueously altered igneous rocks sampled on the floor of Jezero crater, Mars

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Igneous rocks in Jezero crater

The Perseverance rover landed in Jezero crater on Mars in February 2021. Farley *et al.* describe the geologic units investigated by the rover as it began to traverse the crater floor, based on images and spectroscopy. The authors found that the rocks are of igneous origin, later modified by reactions with liquid water. They also describe the collection of drilled samples for potential return to Earth by another spacecraft. Liu *et al.* present compositional data for these igneous rocks based on x-ray fluorescence measurements. They found similarities with some Martian meteorites and conclude that the igneous rocks formed from crystals that sank in a thick sheet of magma. Together, these studies constrain the history of Jezero crater and provide geological context for analysis of the drill samples. —KTS

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