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PLANETARY SCIENCE

Compositionally and density stratified igneous terrain in Jezero crater, Mars

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Before Perseverance, Jezero crater's floor was variably hypothesized to have a lacustrine, lava, volcanic airfall, or aeolian origin. SuperCam observations in the first 286 Mars days on Mars revealed a volcanic and intrusive terrain with compositional and density stratification. The dominant lithology along the traverse is basaltic, with plagioclase enrichment in stratigraphically higher locations. Stratigraphically lower, layered rocks are richer in normative pyroxene. The lowest observed unit has the highest inferred density and is olivine-rich with coarse (1.5 millimeters) euhedral, relatively unweathered grains, suggesting a cumulate origin. This is the first martian cumulate and shows similarities to martian meteorites, which also express olivine disequilibrium. Alteration materials including carbonates, sulfates, perchlorates, hydrated silicates, and iron oxides are pervasive but low in abundance, suggesting relatively brief lacustrine conditions. Orbital observations link the Jezero floor lithology to the broader Nili-Syrtis region, suggesting that density-driven compositional stratification is a regional characteristic.

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INTRODUCTION

Jezero crater was selected as the landing site of the Perseverance rover based on strong astrobiological potential and attributes important for sample return (*1*). Jezero is located (18.4°N, 77.5°E) near the western edge of Isidis Planitia and east of Nili Fossae in Noachian terrain. Orbital images indicate that this crater hosted a lake with two major inlet channels and one outlet channel, suggested to be fluvially active as early as the late Noachian period (*2*). The western sedimentary fan was recently confirmed as a delta deposited within a lake with fluctuating water levels (*3*). These features suggest a formerly habitable environment with a high biosignature preservation potential, motivating exploration and plans for sample return. Moreover, constraining the time period(s) of fluvial activity at Jezero could provide important information about the timing of global fluvial activity on Mars. Jezero also contains the largest, most obvious deposits of carbonates detected on Mars from orbit that typically exhibit strong olivine signatures as well (*4*–*10*). Surface exploration of these deposits could yield unique insights into the climate history and carbon cycle of Mars. Specifically, a formerly water-rich planet with a CO_2-dominated atmosphere should have left ubiquitous carbonate deposits (*11*), but these are unexpectedly sparse. Exploration of the existing carbonates at Jezero and the specific conditions that produced these carbonates should help understand the common association of carbonate and olivine signals in orbital spectra and the processes that formed the rare carbonate deposits on Mars. Last, Jezero crater has been suggested to contain an igneous mafic floor unit (*7*, *8*, *10*–*17*), which may facilitate the return of radiometrically datable samples to calibrate Mars' crater-derived surface ages, as well as a high priority for sample return (*18*, *19*). However, before the landing of the Perseverance rover, the origin of the units on Jezero crater's floor remained debated; earlier igneous interpretations (*7*, *8*, *12*, *13*, *20*) were called into question in favor of ashfall, aeolian, or sedimentary emplacement [e.g., (*15*–*17*)].

Here, we present the first mineralogy and chemistry results of SuperCam observations made along the rover traverse in the mission's first 286 solar days (sols) on Mars (e.g., to mid-December 2021). SuperCam coaligned observations include the first surface-based near–infrared (IR) reflectance spectra in the 1.3 to 2.6 μm range

along with visible-range (VIS) spectra (0.4 to 0.85 μm), elemental compositions obtained by laser-induced breakdown spectroscopy (LIBS), remote time-resolved Raman spectra, and the rover's highest-resolution remote images using SuperCam's remote micro-imager (RMI) (*21*–*23*). More than 1450 observations for chemistry and a similar number of VISIR (VIS+IR) reflectance spectra on >180 targets up to Sol 286 provide a record of chemical and mineral compositions and alteration at nearly every rover stop along the traverse (Fig. 1A). These observations reveal the igneous nature of the rocks encountered so far, which shows a gradient toward progressively more mafic compositions with lower stratigraphic position, and a generally low level of aqueous alteration.

RESULTS

Geological description and stratigraphic nomenclature

Initial observations of mineralogy and chemistry were made at the Octavia E. Butler (OEB) landing site, ~2.2 km southeast of the nearest deposits of the main delta formation (fm) (*3*). OEB is on the western edge of a geologic unit that is relatively homogeneous in morphology as seen from orbit and covers nearly 400 km^2 (*14*) of the Jezero crater surface (Fig. 1A). This relatively thin (~13 m) (*14*) stratigraphic unit exhibits a rough surface texture and distinctive lobate margins. It has been mapped recently (*15*–*17*) as the crater floor fractured rough (Cf-fr) unit and is called the Máaz fm (*24*) in the region of the initial rover traverse (Fig. 1A). Just west of OEB lies an exposure of a stratigraphically lower unit visible as an inlier in the Máaz fm. The unit exhibits layered ridges and was mapped from orbit as the crater floor fractured (Cf-f-1) unit and is informally called "Séítah" ("among the sand" in Navajo) by the Perseverance team. From OEB, Perseverance traveled ~1.5 km south until it rounded the southernmost point of Séítah (Fig. 1A). From there and after producing and making observations on an abrasion patch ("Guillaumes"), Perseverance traveled ~1 km northwest below and along an exposed ridge ("Artuby") that protrudes above Séítah, producing and observing another abrasion patch ("Bellegarde") and collecting two samples at the same location at the top of the ridge (Fig. 1A). Thereafter, Perseverance entered Séítah and explored this unit until Sol 340, producing and observing two more abrasion patches ("Garde" and "Dourbes") and collecting four more samples.

The crater floor surface is relatively flat in the area covered in the rover's first 286 sols. Elevations along the initial southward traverse ranged from −2570 m at OEB down to −2583 m at Rochette on Sol 168, at the southern tip of Séítah (Fig. 1A). The trough along the southwest edge of Séítah is at the same general elevation. For example, the rover was at −2584 m on Sol 171. The top of Artuby ridge is as high as −2580 m. On the northeast side of the trough, Séítah is actually higher than Artuby ridge in most locations, as shown in the topographic profile in Fig. 1, ranging from −2574 to −2568 m. The slightly higher elevations of Séítah relative to the Máaz fm were also noted before the landing [e.g., (*15*)]. Surface observations show that strata along Artuby ridge dip to the south-southwest, away from Séítah, by up to ~10°. Observations made by the Radar Imager for Mars' Subsurface Experiment (RIMFAX) confirm this dip and indicate further that rocks dip away from Séítah on all sides, observed on traverses on sols 135 (east of Séítah), 168 to 170 (south), 180 (southwest), and 200 to 202 [southwest; (*25*)].

The Mars 2020 team has adopted a nomenclature for the region traversed thus far by the rover, in which the Máaz fm (Fig. 1A) is divided into several members based on morphology (*24*). We found that adjacent morphological members in the early part of the traverse (to Sol 173) are compositionally indistinguishable, and so we refer to all rocks in this eastern area as "Máaz." We make a distinction between lighter-toned flat rocks ("pavers") and darker, higher-standing rocks ("Ch'al-like"), the latter in reference to a member proposed (*24*) to consist of massive high-standing rocks to the east of the traverse (text S1), which were sampled later, on the return route, not covered in this work. Starting at Sol 177, SuperCam observed variably recessive layered outcrops below Artuby ridge (Fig. 1A) and massive outcrops at the top of the ridge (*26*). As we show later, both members have similar compositions that are distinct from that of Máaz, so we group these together as Artuby observations. References to Máaz fm compositions in this paper exclude observations along Artuby ridge, which are distinct. Last, we use the designation of Séítah fm for all rocks from sols 202 to 286 except for observations of six pitted targets that are part

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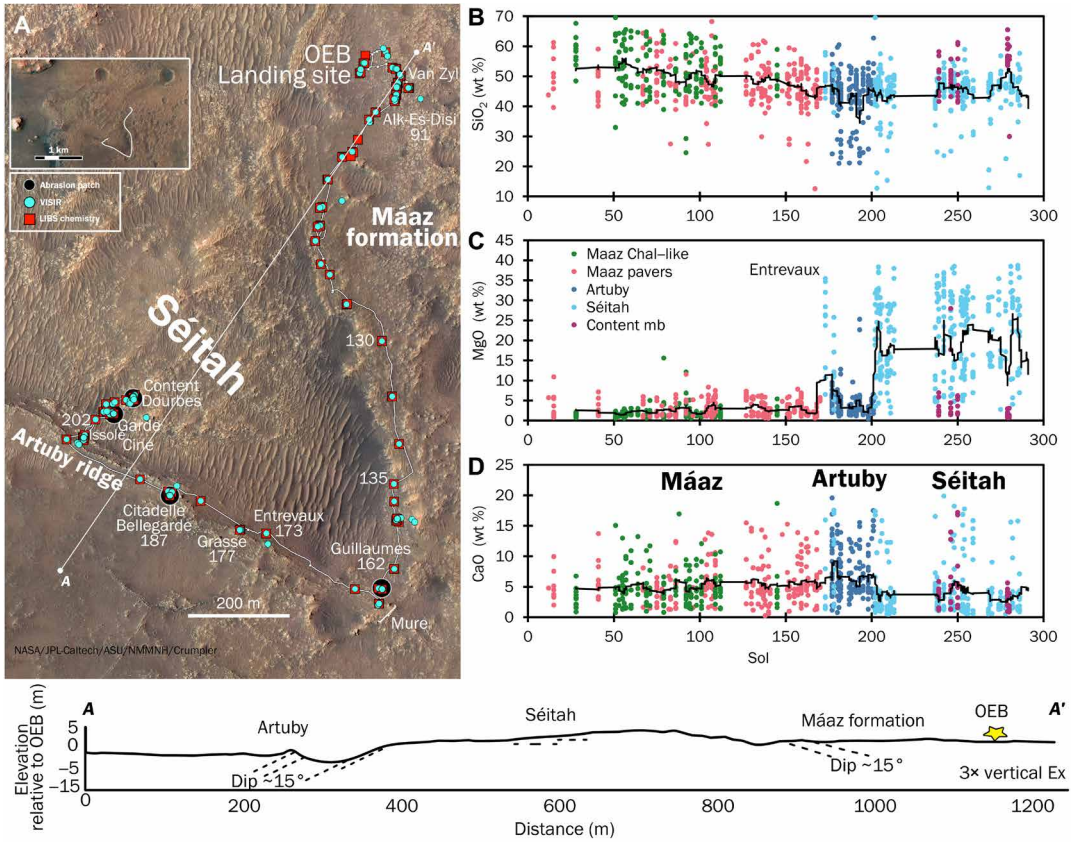


Fig. 1. Perseverance rover traverse and compositions over the first 286 sols of the mission. (**A**) Traverse is shown as a light gray line starting at the OEB landing site. Inset: Traverse location relative to a larger portion of Jezero crater floor. Locations of SuperCam VISIR spectral (blue circles) and LIBS chemistry observations (red squares) as well as abrasion patches (black circles) are indicated. Names of targets mentioned in this work and sol numbers are also indicated. The topographic profile follows the white line and has been extracted from the Mars Reconnaissance Orbiter High-Resolution Imaging Science Experiment (MRO/HiRISE) digital elevation model (DEM) sampled every 100 m. The dip angles are from (*25*). Vertical exaggeration ("Ex") is 3×. (**B** to **D**) Elemental abundances versus sol number for bedrock observations. Scatter in the data is due to the influence of individual mineral grains at or near the size of the laser beam (~350 μm; see Methods). The solid line is a 31-point running average, showing trends. Overhead images in (A) are from MRO/HiRISE. NASA/JPL-Caltech/ASU.

of the compositionally and morphologically distinct "Content member" (mb) (*24*, *26*).

Morphology and textures

The Máaz fm rocks near OEB are composed of pavers juxtaposed with Ch'al-like rocks (Fig. 2, A and B, and fig. S1, A to F) with no obvious layering. Contacts between the two morphologies are exposed in some locations, which show that pavers grade into darker, taller protrusions (fig. S1, A to D). Both morphologies were present along the early traverse although more Ch'al-like rocks were observed close to OEB and Van Zyl (Fig. 1A). To the east, these morphologies transition into a landscape dominated by massive, blocky outcrops that were not analyzed at close range (<20 m). Elongated, curved patterns were also observed from a distance (>20 m) that appeared to show viscous flow textures (*26*). A number of rocks observed locally along the traverse in the Máaz fm contain distinct pits (fig. S1, G and H).

RMI images from the Máaz fm show a rough texture (Fig. 2, A and B) characterized by coarse grains (0.5 to 3 mm) protruding from rock surfaces of both pavers and Ch'al-like rocks. Pavers frequently have a rough surface, in which 1- to 3-mm-wide grains with angular shapes protrude, suggesting euhedral crystals (arrows in Fig. 2B, inset). The surfaces of Ch'al-like rocks are smoother, with local color differences suggesting variable grain compositions or polymineralic grains (fig. S1, E and F). However, aeolian abrasion precludes identification of distinct grains across much of the observed Máaz fm.

The rover first reached clearly layered rocks at the "Mure" outcrop shortly after Sol 160, at the southern extremity of the rover traverse (Fig. 1A). Relatively indistinct subhorizontal fabric with one to several centimeter-thick layers is isolated to one small (meter size) outcrop. More layering was observed to the northwest below massive rocks comprising the top of Artuby ridge (Fig. 2C). These outcrops are variably recessive and typically exhibit a broken-up surface texture, suggesting relatively low resistance to mechanical erosion. Layers are generally indistinct and were not visible across the entire length of the outcrops, preventing identification of depositional beds or planar joints. At close range, rocks from Artuby ridge and Máaz terrain are both dominated by 1- to 2-mm-size grains, but Artuby rocks have more variability in grain size and have a strong imprint of the planar fabric/layering visible down to the millimeter scale that complicates a more definitive assessment of the texture (Fig. 2D).

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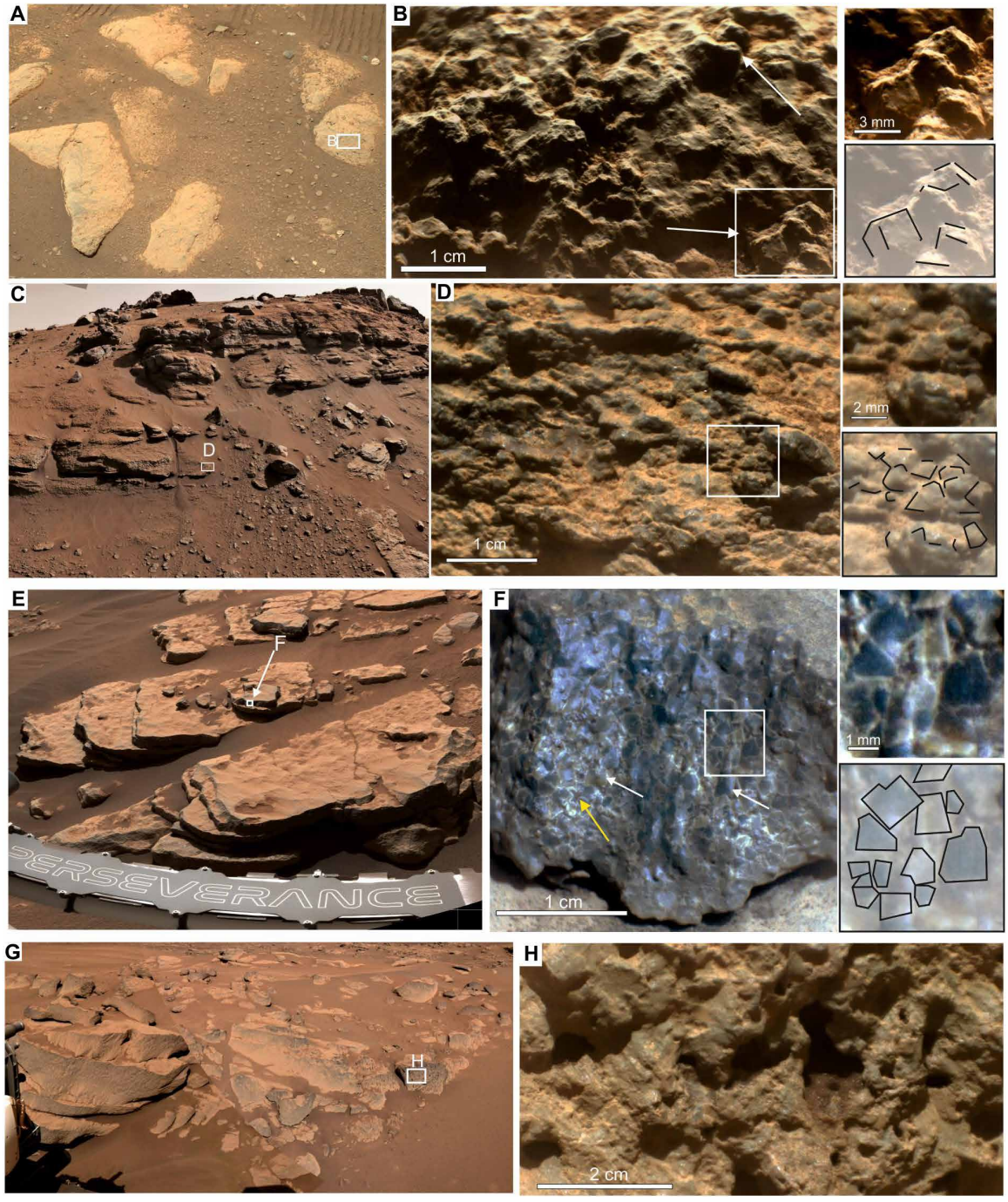


Fig. 2. Rock texture of the units observed during the traverse. Textures are shown at Mastcam-Z and Navcam scales (left side) and SuperCam RMI scales (right side); hand-drawn lines at far right indicate potential grain boundaries for several targets. (**A** and **B**) Target Peppermint (Sol 46), a Máaz fm paver near the OEB landing site. The tangential sunlight highlights grains with angular shapes (nearly cubic for one of them) reaching up to 3 mm in size (white arrows). (**C** and **D**) Rock texture at Artuby ridge, which displays a subhorizontal parallel-layer fabric with poor continuity from one layer to the other. The target Grasse (Sol 175) displays a granular texture with millimeter-size grains with planar arrangements of platy cumulus minerals. Grains appear subangular to subrounded. (**E** and **F**) Target Cine (Sol 204) at the Bastide outcrop in Séítah (fig. S2) showing centimeter-thick layers, using Gaussian color stretch for the RMI image. The clean ledges (E) have relatively fresh surfaces dominated by angular grains (1 to 2 mm) suggestive of euhedral crystals (F). White arrows indicate euhedral grain shapes; yellow arrows indicate interstitial fill with noneuhedral shapes. (**G** to **H**) Target Content (Sol 238), defining the Content mb within the Séítah fm, showing pitted rocks in continuity with layered outcrops. Image designations are described in text S10 and provided in table S6.

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In contrast to the Máaz fm, rocks in the Séítah fm have well-developed layering at scales from a few centimeters to tens of centimeters (Fig. 2E), traceable more than tens of meters in some cases. Layers near the edge of Séítah dip in the same direction as layers in Artuby ridge (10°SSW); however, some layers farther into the interior of Séítah are flatter. Rocks in Séítah show a distinctive holocrystalline texture, most evident in broken rock faces (Fig. 2F). Table S1 shows grain size distributions observed in several locations in Séítah. Overall, the sizes cluster in a relatively tight distribution with a mean and SD of 1.45 ± 0.20 mm (text S2 and table S1). Grains are predominantly angular to very angular, suggesting euhedral shapes (Fig. 2F) with predominantly equant dimensions (defined as the ratio between the longest axis and the perpendicular short axis being >1:2). The space between grains is filled by relatively homogeneous material with irregular boundaries at the scale of the RMI. One exception to the granular nature of the Séítah fm is a group of pitted rocks observed to be in continuity (e.g., no clear boundary) with the layered rocks of Séítah, typified by a target named Content (Figs. 1A and 2, G and H). In addition to being pitted, their textures appear less crystalline.

Elemental compositions and inferred minerals present along the traverse

The overall trend of elemental compositions observed by SuperCam LIBS along the traverse is shown in Fig. 1 (B to D). The trend shows progressively decreasing mean SiO_2 abundances with increasing sol number, as seen by the solid line showing the running average in Fig. 1B with a strong increase in MgO in Séítah (Fig. 1D). Observations along the traverse up to Sol 173 indicate that the Ch'al-like rocks are the richest in SiO_2, with a Ch'al-like mean abundance of 52.6 ± 0.6 weight % (wt %) versus 47.5 ± 0.5 wt % for the pavers, where the uncertainties are the SEMs (table S2).

As the rover encountered Artuby ridge (sols 177 to 201), SiO_2 continued to decrease. Artuby ridge has a mean SiO_2 abundance of 43.5 ± 0.6 wt %, nearly 10 SDs of the mean below that of the Máaz fm (Table 1). Other differences are observed in Artuby compositions. In particular, more high-CaO points are seen in Artuby, leading to a higher mean CaO abundance (Table 1). Artuby also has distinctly higher TiO_2 abundances (Table 1 and fig. S3). Comparison of Fig. 3 (B to A) shows that Artuby compositions also differ from Máaz in Al/Si and (Mg + Fe)/Si. The statistical differences between Artuby and Máaz are described and illustrated further in text S3 and figs. S4 and S5.

The Séítah fm is characterized most strongly by a large increase in MgO (Fig. 1C). The first Séítah target, Entrevaux, was encountered on Sol 173 in the trough along the southwest edge of Séítah (Fig. 1A). MgO returned to its previously low values on Artuby ridge and rose again as soon as the rover descended into Séítah on Sol 201.

The differences in elemental compositions suggest variable mineralogies for the different localities and rock types as represented in Fig. 3, which shows the compositional ranges of Máaz and Séítah in Al/Si and (Mg + Fe)/Si. In this figure, felsic minerals plot along the *y* axis and mafic minerals plot along the *x* axis. Onboard standards representing igneous mineral compositions (andesine, diopside, enstatite, ferrosilite, and olivine) provide reference points for these observations. Máaz compositions at the scale of the laser beam (~350 μm) appear to be mostly mixtures between plagioclase and pyroxene. These mineralogies are also inferred directly from the elemental abundances.

Overall, we infer that Artuby ridge has a different mineral assemblage than the Máaz fm, and, based on the CaO and TiO_2 abundances, it contains more augite. Plagioclase abundances appear lower in Artuby compared to the Máaz fm. In particular, plagioclase grains matching the size of the laser beam were not observed in Artuby, as indicated in Fig. 3B by the lack of Artuby data points near the andesine standard. The statistical differences between Artuby and Máaz are described and illustrated further in text S3 and figs. S4 and S5. VISIR observations confirm the presence of high-calcium pyroxene in Artuby and Máaz; given that VISIR spectroscopy lacks the ability to identify plagioclase, pyroxene is the main observable primary mineral in these units (see Methods).

In contrast to Máaz and Artuby, Séítah is dominated by olivine, confirmed by all three SuperCam spectral techniques. LIBS observations cluster around the onboard olivine standard in Fig. 3B, with trends toward the onboard orthopyroxene (enstatite and ferrosilite) and augite (diopside) standards. SuperCam's VISIR spectra detect olivine by a broad absorption near 1 μm (Fig. 4B) with strong downturns in both SuperCam's visible (up to 0.85 μm) and IR (down to 1.3 μm) spectral ranges (Fig. 4A). The IR spectral slope between 1.3 and 1.8 μm (fig. S6) provides a good indicator of the olivine signal strength and mimics the MgO trends (Fig. 1C). Olivine is also

Table 1. Major element compositions of major units and the abrasion patches where proximity instruments were used. Numbers in parentheses are SEM. *N* is the number of observation points. Abrasion patches are described in text S9.

Mean wt %	SiO_2	TiO_2	Al_2O_3	FeO_T	MgO	CaO	Na_2O	K_2O	Total	*N*
Máaz (sols <177)	49.6(0.4)	0.57(0.02)	9.4(0.2)	18.4(0.6)	2.7(0.1)	5.1(0.1)	2.9(0.1)	1.07(0.05)	89.8	438
Artuby (sols 177–201)	43.5(0.6)	0.90(0.04)	6.9(0.2)	22.2(0.8)	3.9(0.2)	7.0(0.3)	2.4(0.1)	0.53(0.04)	87.4	179
Séítah (sols 202–286)	45.1(0.4)	0.24(0.02)	4.1(0.2)	23.0(0.4)	21.4(0.5)	3.8(0.2)	1.3(0.1)	0.21(0.02)	99.8	344
Content mb (sols 239–279)	51.8(1.0)	0.49(0.08)	12.1(0.9)	15.9(2.2)	3.2(0.7)	4.5(0.5)	4.0(0.2)	1.39(0.15)	93.3	47
Abrasion patches										
Guillaumes (Máaz)	44.4(1.7)	0.42(0.11)	8.1(1.1)	22.7(3.0)	2.0(0.2)	6.5(0.8)	2.7(0.3)	0.56(0.15)	87.5	23
Bellegarde (Artuby)	44.6(1.4)	0.92(0.07)	7.0(0.5)	25.9(2.1)	2.0(0.1)	5.7(0.5)	2.6(0.2)	0.69(0.11)	89.4	31
Garde (Séítah)	42.0(1.9)	0.12(0.07)	4.2(0.5)	21.9(1.1)	17.5(1.6)	3.1(0.8)	0.9(0.2)	0.13(0.06)	89.9	22
Dourbes (Séítah)	41.4(1.9)	0.10(0.03)	2.8(0.2)	25.6(1.9)	21.0(1.7)	5.1(1.2)	0.7(0.1)	0.01(0.01)	96.6	23

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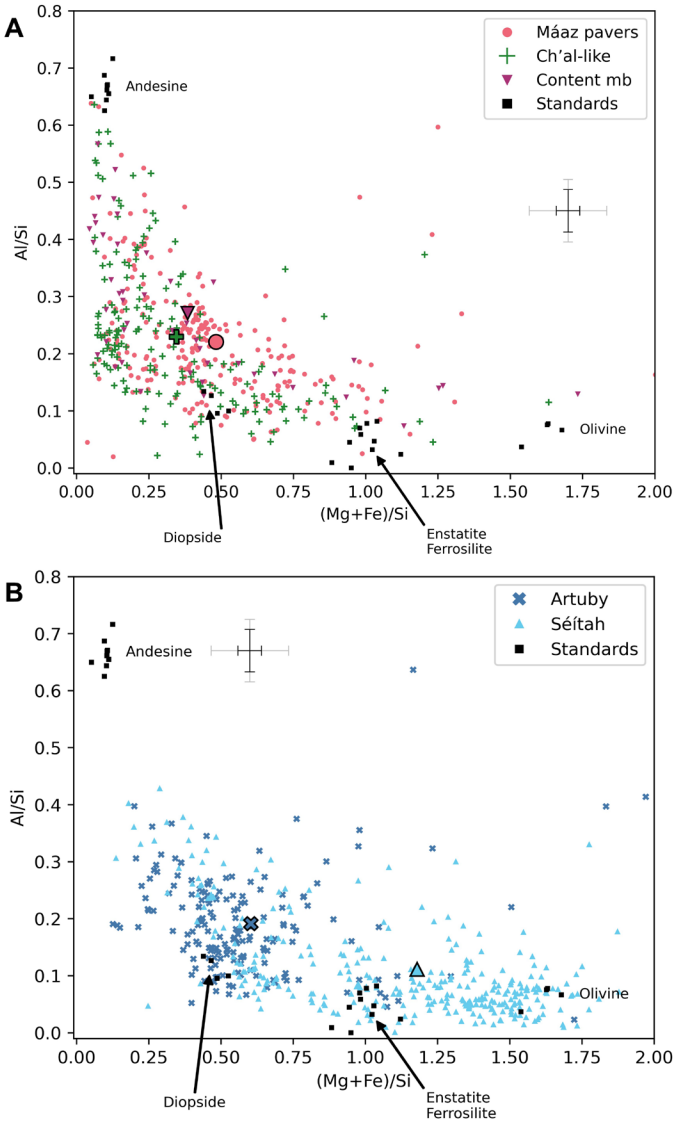


Fig. 3. Molar ratios showing contrasting compositions sampled by SuperCam's 350-μm laser beam. (**A**) Plagioclase- and silica-rich compositions observed in the Máaz fm pavers and Ch'al-like rocks and later in the Content mb of the Séítah fm. In (A), the points consist of mixtures of plagioclase, represented by the onboard andesine target (black squares in top left) with pyroxene, represented by the diopside (high-calcium pyroxene), and enstatite and ferrosilite (low-calcium pyroxene) targets. A few iron oxide points scatter up and to the right of the main group. (**B**) Observations from Artuby ridge, which clusters around the diopside standard (but are the Fe-rich variety of augite), with trends toward ferrosilite and andesine, although there is a clear lack of points near the andesine standard. Also shown in (B) are the Séítah observations, most of which trend between the olivine and pyroxene standards, with a small amount of scatter partway in the direction of plagioclase. Both panels show the mean compositions of each unit in larger symbols. SEMs are shown in fig. S7. The mean single-observation precision and accuracy are represented on each panel as superposed dark and light crosses, respectively.

confirmed by Raman spectra exhibiting the characteristic doublet peaks around 820 and 850 cm^{-1}. A small number of Séítah points trend upward and to the left in Fig. 3B, indicating the presence of plagioclase at a low abundance in this unit. Last, the Content mb differs from the main body of Séítah in that it lacks olivine (not observed by any of the three SuperCam spectral techniques) and is compositionally similar to Máaz. In particular, it shows relatively high Al/Si, similar to Máaz (Fig. 3A) and unlike Artuby or Séítah (Fig. 3B).

In terms of mineral stoichiometry derived from LIBS, Máaz and Séítah fms show considerable differences, including in their inferred pyroxene compositions (Fig. 5A). The Máaz fm actually contains both augite ($Wo_{43–48}En_{25–30}Fs_{22–31}$) and Fe-rich orthopyroxene/pigeonite grains ($Wo_{3–15}En_{4–11}Fs_{74–93}$). By contrast, in Séítah, both the augites and the low-Ca pyroxene are much more Mg-rich, showing a trend from low-Ca pyroxene ($Wo_{3–10}En_{44–50}Fs_{40–51}$) to augite ($Wo_{32–38}En_{38–44}Fs_{18–27}$). Olivine compositions in Séítah range from Fo_{54} to Fo_{72} (Fig. 5A).

The overall results show at least four compositionally distinct units: Máaz fm, Artuby ridge, Séítah fm, and Content mb, for which we present the mean abundances in Table 1. Here, we combine pavers and Ch'al-like into a single Máaz fm entry due to their colocation and contiguous nature. On the other hand, the Content mb, while located within Séítah, is kept separate because of its very significant difference in composition relative to the surrounding Séítah rocks. We will use the four sets of mean abundances in Table 1 as the basis for discussion and comparison.

Aqueous alteration and deposition: VISIR observations and constraints from chemistry

Nearly all of SuperCam's VISIR reflectance spectra indicate some degree of hydration. We evaluate these data to understand the secondary phases and the extent of aqueous alteration. While a few (<10) fine-grained Máaz fm targets show almost featureless VISIR spectra (Fig. 4A, gray spectrum), most targets indicate some degree of hydration, most commonly seen as a ~1.9-μm absorption feature exceeding a 0.02–band depth threshold on 92% of observation points, and extending up to 0.2 band depth. The depth of this hydration band is greater than that observed in spectra from the Mars Reconnaissance Orbiter's Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (0.05 to 0.1). The Máaz rocks also commonly show a 2.28-μm absorption feature in SuperCam spectra, with a downturn above 2.3 μm due to a 2.4-μm absorption (Fig. 4A, dark mean spectra of Máaz fm rocks). The 2.28-μm absorption band is frequently paired with absorptions at 1.42, 1.92, and 2.4 μm, indicating that Fe(III)-rich phyllosilicates such as nontronite or hisingerite are relatively abundant (20% of points surpass a 0.02–band depth threshold for the 2.28-μm feature, and 40% surpass 0.01). While these absorptions are frequently present, their features are weak—the majority of the 2.28-μm band depths does not exceed 0.02 to 0.03—suggesting a limited proportion of Fe-phyllosilicates and/or the presence of (an) additional hydrous phase(s) in the Máaz fm rocks.

We identified possible monohydrated Mg sulfates in the abraded surfaces of the Máaz fm by a combination of 1.92- and 2.14-μm absorptions and a downturn of >2.3 μm (Fig. 4, A and B, yellow spectra). These measurements from the cleanest surfaces, exposed by the rover's abrasion tool, may explain the widely observed shallow downturn past 2.3 μm in the Máaz fm rocks, although this feature is not unique to sulfates and might be attributed to any poorly crystalline mineral with water, including oxyhydroxides and sulfates. VISIR observations also show the presence of an absorption near 2.2 μm, either indicative of Al-OH species, hydrated silica, or gypsum (Fig. 4A, orange spectrum). In addition to VISIR spectra,

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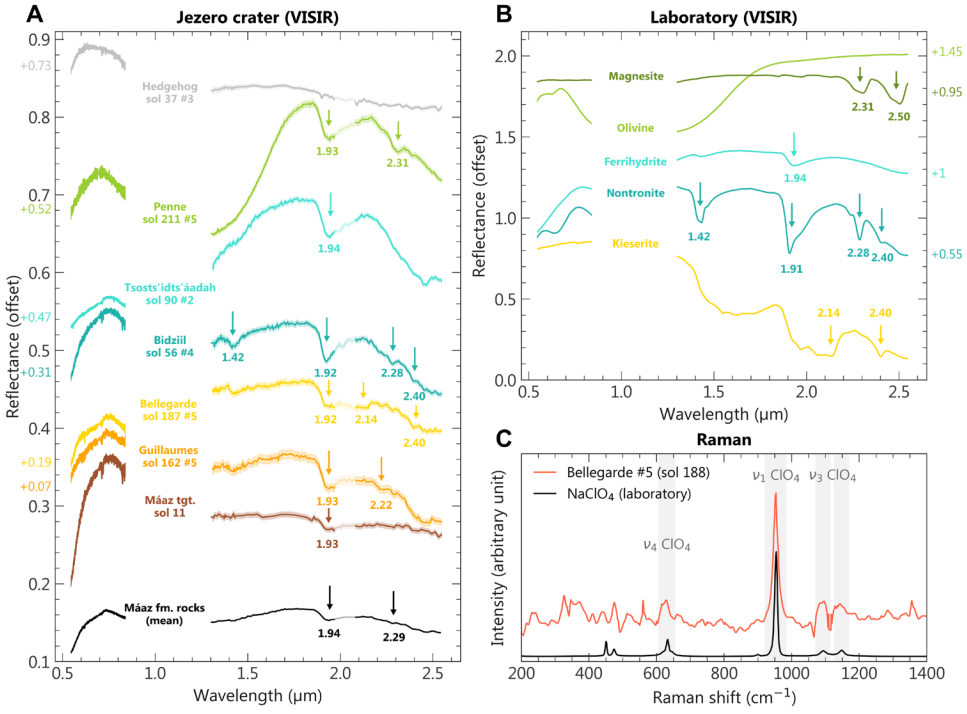


Fig. 4. Representative spectra showing the diversity of VISIR and Raman spectral features. (**A**) VISIR reflectance spectra observed in the Séítah ("Penne," second from top) and Máaz fms (all other plots). (**B**) Laboratory spectra of pure minerals (see text S7). Spectra are offset for clarity. A few targets have nearly featureless spectra [e.g., "Hedgehog" in (A)], but the mean signature of the Máaz fm [(A), bottom] is consistent with the presence of hydrated surfaces. The spectral features best exemplified in targets "Tsosts'idts'áadah," "Bidziil," Bellegarde, and Guillaumes are potentially explained by contributions of oxyhydroxide, Fe-phyllosilicate, monohydrated sulfate or perchlorate, and gypsum or an Al-OH or Si-OH phase, respectively (see the text S7 for band attribution). The "Máaz tgt." spectrum is from the namesake of the fm and is typical of targets with strong dust coatings. The Penne spectrum was collected in Séítah and is consistent with the presence of olivine and traces of a Mg-OH phase and/or a carbonate (e.g., magnesite). (**C**) Raman spectrum of sodium perchlorate observed on one point in the Bellegarde abrasion patch, compared with a laboratory spectrum of sodium perchlorate (*69*).

a Raman spectrum from the Bellegarde abrasion patch (Fig. 4C) indicated the presence of sodium perchlorate.

The VISIR spectra of Séítah rocks also contain alteration-related absorption bands in the form of a wide band centered at 2.31 μm accompanied by a 1.93-μm band (Fig. 4A, green spectrum). A complex mixture of Mg-rich phyllosilicate and/or Fe-Mg carbonates can explain these signatures. A few LIBS observations in Séítah have low SiO_2 (Fig. 1B) and increased C emission-line peak areas, indicating carbonates. Carbonate was also detected in a Raman spectrum of the Garde abrasion patch (Sol 209). Overall, Fe-Mg carbonates comprise a very small fraction (likely <5%) of the composition of Séítah based on the fraction of occurrences and extent of influence in LIBS observations.

While VISIR observations identify the alteration species, we look to a combination of chemistry and VISIR spectra to understand the magnitude and style of alteration. Figure 6 shows the chemistry relevant for characterizing aqueous alteration in a plot of molar Al_2O_3 versus ($CaO + Na_2O + K_2O$) and ($FeO_T + MgO$). We do not detect enrichment of Al_2O_3 relative to the more water-soluble cations, Ca, Na, and K. Such an enrichment, the direction of which is indicated by arrows in Fig. 6, would result in compositions plotting well above the line between plagioclase and the FeO + MgO apex (*27*). Their absence indicates limited removal of soluble cations. The relatively low abundances of some cations also constrain the amounts of secondary materials added by precipitation. For example, MgO ≤ 2.0 wt % in the Ch'al-like rocks and in abrasion patches Guillaumes and Bellegarde (Table 1 and table S2) limits Mg-dominated sulfates and carbonates in these locations to at most only several percent on average. As discussed below, the extent of bulk chemical weathering and addition of precipitated salts are limited by the overall chemistry and the fact that we observe the primary igneous mineral signatures such as olivine in VISIR spectra in Séítah (Fig. 4, A and B, green spectrum). Isochemical weathering still played a role in producing some in-place alteration. In particular, IR spectra suggest that rocks include some Fe(III) phyllosilicates.

Modal mineral abundances estimated from elemental compositions

The relatively limited extent of alteration allows us to study the igneous compositions of the rocks observed along the traverse. However, some alteration materials were part of the LIBS observations. Máaz fm and Artuby ridge observations included points with low SiO_2 (e.g., <35 wt %; Fig. 1B) and low totals of the eight major elements (see Methods and data file S1), signaling the occasional presence of up to >20 wt % of other elements such as S, C, H, and Cl that are not currently quantified. After excluding these LIBS observation points (text S4), using the remaining dataset, we estimated the mean igneous compositions, CIPW normative mineral compositions, An (plagioclase) and Mg numbers, and corresponding rock densities of Máaz, Artuby, and Séítah, presented in Table 2. We

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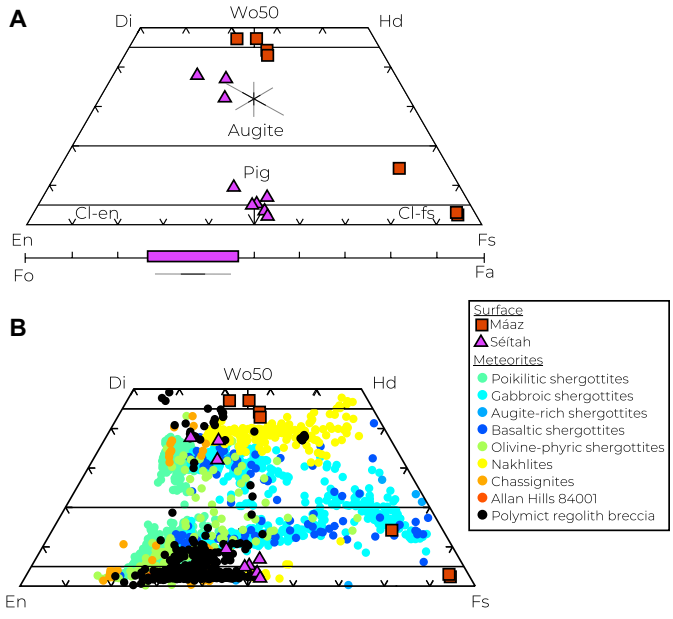


Fig. 5. Pyroxene quadrilateral. (**A**) Pyroxene compositions observed in Máaz fm (red squares) and Séítah (purple triangles). The range of Mg numbers of Séítah olivines is shown below (see fig. S8). Superposed error bars show mean precision (dark lines) and accuracy (light lines). (**B**) Comparison with pyroxene composition found in martian meteorites. The Máaz fm contains augite and Fe-rich pyroxenes, similar to basaltic shergottite meteorites, whereas the Séítah fm contains pyroxenes more enriched in Mg, similar to poikilitic and olivine-phyric shergottites. End members and compositions are indicated as follows: Di, diopside; Hd, hedenbergite; Wo50, wollastonite 50%; Pig, pigeonite; Cl-en, clinopyroxene enstatite; Cl-fs, clinopyroxene ferrosilite; En, enstatite; Fs, ferrosilite; Fo, forsterite; Fa, fayalite. Meteorite data in (B) are from references given in reference file S1.

Table 2. CIPW norms and calculated parameters derived from normalized abundances of the main observed units. Elemental abundance totals are normalized to 100 wt % as described in Methods and assume Fe^{2+}/total Fe = 0.95. Error on density is propagated from SEMs for compositions (see Methods).

Weight %	Máaz	Artuby	Séítah
SiO_2	54.2	49.7	44.8
TiO_2	0.6	0.9	0.2
Al_2O_3	10.5	7.4	3.9
FeO_T	20.2	25.3	22.6
MgO	2.7	3.8	21.4
CaO	5.5	7.7	3.6
Na_2O	3.3	2.7	1.3
K_2O	1.2	0.6	0.2
Quartz	5.6	0.0	0.0
Plagioclase	37.9	30.0	15.2
Orthoclase	7.1	3.6	1.2
Diopside	4.8	16.7	1.5
Hypersthene	37.9	41.5	34.7
Olivine	0.0	0.9	41.1
Ilmenite	1.1	1.7	0.4
Magnetite	1.6	2.0	1.8
An # plagioclase	25.3	22.7	26.5
Mg #	19.3	21.1	62.8
Density (g/cm^3)	3.10	3.27	3.37
	±0.02	±0.03	±0.01

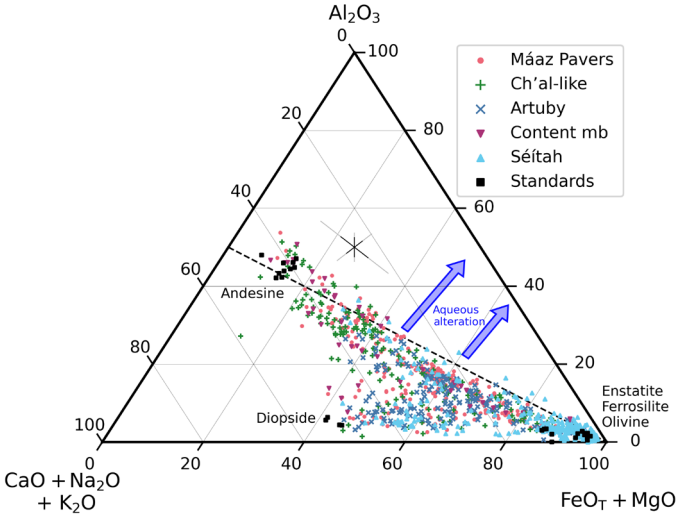


Fig. 6. Elemental compositions indicating the relative absence of chemical weathering by aqueous leaching of soluble elements. Trends in the direction of the blue arrows, above the dashed line from the iron-magnesium corner to the ideal plagioclase composition on the left, would indicate leaching of mobile elements represented at the base of the triangle. Observations of onboard standards (*63*) are plotted along with the compositions of observed points. Dark error bars indicate precision; light error bars indicate mean accuracy (*62*).

ignore the Content mb here due to its relatively few observations. Relative to the less mafic Máaz, the Artuby normative mineral abundances decrease in amounts of silica (as quartz in the norm calculation), plagioclase, and orthoclase while increasing in diopside (to 17 wt %), hypersthene (to 42 wt %), and the metal oxides ilmenite and magnetite. For these four minerals, Artuby has the highest normative abundances among the three units, resulting in a significantly higher inferred density than Máaz. CIPW norm calculations of Séítah's mean igneous composition yield normative 41% olivine, while normative plagioclase drops to 15 wt %. Observations show similar results across three different regions of Séítah (fig. S2). This composition is strongly mafic although not technically ultramafic (defined as ≤10 wt % plagioclase). The Mg# [Mg/(Mg + Fe) molar ratio] of the bulk Séítah is 63 (Table 2). Comparison to the onboard olivine standard suggests that our calibration gives a slight overestimate of SiO_2 and underestimate of FeO_T, implying that Séítah could contain more than the 41% normative olivine given in Table 2, characterized by a slightly lower Mg number (cf. 28; text S4).

On Mars, the presence of igneous minerals does not necessarily imply an igneous deposit, given the low degree of alteration that is typically observed. For example, much of the Murray fm of Gale crater, which is a lacustrine deposit, consists of mostly igneous minerals (*28*). On that basis, careful consideration must be given to the depositional nature of the fms regardless of the presence of igneous minerals. Although Perseverance landed in a lacustrine basin

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in Jezero crater, we present arguments in the next section in favor of an igneous deposition for all of the units traversed during these sols.

DISCUSSION

Igneous characteristics

A number of features suggest that the rocks observed along the traverse are igneous. We start with Séítah's defining features, in particular the abundant, euhedral, large (~1.5 mm), monocrystalline-appearing olivine grains (Fig. 2, E and F). Fine-scale observations in Séítah by the Planetary Instrument for X-ray Lithochemistry (PIXL) instrument show that olivine and pyroxene are intergrown in a pattern that clearly demonstrates they are cogenetic (*29*). The prevalence of olivine is consistent with a density-driven cumulate rather than classical coarse-grained igneous rocks that contain various crystals of similar sizes such as pyroxene, olivine, and plagioclase in a basalt. The observed olivine crystals do not show evidence of intergrowth with each other, but rather are closely packed with abundant face-to-face contacts (Fig. 2F) (*29*), suggesting settling as a mechanism for concentrating olivine. Settling by gravity within a melt is also consistent with the narrow grain size distribution observed in most of the SuperCam RMI images of Séítah (table S1). The mean composition of Séítah yields a Mg number (Table 2) in the same range as the individual olivine grains (Fig. 5A). This is generally consistent with CRISM orbital estimates of the unit inside and outside Jezero as $Fo_{44–65}$ (*30*). Given the Fe-Mg partitioning between olivine and basaltic melt [$K_D{}^{Fe\text{-}Mg}{}_{ol\text{-}melt} \sim 0.35$; (*31*) and references therein], the olivine grains are out of equilibrium with the bulk material, consistent with their concentration by density settling at the base of the melt. On Earth, most ultramafic rocks are intrusive cumulates and mantle peridotite but can be a product of eruptions, more common in the Archean eon [e.g., (*32*, *30*) and references therein]. Although layering is well known to occur in terrestrial lavas and intrusive bodies [cf., (*33*)], within Séítah, we do not observe either changes in mineralogy, chemistry, or grain size from one layer to the other, suggesting that layers may reflect reorganization of grains during cumulate packing (*34*). Séítah differs from terrestrial analogs in that its thin layers (Fig. 2E) occur without accompanying changes in chemistry, and we find this difference to be the biggest challenge to the cumulate hypothesis.

The layering of Séítah could be construed as an argument for a sedimentary instead of igneous origin. However, the internal structures of these layers do not readily fit those usually expected for sedimentary structures. Séítah layers, for instance, do not contain internal laminations (e.g., planar or cross-lamination) indicative of traction-deposited sediments (*35*, *36*). Although deposition from heavily laden turbidity currents or fallout associated with hypopycnal flows (*37*) can produce planar beds lacking sedimentary laminae, such deposits often display systematic changes in grain size associated with settling (*38*, *39*) that are not observed in Séítah. Observed grains within Séítah are predominantly angular and monomineralic (Fig. 2F), consisting of olivine and, more sparsely, pyroxene and plagioclase within interstitial spaces (*29*). Although the mean grain size and narrow range of sizes of Séítah are consistent with dynamic sorting typical of sedimentary deposits, grains do not show any indication of preferential sorting within individual layers (e.g., graded bedding) that might be attributed to either waning flow or fallout, with no obvious rounding of grains. We did not observe any systematic differences in grain size or the presence of fines between successive centimeter-scale layers (Fig. 2E) that could be attributed to fluctuations in the energy of successive depositional events [e.g., (*38*, *39*)].

Alternatively, regional olivine-bearing units observed from orbit have been hypothesized as tephra deposits (*40*, *41*). In contrast to pyroclastic deposits, Séítah rocks are predominantly crystalline, not glassy, based on spectra and imaging, and do not contain distinct clasts of pyroclastic origin, lapilli, indications of grain sorting, or extensive evidence for hydrolytic alteration (*42*), and so our observations do not favor a pyroclastic origin for Séítah. In summary, we find that Séítah is the first igneous cumulate body observed on another planet.

The Máaz fm, including Artuby ridge, also displays characteristics consistent with an igneous origin. Its textures contain 0.5- to 3-mm grains (e.g., Fig. 2, B and D) with local angular textures typical of euhedral shapes in the whole area. Local viscous-flow patterns similar to pahoehoe lavas could favor a lava flow origin, but the crystalline, phaneritic texture is distinct from classical aphanitic texture of lava flows and suggests a prolonged crystallization period for at least parts of Máaz. Similar to Séítah, there is a lack of features expected in a sedimentary unit, such as laminations, visible clasts, and cross-stratifications. The observed fabric at Mure and Artuby ridge could be related to either cumulate layers as in Séítah, which starts immediately below, or planar joints (*33*). Recessive layers in Mure and Artuby could represent poorly crystalline igneous material. This material was never successfully targeted by SuperCam.

Density stratification and scenarios for emplacement

The data from the entire traverse reveal a notable progression of increasingly mafic material and increasing inferred density from Máaz to Artuby to Séítah. This is best seen in Fig. 7B, which shows the compositions of SiO_2, Al_2O_3, and alkali elements all trending progressively downward across these three units. These decreases are accompanied by concomitant increases in mafic elements MgO and FeO_T (Table 2). Calcium oxide shows a peak at Artuby, which could be expected because of its higher abundance of augite as an intermediate density material. Figure 7B and Table 2 are ordered according to the inferred original stratigraphic position, illustrated in Fig. 7A and derived from the surface observations and RIMFAX subsurface observations [Fig. 1A and (*25*)]. The current observations allow for Artuby ridge to be stratigraphically below the portion of the Máaz fm traversed on the east side of Séítah and subsequently uplifted. In this scenario, SuperCam observations show a progression of compositions and derived density through three vertical regions of igneous material (Máaz, Artuby ridge, and Séítah).

The relationship between the three units poses several possibilities for their emplacement: (i) The units are part of one continuous igneous body, such as a thick cumulate, or (ii) they represent separate, increasingly evolved magmas (with or without genetic association). In both cases, Séítah is interpreted as a cumulate. In the first case, it is overlain by a more pyroxene-rich layer (Artuby), with lower-density material of the same igneous body above it (Máaz), as shown in Fig. 8A. Artuby ridge is enriched in normative pyroxene to 58% on average (Table 2) with higher abundances in some targets (data file S1). Artuby lacks the well-organized coarse grains that characterize Séítah (Fig. 2F); however, pyroxene zones in terrestrial cumulate bodies can also be characterized by finer grains. On Earth, not all cumulates may have pyroxene cumulate zones, and some concentrate clinopyroxene and orthopyroxene variably, depending

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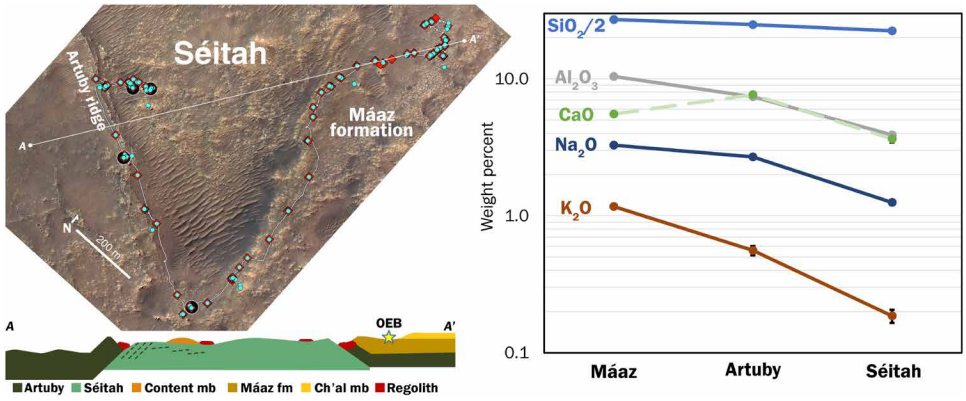


Fig. 7. Stratigraphic concept and mean elemental composition trends. (**A**) Conceptual view of the current stratigraphic positions of Máaz, Artuby, and Séitah. The outcropping portion of Artuby and the SW portion of Séitah adjacent to it show dipping strata in exposure and in RIMFAX radargrams. Artuby was not seen to be exposed on the NE side of Séitah. RIMFAX data indicated dipping strata on that side of Séitah too. Máaz is inferred to be overlying both Artuby and Séitah. All units were emplaced after the fm of Jezero crater and well above the base of the crater. (**B**) Elemental trends progressing from Máaz to Artuby to Séitah. This plot shows, on a logarithmic scale, a systematic decrease in felsic elements (SiO_2, Al_2O_3, Na_2O, and K_2O) with decreasing proposed original stratigraphic elevation. CaO (dashed line), which occurs in both plagioclase and orthopyroxene, is highest at Artuby due to its enrichment in augite. Error bars indicate SEMs where large enough to be seen, for comparison between points (see Methods).

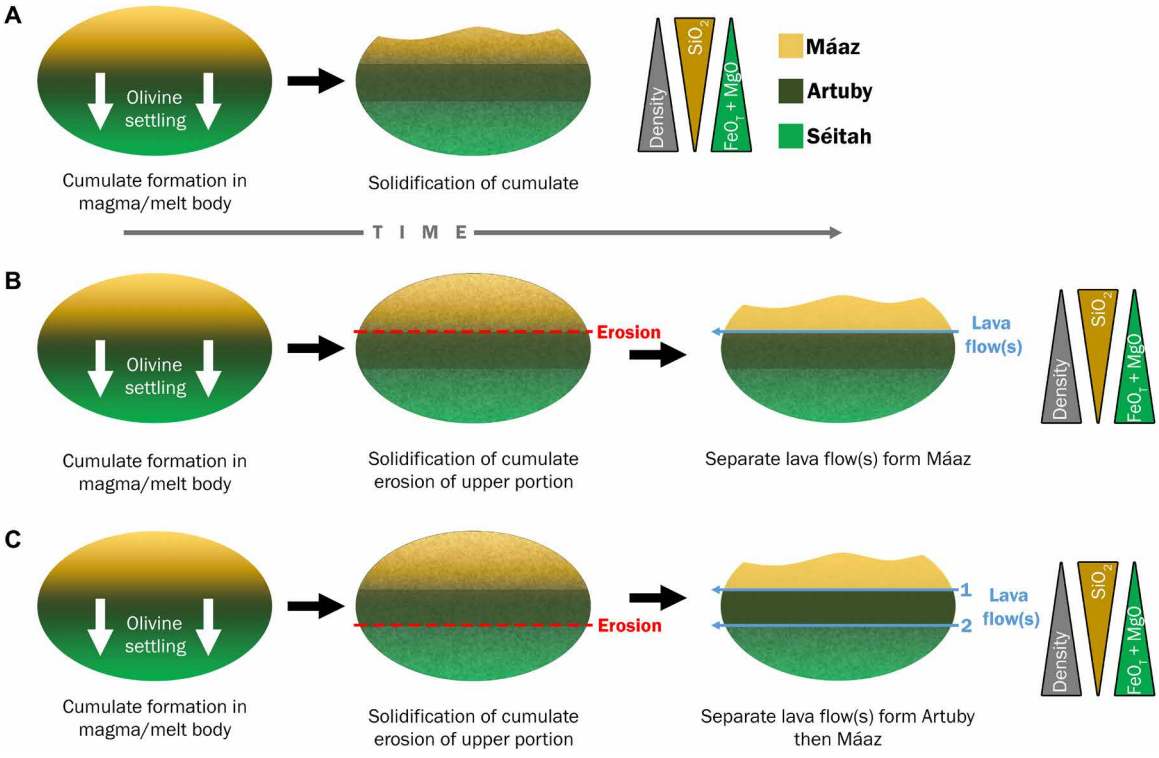


Fig. 8. Formation scenarios. (**A**) Cumulate formed from stratification of a single melt in which olivine phenocrysts were segregated by gravity in a magma body, which subsequently solidified. All of the rocks observed by SuperCam were produced within this igneous body in this scenario. (**B**) Cumulate plus lava flow(s) scenario, initiated with the fm of Séitah and Artuby as a cumulate as in (A). The depleted upper portions of the body were removed and subsequent lava flow(s) produced Máaz. (**C**) Third scenario in which Artuby was also produced by a relatively viscous lava flow before emplacement of Máaz by later and more evolved lava. Triangles at the right indicate overall composition and density trends.

on the physical conditions including convection, size of the melt region, cooling rates, duration, and chemistry [e.g., (*43*)]. Several other features of the Máaz and Séitah fm rocks appear to fit the cumulate model, including the lack of observed contacts between the different units.

In the second scenario, Séitah is an olivine cumulate, but the upper portions of that body were removed over time at the surface. Subsequently, successive surface or near-surface igneous activity emplaced material stratigraphically above Séitah. In one version of this scenario (Fig. 8B), Artuby is the pyroxene-enriched portion of

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the same igneous body as Séítah, with Máaz emplaced later as a more evolved extrusive igneous unit. A third possibility, shown in Fig. 8C, is that Artuby was also emplaced as a lava flow, somewhat more mafic than Máaz and not originating from the same magmatic body. However, the pyroxene compositions show no distinction between Artuby ridge and the rest of the Máaz fm (Fig. 5A), suggesting a petrogenetic link between the two.

One exception to the olivine-rich nature of Séítah is the Content mb. Its existence and physical continuity with the rest of the Séítah rocks (Fig. 2G) call into question the cumulate scenario of Fig. 8A because of the abrupt change in composition. However, cumulates are known to have heterogeneous layering in different locations, attributed to injection of fresh material or entrainment of lighter material with denser, sinking material [e.g., (*30*)]. A second possibility is that the Content mb is a section of more differentiated Séítah cumulate that fell down the sequence during compaction. A third possibility is that the Content mb rocks are from a later-stage unconformable lava flow that was emplaced after Séítah was exhumed (Fig. 8, B or C). This may be more consistent with the pitted texture of the Content mb (Fig. 2H), which may be difficult to reconcile with a cumulate origin.

Current data do not enable a clear distinction among these scenarios, including the possibility of multiple lava flows from the same magma chamber producing progressively more evolved compositions over time. However, a potential weakness of this scenario is the lack of regional topography that would drive flows of relatively viscous material into this region. Melt sheets from a large, unidentified impact not far away (<150 km) might also produce these igneous features along with others outside of Jezero (see below). In the end, the first samples collected by the Perseverance rover may hold the clues needed to solve this question upon their return to Earth.

Comparisons to Mars meteorites

The mineralogical and chemical compositions of primary minerals in the Máaz and Séítah fms can be directly compared with the current suite of martian meteorites, which are igneous samples of other locations on Mars. Similarities shared by Jezero observations and Mars meteorites may suggest that these features are common on Mars, and their comparisons will aid in understanding Mars's igneous activity, chemical and mineralogical diversity, and thermal evolution.

The augite composition of Máaz (Fig. 5, A and B) is close to the compositions of the nakhlite pyroxene cores and Fe-rich rims as well as a few shergottites (*44*–*46*). The Máaz ferrosilite and pigeonite compositions are similar to those found in pyroxenes in basaltic shergottite Los Angeles and gabbroic shergottite Northwest Africa (NWA) 7320 (*47*), showing a similar evolution trend from calcic to ferric compositions, although Máaz pyroxenes are more Fe-rich than the corresponding meteorites. In general, pyroxenes in the Máaz and Séítah fms are lower in MgO and higher in FeO_T than most Mars meteorites (Fig. 5). The very high Fe compositions in Máaz pyroxenes likely indicate the presence of pyroxferroite, a metastable pyroxene formed at subsolidus, as also seen in Los Angeles and NWA 7320 (*47*, *48*). The pyroxene compositions observed in Séítah are similar to those in olivine-phyric shergottites and to the NWA 7034 polymict breccia pyroxenes (*49*, *50*). Olivine compositions in Séítah overlap those observed in olivine-phyric and poikilitic shergottites (*50*, *51*).

The Máaz and Content mb rocks are similar in bulk major element compositions to the basaltic shergottites, which contain pyroxene and plagioclase, although Máaz is enriched in SiO_2 compared to most martian meteorites. The basaltic shergottites represent flows, some of which have undergone fractionation of olivine and/or pyroxene. The Séítah fm bulk major element compositions fall within the compositions of poikilitic shergottites, also sharing a similar mineralogy. Last, the compositional relationships that we observed at Jezero crater appear to confirm the occurrence of density-driven fractionation on Mars that has been noted in martian meteorites [e.g., (*46*, *50*)]. This fractionation could occur early in Mars history in both melt sheets produced by large impacts and in magmatic processes, while the Mars meteorites are generally Amazonian and their fractionation is most likely from magmatic processes.

Martian meteorites preserve a long record of limited aqueous alteration in the form of carbonates, amorphous phases, and silicate minerals [e.g., (*52*)]. In the nakhlites, these carbonates are often associated with olivines and consist mainly of Fe carbonates with varying amounts of Mg, Ca, and Mn carbonate phases (*53*). Similar to carbonates in Séítah (*27*), carbonates in the martian meteorites appear to originate from aqueous alteration of olivines, suggesting that the source region of the carbonate-bearing martian meteorites experienced similar alteration processes to Séítah. Observation of organic materials associated with carbonates in ALH 84001 [e.g., (*54*)] suggests that organic-molecule production was likely active in association with carbonates in Jezero crater too.

Regional implications

The chemical and mineralogical information gained by in situ exploration and subsequent sample return of rocks on Jezero crater's floor may place valuable constraints on the origin of olivine-bearing rocks revealed by orbital and telescopic detection of olivine [e.g., (*50*, *51*, *53*)]. While the extent of olivine-rich rocks on Mars' surface appears limited, our study sheds light on Mars' largest olivine-bearing region, Nili Fossae. The nature of this peculiar, widespread regional unit is strongly debated: Studies have suggested various emplacement processes including volcanic flows, tephra deposits, impact melts, or sedimentary deposits (*40*, *41*, *55*–*58*). Our study provides an alternative scenario in which cumulates (formed intrusively or on the surface by thick lava flows or impact melts) explain the olivine enrichment.

However, the cumulate model does not easily extrapolate to the entire regional unit. In particular, a cumulate process cannot explain an olivine-rich unit with a draping geometry observed regionally and on Jezero crater's rim (*40*, *41*), since cumulates form by gravity either intrusively or by thick melt ponds on flat surfaces. Hence, it seems that olivine-rich materials may have been emplaced by a variety of processes, as may be expected for volcanism of highly mafic compositions [e.g., (*59*)]. The question of correlation between traverse observations and regional orbital observations is especially relevant for locations where a cap rock (<10 m in thickness) similar to Máaz capping Séítah exists over the olivine-bearing unit (*7*, *41*, *60*). In a scenario in which the whole crater floor is a cumulate, such cap rocks may correspond to the less mafic complement just as Máaz overlies Séítah. Future rover observations on the olivine-bearing unit on the rim or outside Jezero crater, especially if connected to a cap rock, will help to connect these findings within Jezero crater to the broader regional unit. Detailed investigation of other olivine-bearing regions on Mars could identify similar stratigraphic sections.

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Our observations also highlight the role of aqueous alteration at a regional scale. Carbonates observed within Séítah provide a link to carbonates found regionally within the olivine-bearing unit (*4*, *7*, *8*, *10*, *41*), suggesting that the process of aqueous alteration is regional. Exploration by the rover of the marginal carbonates observed at the base of Jezero's inner rim where strong signatures of carbonates have been detected from orbit [e.g., (*8*)] will help identify the variability in this alteration and provide further constraints on its nature, diversity, and origin. Salts observed within Máaz were formed after the emplacement of these rocks, likely by filling pores and vesicles from a top-down aqueous circulation. Assuming the delta deposits were emplaced subsequent to the Cf-fr unit (*17*), the origin of salt deposition may be connected to the period of lake activity within Jezero crater, especially since the lake was closed for a substantial fraction of its history (*3*) and was therefore favorable to evaporative salt precipitation.

A notable finding of this work is the limited nature of alteration in the Jezero lake basin. It is difficult to extrapolate to any limits on the duration of the lake, since relative timing of the igneous activity can only be constrained to have occurred before the latest period of delta formation (*3*). A lake could well have existed before the igneous activity that emplaced the Máaz and Séítah fms. Other conditions such as an impermeable layer could have limited the alteration of the igneous materials during the subsequent lacustrine period. In any case, observation of relatively unweathered igneous material in the floor of Jezero crater does suggest a relatively limited lacustrine period postdating emplacement of these igneous bodies.

Before the landing of Perseverance, the origin and lithology of Jezero crater's floor were strongly debated, whether igneous (lava flows or pyroclastic) or sedimentary (*7*, *8*, *12*–*17*, *20*, *41*). SuperCam's compositional observations throughout the traverse indicate an igneous origin for all of the Máaz fm, Artuby ridge, and Séítah fm (including the Content mb), showing a compositional progression and implying a gradient of increasing density from upper to lower units. As the lowest observed unit, with the highest apparent density, the olivine-rich Séítah fm has the characteristics of a cumulate. Artuby ridge is a compositionally distinct unit, richer in pyroxene, and intermediate in inferred density, potentially located stratigraphically between the other two units. We find that the entire traversed region shows interesting comparisons to the igneous martian meteorites, regarding both mineralogy and bulk composition (e.g., *50*). At a larger scale, the cumulate scenario (formed intrusively or by lava flows or by impact melts) may provide important clues to the igneous nature of the Nili Fossae region with its olivine enrichment (*30*, *40*, *41*, *52*, *55*, *56*, *58*, *60*) and will provide a framework for analyzing the drill cores collected by Perseverance in the crater's floor after their return to Earth.

METHODS

Experimental design

SuperCam uses a 110-mm-diameter telescope on the mast of the rover to project laser beams and collect light for all of its optical observations (*21*, *22*). Fields of view of the various spectral techniques are coboresighted and coaligned but of varying diameter. Elemental composition observations cover the size of the focused IR laser beam used for LIBS, ~350 μm in diameter. Raman and VIS reflectance spectra cover ~0.71 mrad (e.g., 1.9 mm at the median target distance of 2.7 m), while the IR spectra cover ~1.15 mrad (3.2 mm at the same distance). SuperCam's images cover 18.8 mrad at a resolution of ~0.050 mrad. SuperCam operates in a raster mode, typically obtaining spectra from 5 to 10 locations per target and enough images to cover the raster. The IR spectrometer scans across the 1.3- to 2.6-μm spectral range using an acousto-optic tunable filter (*23*). All other spectrometers use gratings to disperse the light by wavelength (*21*). The sections below are presented in the order in which they appear in the manuscript, starting with the RMI images.

RMI images and grain size studies

RMI images were corrected for vignetting and other artifacts using a flat-field template produced by imaging the Mars sky in defocused mode. Exposure durations were generally between 5 and 20 ms. The process of mosaic generation is described in text S5.

Two different color schemes were used for the RMI images in this work: natural color, which was obtained by refining the red, green, and blue pixel intensities based on observation of a white target on the rover (*61*). The Gaussian stretch offers a different view of the image, by enhancing color differences that would be more difficult to see in the more natural color images. To obtain this stretch, each color channel composing the image was stretched independently, such that the intensity distribution of the pixels in each color layer follows the same Gaussian distribution. All RMI images in Fig. 2 and fig. S2 are in natural color except Fig. 2F, which uses the Gaussian stretch to enhance the visibility of the grain edges.

Grain sizes and grain size distributions were calculated on the basis of measurements from RMI images in three different regions of Séítah (fig. S2). Individual and composite RMI images were imported into NIH ImageJ (https://imagej.nih.gov/ij/). Scales for each image set were determined on the basis of the distance from SuperCam to the target and imported for each image set into ImageJ. The resolution of the RMI allowed characterization of grain sizes down to ~160 μm. Further description, including conversion from two to three dimensions, is provided in text S2.

LIBS spectra and derived elemental compositions

Nearly all LIBS observations were made with 30 laser shots, and the spectra collected from the first five shots were discarded to avoid dust contamination. The remaining 25 spectra were averaged together and processed. Elemental compositions were derived from LIBS spectra by methods described in (*62*) involving a library of >1000 spectra from >320 standards. Onboard standards (*61*, *63*) were not used in the calibration model but, instead, were used to check its accuracy and precision. Targets used in Tables 1 and 2 spanned a range of distances from 2.0 to 6.5 m; data in Fig. 5A used a few points at longer distances. Tests of the calibration model and analysis of Mars observations suggest that accuracies and SDs remain relatively constant within this distance range (*62*).

For Figs. 1 (B to D), 3, and 6 and Table 1, all LIBS data on bedrock targets were used except for those taken at excessive distances and for points with TiO_2 > 2.4 wt % due to a known deficiency in calibration of high-Ti compositions. Some other points with TiO_2 > 2.0 wt % and low Al were also removed because of interferences with the Al peaks (*62*). Data were also removed if the total emission was less than 10^{14} photons per pulse per square millimeter per steradian per nanometer (*62*), which usually indicates poor focus, or if the major element total was excessively high, e.g., >120 wt %. Laboratory calibrations are ongoing to address and improve on the results provided here.

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SuperCam elemental abundances in the form of eight major-element oxides (*62*) are normally used without normalization. Sums of less than 100 wt % can provide information about the presence of other constituents such as CO_2, SO_3, Cl, H_2O, P_2O_5, MnO, and other minor and trace elements, if present in sufficient abundances. The abundances in Table 2 have been normalized, since we are interested in the igneous composition and the unquantified elements are generally products of alteration. The exceptions are P_2O_5 when present as apatite, and MnO, which is often in solution with Fe and Ti in mafic phases. The normalization makes exception for these elements using a total of 98 instead of 100 wt %. This is consistent with 0.4 wt % of MnO (quantification described in text S6) and the observation of a small amount of Ca-phosphorous materials by both SuperCam and PIXL, estimated on the order of 1.6 wt %. Table S3 gives the equivalent details without normalization.

Modal mineral abundances in Table 2 were derived, assuming that 5% of Fe is in the +3 charge state, with 95% in the +2 state. This assumption is consistent with the presence of iron oxides that we observed, especially in the Máaz fm. Assuming a larger fraction of Fe in the +2 state results in no iron oxides (contrary to those observed) and slightly higher olivine abundances in Séítah and Artuby. Modal mineral abundances for 0 and 10% Fe^{3+} are given in table S4.

The stoichiometric pyroxenes plotted in Fig. 5 were selected from all LIBS data up to Sol 217, calculating the stoichiometry using methods in (*64*). The selected pyroxene data points have a total of four (±0.2) total cations with six O including $Si^{4+} + Ti^{4+} = 2$ (±0.15) and Ti + Fe + Mg + Ca + Na + K = 2 (±0.15); 0 < Ca < 0.55; 0.85 < (Fe + Mg + Ca)/Si <1.15; Al/Si < 0.1; 2 (±0.15) = $Si^{4+} + Ti^{4+}$; totals of the eight major-element oxides = 82 to 105 wt %; Al_2O_3 < 5 wt %, Na_2O < 1.5 wt %; and K_2O < 0.5 wt %. The selected stoichiometric olivine data points have a total of three (±0.2) cations with four O including $Si^4+ = 1$ (±0.15) and (Fe + Mg)/Si in the range of 1.5 to 2, lower than the theoretical value of 2 but in agreement with the value measured on Mars on the onboard olivine standard (Fig. 3).

VISIR and Raman spectra

The VISIR spectra presented in Fig. 4A were obtained using two SuperCam spectrometers. VIS reflectance spectra were taken with a spectrometer covering 535 to 853 nm, the same used for LIBS and Raman spectra (*21*). Its calibration is described in (*65*). For each observation, 50 VIS spectra were collected and averaged on board for downlink. The IR spectra were collected with a wavelength-scanning spectrometer (*22*, *23*), using 80- to 140-μs exposures for each channel. The IR spectrometer was calibrated on the ground before launch (*66*). Full characterization of the instrument and its performance assessment are ongoing. Both VIS and IR spectra are ratioed to those collected on a white calibration target (*61*). Details of the laboratory spectra in Fig. 4B are given in text S7.

Data considered for IR band-depth statistics used rock targets of the Máaz fm, excluding observations with major shadowing, regolith and dust cover (validated by inspection of RMI images), radio-frequency power drops, and saturated measurements. The band depth was obtained by dividing the spectra (lightly smoothed using wavelet denoising) by their continuums (modeled as upper convex hulls of the spectra), where one minus the continuum-removed spectra values at the band centers is equal to the band depth (*67*). For the 2.28-μm band depth, bands centered between 2.26 and 2.3 μm were considered. This is generally the Fe-OH absorption range and the extent of band positions observed in the Máaz fm spectra. For attribution of pyroxene in the Máaz fm and Artuby ridge, spectral deconvolution was used (*68*).

A SuperCam Raman spectrum obtained from a light-toned spot in the Bellegarde abrasion patch displayed peaks diagnostic of sodium perchlorate, shown in Fig. 4C. This spectrum was obtained by averaging the signal accumulated over 200 laser shots at 10 Hz, collected in 20 exposures of 905 ms each with the intensifier gain set to 3400. All of the Raman spectra were processed by denoising the signal, subtracting the nonlaser "dark" spectra, and removing a laser-induced signal produced in the ~6-m fiber connecting the telescope on the mast with the spectrometers in the rover body (*21*).

Uncertainties

Average elemental abundances in Table 1 are accompanied by the SEM, which is the SD divided by the square root of the number of observations. This SE is useful for comparing compositions to determine whether they differ from each other. SEMs are generally applicable for Gaussian distributions, which is not necessarily the case with the data presented here (see fig. S4 for histograms). Figure S3 shows distributions by quartile. Text S3 associated with figs. S4 and S5 show additional details on the statistical differences between the units.

Precisions for single observations, such as the points displayed in Figs. 1 (B to D), 3, 5, and 6 and figs. S3 and S8, were obtained from SDs of elemental abundances derived from observations made on a large number of standards during cleanroom characterization and on rover calibration targets (*62*). General precisions for SiO_2, TiO_2, Al_2O_3, FeO_T, MgO, CaO, Na_2O, and K_2O are ±1.6, 0.06, 0.7, 1.3, 0.5, 0.5, 0.3, 0.3 wt %, respectively [using the largest values from (*62*)]. These precisions were propagated from oxide weight % to molar abundances where applicable.

Accuracies are useful for comparisons with other instruments or to mineral compositions. SuperCam elemental abundance accuracies were determined by tests against standards that were not used to build the calibration models. The absolute accuracies vary as a function of the abundance of each element. General averaged one-sigma accuracies for SiO_2, TiO_2, Al_2O_3, FeO_T, MgO, CaO, Na_2O, and K_2O are ±6.1, 0.3, 1.8, 3.1, 1.1, 1.3, 0.5, 0.6 wt %, respectively (*62*). On the basis of experience with ChemCam, these are thought to be overly conservative in most cases, but it is possible that, for olivines, FeO_T and/or MgO accuracies are not within these standard accuracies, given that they are somewhat extreme values relative to the spectral library (see text S8).

The uncertainties associated with the derived densities reported in Table 2 were obtained by propagating the SEMs toward higher density compositions (increasing Fe and Mg; decreasing Si, Al, Na, and K), and vice versa. These uncertainties are measures of the precision, useful for comparing between units, e.g., to show that the density differences are statistically significant. Absolute accuracy of the predicted mineral compositions is given in table S5 and was obtained by propagating the accuracy extremes toward different mafic and felsic mineral groups, similar to the process described above for density.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abo3399

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Compositionally and density stratified igneous terrain in Jezero crater, Mars

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