Spectral Variability of Rocks and Soils on the Jezero Crater Floor
A Summary of Multispectral Observations From Perseverance's Mastcam-Z Instrument


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Spectral Variability of Rocks and Soils on the Jezero Crater Floor: A Summary of Multispectral Observations From Perseverance's Mastcam-Z Instrument


Abstract NASA's Mars-2020 Perseverance rover spent its first year in Jezero crater studying the mafic lava flows of the Máaz formation and the ultramafic cumulates of the Séítah formation, both of which have undergone minor alteration and are variably covered by coatings, dust, and/or soil deposits. Documenting the rock and soil characteristics across the crater floor is critical for establishing the geologic context of Perseverance's cached samples—which will eventually be returned to Earth—and for interpreting the deposition and modification of the Máaz and Séítah formations. Mastcam-Z, a pair of multispectral, stereoscopic zoom-lens cameras, provides broadband red/green/blue and narrowband visible to near-infrared images (VNIR, 440–1,020 nm). From multispectral observations from sols 0 to 380, we compiled a database of ~2,400 representative Mastcam-Z spectra. We analyzed principal components, spectral parameters, and laboratory spectra of pure minerals and natural rock surfaces to interpret the spectral diversity of rocks and soils. We define eight spectral classes of rocks: Dusty, Hematite-like, Coated, Low-Ca Pyroxene-like, Olivine-like, Weathered Olivine-like, Fe-rich Pyroxene-like, and Dark Oxide-like. The variability of soil spectra in the Jezero crater floor is controlled primarily by the amount of dust and indicates a largely consistent soil mineralogy across the traverse, with the exception of the area disturbed by the landing event. In comparison to rock spectra from the Curiosity rover’s Mastcam instrument in Gale crater, rocks on the Jezero crater floor are generally less spectrally diverse, but the Olivine-like rocks within the Séítah formation represent a new spectral rock class in Mars surface exploration.

Plain Language Summary NASA’s Mars-2020 Perseverance rover spent its first year in Jezero crater studying rocks that formed in lava flows. These rocks were altered slightly by small amounts of water and are covered with dust and other coatings. Understanding these rocks, and the soils across Perseverance’s traverse, is important for two reasons: Perseverance has collected rock and soil samples, which will be the first samples from Mars to be sent back to Earth, and they give insights into the history of Jezero crater. Here, we describe a database of spectra that we compiled from the Mastcam-Z instrument, which is a pair of science cameras on Perseverance’s mast. We analyzed ~2,400 spectra representing the diversity of rocks and soils across the first 380 Martian days of the mission. We find that the amount of dust in the soils controls their spectral variability. We define eight classes of rock spectra, which are controlled by varying amounts of pyroxenes, olivines, hematite, and other oxides. Compared to spectra from the Mastcam instrument, which documented the Curiosity traverse in Gale crater, the Mastcam-Z spectra are generally less diverse. However, the Mastcam-Z spectra of olivine-like rocks are new, as they have not been previously encountered on Mars.

1. Introduction

In its first year of exploration, NASA’s Mars-2020 Perseverance rover traversed multiple units in the floor of Jezero crater and encountered rocks with a diversity of textures, morphologies, surface coatings, colors, and spectral properties. These rocks had been mapped as a “volcanic floor” (Goudge et al., 2015) or “mafic floor” (Horgan, Anderson, et al., 2020) based on spectral signatures of pyroxenes and olivines in visible to near-infrared (VNIR) spectra from orbital spacecraft. Based on morphology and texture in orbital images, Perseverance's...
landing site region was divided into bedrock units called the “crater-floor-fractured-rough” (Cf-fr) and an older, rougher “crater-floor-fractured-1” (Cf-f1) (Stack et al., 2020). Prior to landing, the crater floor rocks were deemed important targets for sampling, caching, and eventual sample return because—if they are indeed igneous—their samples would allow for absolute age dating (e.g., Simon et al., 2023). Crater counts indicate model retention ages of ∼2.5–3.5 Ga (Goudge et al., 2012; Shahrzad et al., 2019), an important time period in Martian geochronology because it is currently unrepresented in meteorites (e.g., Udry et al., 2020). Absolute age dates for the crater floor would also constrain the timing of a lake within the Jezero basin, as sedimentary strata interpreted as a delta from orbit (Ehlmann et al., 2008; Fassett & Head, 2005; Goudge et al., 2015) and via ground-truth evidence (Mangold et al., 2021) overlay these units along the western margin of the crater.

An igneous origin for the crater floor units has largely been confirmed by Perseverance. From in situ observations, the Séítah formation (corresponding to the Cf-f1 unit) is interpreted as an olivine-rich cumulate formed from the differentiation of an intrusive body or thick lava flow (Farley et al., 2022; Liu et al., 2022; Wiens et al., 2022). The overlying Máaz formation (corresponding to the Cf-fr unit) is pyroxene- and plagioclase-rich and is likely a separate, younger series of lavas (e.g., Horgan et al., 2023; Schmidt et al., 2022; Udry et al., 2023). Both formations have undergone small amounts of aqueous alteration, as evidenced by the presence of minor carbonates, phyllosilicates, sulfates, and perchlorates in the abrasion patches. However, the combination of no enrichment in aluminum and little removal of soluble cations is consistent with a closed system and low water:rock ratios (Wiens et al., 2022). The expression of the Máaz and Séítah rocks suggests a long, complex history of erosion on the crater floor, possibly with episodes of burial and excavation. Specifically, orbital and in situ observations of the topography and distribution of outcrop suggest there were significant periods of erosion between the emplacement of some members of the Máaz and Séítah formations (Horgan et al., 2023). All crater floor outcrops are variably covered by unconsolidated materials, including float rocks (which have been eroded from adjacent outcrop, deposited as a lag from overlying units, and/or delivered as impact ejecta), soils, and aeolian bedforms. Observations of soil in Máaz and Séítah indicate similar mineralogies and grain size distributions, indicating common soil formation processes between these units across the portion of Jezero crater floor explored by Perseverance (Vaughan et al., 2023).

Understanding the full variety of the crater floor rock and soil characteristics, and mapping their occurrences across the rover’s traverse, is key to interpreting the deposition and subsequent modification of the Máaz and Séítah formations. Perseverance has multiple high-resolution imaging and spectroscopic instruments among its payload; of these, the Mast Camera Zoom (Mastcam-Z) instrument is unique in that it can quickly assess VNIR (440–1,020 nm) spectral properties over broad spatial areas. Mastcam-Z’s two cameras are mounted ~1.9 m above the Martian surface on the rover’s mast and utilize 8-position filter wheels behind the zoom lenses (Bell et al., 2021; Figure 1). When images of the same target are acquired through multiple filter positions with both cameras, each pixel in the resulting multispectral observation includes VNIR reflectance data at up to 14 unique wavelengths (Hayes et al., 2021). Mastcam-Z’s filter set has direct heritage from the Mars Science Laboratory...
Table 1

<table>
<thead>
<tr>
<th>Filter position</th>
<th>Mastcam-Z left $\lambda_{\text{eff}} \pm$ HWHM (nm)</th>
<th>Mastcam-Z right $\lambda_{\text{eff}} \pm$ HWHM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0 (Red Bayer)</td>
<td>630 ± 43</td>
<td>R0 (Red Bayer) 560 ± 43</td>
</tr>
<tr>
<td>L0 (Green Bayer)</td>
<td>554 ± 41</td>
<td>R0 (Green Bayer) 554 ± 42</td>
</tr>
<tr>
<td>L0 (Blue Bayer)</td>
<td>480 ± 46</td>
<td>R0 (Blue Bayer) 480 ± 46</td>
</tr>
<tr>
<td>L1</td>
<td>800 ± 9</td>
<td>R1</td>
</tr>
<tr>
<td>L2</td>
<td>754 ± 10</td>
<td>R2</td>
</tr>
<tr>
<td>L3</td>
<td>677 ± 11</td>
<td>R3</td>
</tr>
<tr>
<td>L4</td>
<td>605 ± 9</td>
<td>R4</td>
</tr>
<tr>
<td>L5</td>
<td>528 ± 11</td>
<td>R5</td>
</tr>
<tr>
<td>L6</td>
<td>442 ± 12</td>
<td>R6</td>
</tr>
<tr>
<td>L7</td>
<td>590 ± 88, ND6</td>
<td>R7</td>
</tr>
</tbody>
</table>

Note. Shaded cells indicate filter positions that are new to Mastcam-Z (were not part of the MSL Mastcam filter set).

(MSL) Mast Camera (Mastcam) instrument (Malin et al., 2017). While not a “spectrometer,” Mastcam-Z multispectral images can constrain iron phases and/or oxidation states, and—when coordinated with Perseverance’s other science instruments—can help interpret the compositions of rocks and soil at the landscape scale.

Here, we summarize the spectral diversity observed in all Mastcam-Z multispectral observations across Perseverance’s traverse in the Jezero crater floor (sols 0–380). We performed a systematic analysis of Mastcam-Z spectra from every outcrop, float rock, and soil surface imaged within the Máaz and Séítah formations. This work complements and informs efforts using Mastcam-Z multispectral data to define compositional and morphologic units within the Máaz formation and to determine their extent across the crater floor from comparisons to orbital spectra (Horgan et al., 2023). Mastcam-Z commanded 324 multispectral observations of surface targets during this initial phase of the mission. Each observation contained ~10⁶ spectral pixels with 12 narrowband reflectance measurements. For a comprehensive analysis of this massive data set, we identified the spectroscopic end-members and geologic materials of interest within each observation (typically 4–8 end-members, depending on the diversity within the scene) and compiled a database of ~2,400 representative spectra. This approach follows from comprehensive analyses of the Mastcam multispectral data set from the Curiosity’s traverse in Gale crater (Rice, Seeger, et al., 2022) and adapts the “best practices” for image processing and spectral analysis established over three decades of multispectral imaging on the surface of Mars. We qualitatively compared Mastcam-Z spectral variations to changes in the Máaz and Séítah lithologies across the traverse and quantitatively compared them to laboratory VNIR spectroscopy measurements of pure minerals and natural rock surfaces. Using principal component analysis (PCA), we identified the database’s major components of spectral variability, which helped us define eight major spectral classes of rocks encountered by Perseverance to date. These analyses provide a wide view of the alteration history of the Jezero crater floor and of the spectral variability within the Máaz and Séítah formations at the outcrop scale. They also provide a solid baseline to interpret future observations along the Perseverance traverse.

2. Methods

2.1. Mastcam-Z Instrument and Calibration

Mastcam-Z is a pair of multispectral, stereoscopic zoom-lens cameras that provide broadband red/green/blue (RGB), narrowband VNIR color (VNIR, 440–1,020 nm wavelength range), and direct solar imaging capability (Bell et al., 2021). Mastcam-Z derives its heritage directly from the MSL Mastcam instrument (Bell et al., 2017; Malin et al., 2017). Like the Mastcam cameras, each Mastcam-Z camera uses a Bayer pattern of broadband RGB filters and telecentric microlenses bonded onto the charge-coupled device (CCD) (Figure 1). The cameras’ eight-position filter wheels allow for spectra to be collected in 14 unique wavelengths from 442 to 1,022 nm (Table 1; Figure 2). Each filter wheel has eight positions: a broadband filter with a near-infrared cutoff (for Bayer RGB images); six narrowband filters (for geology investigations); and a solar filter (for atmospheric monitoring and astronomical observations).

The major differences between Mastcam-Z’s and Mastcam’s multispectral imaging capabilities are (a) the update of the filter wheel to use rectangular (instead of circular) holes; (b) the addition of new filter positions; and (c) the rearrangement of shorter wavelength narrowband filters into the left eye, with longer wavelength filters into the right eye. Because Mastcam’s circular filter holes caused vignetting, Mastcam-Z switched to rectangular holes to allow more signal in the corners of the CCD. The new filter positions were made possible by removing some of the stereo redundancy in the Mastcam filter set (Mastcam has three overlapping narrowband filters, while Mastcam-Z only has one at 800 nm). Mastcam-Z’s L4 filter, at 605 nm, fills a gap near 600 nm in Masctcam spectra which is useful for characterizing the reflectance maxima positions of many Fe-bearing phases. At 978 nm, Mastcam-Z’s R5 filter was selected to help capture narrow absorptions due to H₂O and/or OH between 950 and 1,000 nm in hydrated minerals (e.g., Rice et al., 2010). Grindrod et al. (2022) showed that Mastcam-Z indeed has...
improved performance over Mastcam in simulations of both instruments’ spectral responses compared to laboratory spectral libraries and Mars orbital hyperspectral data.

The 4:1 zoom lenses provide continuously variable fields of view (FOVs) ranging from ∼5° (at the 110 mm focal length position, “Z110”) to ∼23° (at the 34 mm focal length position, “Z34”) and allow Mastcam-Z to resolve features ∼500 μm in size in the near field. The zoom capability allows for consistent FOVs between the left- and right-eye Mastcam-Z images, simplifying the analyses of full-filter multispectral observations compared to those of Mastcam (Rice, Seeger, et al., 2022), as Mastcam used a 34 mm fixed focal length in the left camera and a 100 mm fixed focal length in the right camera. The majority of Mastcam-Z multispectral observations described here were acquired at Z110 for the highest possible spatial resolution.

We used near-simultaneous observations of the Mastcam-Z calibration targets (Kinch et al., 2020; Merusi et al., 2022) with preflight calibration coefficients (Hayes et al., 2021) to calibrate Mastcam-Z surface observations to radiance factor ($I/F$). Spectra were then converted to relative reflectance ($R^*$) by dividing by the cosine of the solar incidence angle (Reid et al., 1999), following the procedures first developed for the MER Pancam calibration pipeline (Bell et al., 2006) and used for MSL Mastcam’s radiometric calibration (Bell et al., 2017). While Mastcam-Z’s $R^*$ images are partially “atmospherically corrected” (Kinch et al., 2020), the Perseverance team favors acquiring Mastcam-Z multispectral observations as close to local noon as possible in order to minimize uncertainties that arise from assumptions in the calibration pipeline (e.g., Rice, Seeger, et al., 2022).

2.2. Mastcam-Z Multispectral Analysis

We characterized the spectral variability within each Mastcam-Z multispectral observation through a visual inspection of natural color RGB images, enhanced color images derived by stretching RGB and narrowband images, and decorrelation stretch (DCS) products (Gillespie et al., 1986). Initial versions of these stretched image products, in addition to a number of band parameter maps (e.g., Figure 3), were produced programmatically by the Automated Spectral Data Functions (“asdf”) workflow (Million et al., 2022; St. Clair et al., 2022). We identified end-members within each scene as clusters of pixels from geologically distinct surfaces that exhibited distinct colors in the DCS and false color image products (Rice, Seeger, et al., 2022). Although algorithms exist for automated spectral end-member interpretation, the spectra themselves lack sufficient information about the geologic context and image acquisition conditions. The manual approach allowed us to use our knowledge of location and geologic setting, surface topography, viewing geometry, and plausible geochronology to guide our selection of distinct end-members.

We extracted representative end-member spectra by averaging $R^*$ values of pixels within regions of interest (ROIs) selected from the right and left Mastcam-Z images separately, taking care to select the same regions of the surface. In the resulting spectra, we represent “variation bars” as the standard deviation among the selected ROI pixels; this is a measure of the variability of the $R^*$ values within an ROI and is usually larger than the instrumen-
tal error (Hayes et al., 2021). $R^*$ values from the right- and left-camera filters are scaled to their average value at 800 nm (the stereo overlap position of the L1 and R1 filters, which are the only redundant narrowband filters). This convention follows from the scaling of MSL Mastcam’s right- and left-cameras (which typically uses their overlap at 1,012 nm) (Rice, Seeger, et al., 2022). Because of their larger radiometric calibration uncertainties, we exclude the Bayer filter $R^*$ values from our quantitative parameter analyses below; however, for completeness, we display them in spectral plots (although plotted off the line of the narrowband filters; e.g., Figure 4c).

Figure 3. Examples of composite images and band maps from the sol 282 Mastcam-Z multispectral observation of Norante (zcam03066): (a) Bayer red, green, and blue (RGB) natural color composite; (b) Enhanced color composite from the narrowband L2, L5, and L6 filters; (c) decorrelation stretch (DCS) image from the narrowband L2, L5, and L6 filters; and (d) 528 nm band depth map (calculated as shown in Table 4), which highlights surfaces with strong Fe-oxide signatures in teal colors.

Figure 4. Examples of regions of interest (ROIs) selected from the sol 282 Mastcam-Z multispectral observation of Norante (zcam03066): (a) Left and (b) Right context maps showing ROIs that have been manually drawn for each eye, overlain on Bayer RGB natural color composites; (c) Spectra extracted from ROIs (with left- and right-eye spectra scaled to 800 nm). The width of the Norante float rock is ~30 cm.
We followed a system of “best practices” for selecting ROIs adapted from Rice, Seeger, et al. (2022) to ensure the extraction of geologically meaningful spectra with minimal noise:

1. To increase signal/noise and to account for the lower resolution of filters that overlap with the Bayer bands (L3-L6), we selected ROIs with a minimum 6 × 6 pixels (but larger whenever possible);
2. Where possible, we extracted spectra from near-horizontal surfaces near the image center to best match the assumptions in the calibration pipeline (Hayes et al., 2021);
3. We avoided edges of geologic features to mitigate the effects of small (pixel-scale) shifts between filter images that may be present due to de Bayering and/or chromatic aberration;
4. We avoided surfaces exhibiting specular reflections or shadows;
5. We excluded pixels flagged as “saturated” (those with 11-bit data number (DN) values greater than 2,000 in raw images);
6. Where possible, we avoided surfaces with pixels flagged as “nonlinear” (those with DN values between 1,500 and 2,000).

Context maps with examples of ROI locations and the resulting spectra are shown in Figure 4. With our guidance to favor ROIs greater than 6 × 6 pixels (point 1 above), our database excludes the finest scale spectral variability visible within some observations, notably the abrasion patches, where single mineral grains can often be resolved. Analyses at those scales require analyses beyond the work presented here (e.g., Horgan et al., 2023).

### 2.3. Mastcam-Z Spectral Database

We created a database of representative spectra from Mastcam-Z observations across Perseverance’s traverse, including a total of 311 full-filter images (Table S1). This multispectral database excludes 13 multispectral observations acquired between sols 0 and 380 because of extensive shadowing, failed image execution, known or suspected calibration issues, and/or incomplete downlink (Table S2 in Supporting Information S1). For multispectral mosaics, we treated each pointing as a unique observation. While each pointing of a mosaic shares a common sequence identifier number (seqID), individual pointings can be separated using their remote sensing mast (RSM) position counters. For these multiple observations within mosaics, we appended an incrementing pointing index (with the format “_XofY”) to the name of the sequence (e.g., “Mure_2of3”). Multiple team members (2–4) reviewed ROI selections to verify that they followed the best practices procedures described in Section 2.2.

We compiled each end-member spectrum with extensive metadata (available via Rice, Johnson, et al., 2022). We took observation-level metadata from the Mastcam-Z images’ Planetary Data System version 4 (PDS4) headers, including day of the mission (sol); Mastcam-Z seq ID; RSM position; target name; time of day (the observation’s starting local true solar time (LTST)); solar longitude (L싯); latitude and longitude of the rover’s position; total traverse distance (odometry); and rover elevation. We calculated incidence, emission, and phase angle for each observation using instrument data in the PDS4 headers, as described for Mastcam by Rice, Seeger, et al. (2022).

Each spectrum was assigned a broad “feature type” (soil, rock, pebble, or hardware) and a more specific “surface type” (Table 2). Here, we use the term “soil” to refer to unconsolidated material that is not strongly cohesive, equivalent to “regolith” in other Mars surface studies (e.g., van Es, 2017). For rock spectra, we classified them as “in-place,” “float” (not attached to outcrop), or “unclear” (to indicate uncertainty about whether the rock is in-place). We also gave each spectrum a qualitative distance assignment based on approximate distance from the rover (“nearfield” for ROIs <10 m away, “midfield” for targets up to ~50 m distance, and “farfield” for more distant targets). We assigned specific lithology information (formation and member) from the assignments of Simon et al. (2023) and Crumpler et al. (2023) (Table 3). The stratigraphic relationships within the Séítah formation are not always clear, given the patchy nature of the outcrop exposures and a lack of clear contact relationships; for example, the definition and position of the Issole member are not yet agreed upon (Crumpler et al., 2023; Simon et al., 2023), but here, we adopt the notional stratigraphy from Figure 1 of Simon et al. (2023), which places Issole (their “Séítah Undivided” member) at the bottom of the section. In our member classifications for Sétite, we include the rocks designated as Caille by Simon et al. (2023) with the Bastide member.
From this database and metadata, made available in Rice, Johnson, et al. (2022), we examined variations of spectral parameters with stratigraphy and other aspects of geology. For our comparative spectral analyses, we restricted our database to only include spectra meeting the following criteria: (a) acquired close to local noon (10:30 < LTST < 13:30), when assumptions in the calibration pipeline are most accurate; (b) near-to midfield target distances (to avoid uncorrected atmospheric effects that can influence distant observations with longer path lengths); (c) relative variation bar values <0.1 (for basic quality control); and (d) ROI sizes of at least 15 counted pixels (those that have not been interpolated by the Bayer pattern or masked due to saturation; Million et al., 2022) in each filter (to improve signal/noise).

Unless otherwise indicated, all analyses presented in Section 3 exclude database spectra not meeting these criteria.

### 2.4. Spectral Classification

We quantified a number of key spectral parameters (Table 4). Broad spectral profiles can be characterized with slope or ratio parameters; we favor the use of ratio parameters, following the rationale of Rice, Seeger, et al. (2022). To understand the variance within the entire data set, we also used PCA (e.g., Davis, 1973). First, we normalized spectra to 1.0 at their peak reflectance, so that the components would represent variance in spectral shape independent of overall albedo, as several nonmineralogical factors can darken or brighten Mastcam-Z spectra (e.g., averaging of shadowed pixels on textured surfaces or uncertainties in the $R*$ correction).

In our interpretations of spectral classes, however, we did include albedo information (to constrain compositions that could be consistent with dark phases, such as magnetite).

We performed PCA separately for rock and soil spectra using Scikit-learn Python package (Pedregosa et al., 2011). To represent Mastcam-Z spectra in component space, we plotted the contributions of the various PCs to
each spectrum against one another. The shapes of the spectra with the largest and smallest values of each PC were used to determine the spectral features that contribute to the components. The specific algorithm and approach used here were previously applied to the Mastcam data set along the Curiosity traverse (Rice, Seeger, et al., 2022).

<table>
<thead>
<tr>
<th>Camera</th>
<th>Parameter name (filters)</th>
<th>Parameter name (wavelengths)</th>
<th>Formula</th>
<th>Possible mineralogic indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>R6/R1 ratio</td>
<td>1,022 nm/800 nm ratio</td>
<td>$R_{1022}^* / R_{800}^*$</td>
<td>Used as a proxy for the broad NIR profile; values &lt;1.0 are negative NIR slopes consistent with olivine, clinopyroxene, and basaltic glasses; values &gt;1.05 can be indicative of iron meteorites (e.g., Rice, Seeger, et al., 2022).</td>
</tr>
<tr>
<td>Right + Left</td>
<td>R6/L2 ratio</td>
<td>1,022 nm/754 nm ratio</td>
<td>$R_{1022}^* / R_{754}^*$</td>
<td>Alternate version of the 1,022 nm/800 nm ratio, for a closer comparison to the 1,012 nm/751 nm ratio defined for Mastcam (Rice, Seeger, et al., 2022).</td>
</tr>
<tr>
<td>Left</td>
<td>L5 band depth</td>
<td>528 nm band depth</td>
<td>$1 - R_{528}^* / (0.472R_{442}^* + 0.528R_{605}^*)$</td>
<td>Larger value can indicate higher degree of Fe oxidation (e.g., Farrand et al., 2008).</td>
</tr>
<tr>
<td>Left</td>
<td>L5 band depth (broad shoulders)</td>
<td>528 nm band depth (broad shoulders)</td>
<td>$1 - R_{528}^* / (0.634R_{442}^* + 0.366R_{677}^*)$</td>
<td>Alternate version of the 528 nm band depth with broader shoulder positions, for a closer comparison to the 527 nm band depth defined for Mastcam (Rice, Seeger, et al., 2022).</td>
</tr>
<tr>
<td>Left</td>
<td>L2/L6 ratio</td>
<td>754 nm/442 nm ratio</td>
<td>$R_{754}^* / R_{442}^*$</td>
<td>Termed “red/blue ratio” and can indicate “redness” of spectra; larger values are consistent with higher degrees of oxidation.</td>
</tr>
<tr>
<td>Left</td>
<td>L3/L4 ratio</td>
<td>677 nm/605 nm</td>
<td>$R_{677}^* / R_{605}^*$</td>
<td>Indicates the location of the reflectance maximum between 600 and 700 nm; values &gt;1.0 have peak positions closer to 677 nm, consistent with ferric phases; values &lt;1.0 have peak positions closer to 677 nm, more consistent with ferrous phases.</td>
</tr>
<tr>
<td>Right</td>
<td>R1/R5 ratio</td>
<td>800 nm/978 nm ratio</td>
<td>$R_{800}^* / R_{978}^*$</td>
<td>Large positive values may indicate broad Fe absorptions in the NIR; values close to 1.0 indicate “flat” NIR profiles and are consistent with phases that are spectrally neutral in the NIR (e.g., pure sulfates). Small values are consistent with hematite.</td>
</tr>
<tr>
<td>Right</td>
<td>R5/R6 ratio</td>
<td>978 nm/1,022 nm ratio</td>
<td>$R_{978}^* / R_{1022}^*$</td>
<td>Used to quantify the spectral “downturn” or “uptick” in the longest Mastcam wavelength. Values &gt;1.0 with otherwise flat NIR profiles are consistent with a hydration band at ~980 nm (Rice et al., 2010). Large values paired with large 805/937 nm ratios are consistent with broader 900–1,000 nm absorptions (e.g., olivines and pyroxenes). Values &lt;1.0 are more consistent with 800–900 nm absorptions (e.g., hematite).</td>
</tr>
<tr>
<td>Right + Left</td>
<td>R2 band depth</td>
<td>866 nm band depth</td>
<td>$1 - R_{866}^* / (0.582R_{754}^* + 0.418R_{1022}^*)$</td>
<td>Largest values are consistent with presence of fine-grained, red crystalline hematite, and smaller positive values are consistent with other Fe-oxides. Negative values indicate a convex NIR profile more consistent with olivine, pyroxenes and nontronite. Bands were selected for the closest comparison to the 867 nm band depth defined for Mastcam (Rice, Seeger, et al., 2022).</td>
</tr>
</tbody>
</table>
We used the PCA results as one input for defining spectral rock classes, in addition to visual inspections of spectra and analyses of parameter space plots. Spectral classes were based on similar, compositionally meaningful spectral characteristics that we observed in at least two Mastcam-Z observations. We also avoided defining classes based on spectral features observed only in a single geometry (e.g., only in more distant observations). To minimize the influence of calibration uncertainties, brightness of the scene, and/or viewing geometry effects—which impact the overall reflectance of Mastcam-Z spectra—we based our classifications primarily on spectral shapes rather than albedo. Soil spectral classes were defined separately and are discussed in Vaughan et al. (2023).

2.5. Comparisons to Laboratory Spectra

We compiled a set of published laboratory spectra to serve as a baseline for comparison to and interpretation of Mastcam-Z spectra. These were selected prior to landing as a “Mastcam-Z library” of spectra covering most previously identified and hypothesized mineral phases on Mars, including a representative set of olivines and basaltic glasses, pyroxenes, feldspars, oxides, oxyhydroxides/hydrated oxides, chlorides, carbonates, phyllosilicates, hydrated silicates, sulfates, sulfides, perchlorates, and water ice. Most spectra are available via NASA’s Reflectance Experiment Laboratory (https://pds-speclib.rsl.wustl.edu), the USGS Spectral Library (Kokaly et al., 2017), or the University of Winnipeg Planetary Spectroscopy Facility (https://psf.uwinnipeg.ca); other spectra were compiled from Roush et al. (1990), Crowley (1991), Johnson and Grundy (2001), Minitti et al. (2007), and McCollom et al. (2014), as listed in Table S3 of Supporting Information S1. Following the methodology of Rice et al. (2010), we convolved the high-resolution laboratory spectra of these minerals to the Mastcam-Z bands, using the transmission profiles measured by Hayes et al. (2021) (Figure 2) to visualize their spectra as if they were collected in a Mastcam-Z multispectral image. The distinguishing spectral characteristics of ferrous iron (Fe$^{2+}$) and ferric iron (Fe$^{3+}$) in various minerals have been extensively documented (e.g., Clark et al., 1990), as have the features attributable to hydration (H$_2$O and/or OH) in Mastcam-Z’s wavelength range (e.g., Rice et al., 2010). We adapted several key spectral parameters used by Rice, Seeger, et al. (2022) to distinguish between iron oxidation states and constrain alteration mineralogies (Table 4).

Recognizing the limitations of comparing pure mineral spectra to that of variably altered and dust-covered rocks on Mars, we also used spectra of naturally weathered igneous rocks of different lithologies from Curtis (2022). These include basalts from the Columbia River Basalts, eastern WA, which have been previously used as spectroscopic analogs for Martian crustal basalts (e.g., Michalski et al., 2006); andesites as a more felsic lithology (from Mt. Baker, WA; e.g., Hildreth et al., 2003); and dunites as an ultramafic end-member (from Twin Sisters Mountain, WA; e.g., Onyeagocha, 1978). This suite was not selected to fully represent Mars’ igneous lithologies but rather to sample the spectral diversity of naturally weathered surfaces. Curtis (2022) acquired reflectance spectra from a variety of natural surfaces with different colors and thicknesses of rinds and/or coatings and from cut slabs of rock interiors to represent relatively unaltered lithologies. Compositions and surface textures of these samples are summarized in Table 4. Full resolution spectra were convolved to Mastcam-Z bandpasses so that spectra and band parameters could be directly compared.

3. Results

The locations where Perseverance acquired Mastcam-Z multispectral observations (sols 0–380; Table S1) are shown in Figure 5a. These include rocks and soils primarily within the Máaz formation for the first ~200 sols, with a limited number of observations westward into the Séítah formation. Perseverance traversed around the southeastern margins of Séítah to find an accessible entry point toward the southern end of the exposure and explored within the Séítah formation from sols 201 to 340 (Figure 5b). Afterward, Perseverance largely retraced its path to the Octavia E. Butler landing site before continuing northward toward the Jezero delta. Mastcam-Z acquired full-filter images of all stratigraphic members encountered along this traverse (Table 3), including all abraded surfaces and core sample locations within the Máaz and Séítah formations.

3.1. Spectral Characteristics of Soils

The soil spectra observed in Jezero crater are primarily influenced by their overall “redness,” as can be quantified by the 754 nm/422 nm ratio. In our results of the PCA for soils, 75.5% of the variance lies in the first principal component (PC1) (Figure 6), which corresponds to redness (Table 5). Examples of spectra with minimum and
maximum component values for PCs 1–4 are provided in Figure 7. PC2 characterizes 20% of the variance in soil spectra data set and corresponds to the concavity of the NIR profile and the peak reflectance position (high PC2 spectra have peaks closer to 754 nm and low PC2 spectra have peaks near 677 nm). PC3 and PC4 represent minor components of the soil spectral variability (each <2% of the total variance). Differences in PC3 correspond to the NIR band shape, as a weak 866 nm band with high PC3 values and a negative NIR slope with low PC3 values. PC4 corresponds to an 866 nm band versus a flat NIR profile between 800 and 978 nm.

Soil spectra follow a linear trend on the plot of 528 versus 754 nm/442 nm (Figure 8). Observations from soils in the region disturbed by Perseverance's landing event (target Ahyeeh) follow a similar linear trend that is offset below the rest of the data set (large diamond symbols in Figure 8). Beyond the scour marks, we observe no clear trend between these band parameters or the PCs and Perseverance's traverse location (indicated by sol in Figures 6 and 8).

3.2. Spectral Characteristics of Rocks

In the rock spectra across the traverse, 75% of the variance lies in PC1, 18% in PC2, 6% in PC3, and <2% in PC4 (Table 6). In the coordinate space of these components (Figure 9), some trends with rock surface type are apparent: very dusty surfaces and coatings have negative values of PC1 whereas dark natural surfaces have positive values. Abraded surfaces occupy the extremes of the PC2 versus PC1 plot, with Séítah abraded surfaces (Dourbes and Garde) in the lower right quarter and Máaz abraded surfaces (Guillaumes) in the upper right. Figure 10 shows minimum and maximum PC examples for PCs 1–4. The first component of the rock data set's variability corresponds to “redness” and the overall NIR profile between 754 and 1,022 nm (negatively sloped for maximum PC1, flat to slightly positive for minimum PC1). PC2 characterizes the overall spectral shape, as either generally flat in the maximum examples or convex with a reflectance peak at 754 nm in the minimum examples. PC3 corresponds to the presence of the 528 nm band in the maximum examples and the position of the reflectance peak (677 nm in minimum examples vs. 754 nm in maximum examples). PC4 relates to the NIR slope from 866 to 1,022 nm where the slope is positive in maximum examples or negative in the minimum examples.

The spectral parameters that best distinguish Máaz and Séítah formation rocks are the 677 nm/605 nm ratio and the 800 nm/1,022 nm ratio (Figure 11). Rock spectra from the Máaz formation have a range of 800 nm/1,022 nm ratios, indicating both positive and negative NIR slopes in their spectra, while almost all rocks encountered in Séítah have values >1.0, indicating negatively sloped NIR spectra. The lower right corner includes the spectra with the most negative NIR slopes and peak reflectances at the shortest wavelengths; this space is occupied exclusively by abraded surfaces and drill tailings from the Bastide member of Séítah. Many natural rock
Figure 6. Principal component plots for soils in the multispectral database. Color scale indicates sol, with lighter shades corresponding to earlier in the mission. Labeled points indicate spectra included in Figure 5.
3.3. Laboratory Spectra of Minerals and Rock Analogs

Examples of published laboratory spectra that are most relevant to the measured compositions of Máaz and Séítah formation rocks (e.g., Farley et al., 2022; Liu et al., 2022; Wiens et al., 2022) are shown in Figure 12 as convolved to Mastcam-Z bandpasses: oxides, olivines and basaltic glasses, low-Ca pyroxenes, high-Ca pyroxenes, and feldspars. Convolved spectra of example phyllosilicates, sulfates, and other alteration minerals are provided in Figures S1 and S2 of Supporting Information S1. Details of the laboratory mineral spectra used and their references are given in Table S3 of Supporting Information S1. For Mastcam-Z, the main distinctions between spectra of ferric iron (Fe\(^{3+}\); Figure 12a) and ferrous iron (Fe\(^{2+}\); Figures 12b–12e) are the 528 nm band absorption due to olivine (forsterite; Table S4 in Supporting Information S1), and the position of absorptions between 800 and 1,022 nm can help distinguish between the ferrous phases. Olivines, basaltic glasses, and high-Ca pyroxenes have bands centered longward of Mastcam-Z’s wavelength range, leading to negative NIR slopes. Low-Ca pyroxenes, in contrast, have broad absorptions centered near 900 nm. Feldspars are generally spectrally neutral across these wavelengths, and thus we do not expect them to contribute significantly to Mastcam-Z spectral profiles.

Examples of laboratory spectra of rocks with naturally weathered surfaces (Curtis, 2022) are shown in Figure 13, as full-resolution and Mastcam-Z convolved spectra. Dunite surfaces exhibit a broad range of colors, from blue-greens in sample interiors and freshly exposed surfaces to tans to oranges and reds where the weathering rinds are thickest. The spectra of dunite interiors and less-altered surfaces are dominated by broad ~1,000 nm absorptions due to olivine (forsterite; Table S4 in Supporting Information S1), and spectra of the more-weathered surfaces are more consistent with ferric oxides such as hematite, with reflectance peak positions shifted longward (from 528 to 754 nm) in Mastcam-Z convolved spectra. The negative NIR slope flattens and the 866 and 528 nm hematite absorptions become dominant, masking the presence of olivine in the more altered surfaces (even though the total Fe-oxide abundances are small; Curtis, 2022).
Figure 7. Example soil spectra with maximum and minimum values of each of the first four principal components. Observation details provided in Table 5.
The spectra of natural basalt surfaces are more neutral in Mastcam-Z wavelengths, with flat to shallowly dipping NIR profiles. The broad ∼1,000 nm band in the basalt samples is attributable to clinopyroxenes, and the band remains resolvable in the lab spectra of all weathered surfaces. Andesite surface spectra are characterized by a broad band closer to ∼950 nm, consistent with orthopyroxenes, which has a band minimum at 938 nm in the Mastcam-Z simulations for all but the most weathered samples. Moving from the grayer interiors to the redder,

**Figure 8.** Above: Soil spectra follow a linear trend on the plot of 528 versus 754 nm/442 nm, parameters which correlate with Fe^{3+}. Large diamond symbols correspond to soil spectra from the landing site scour marks (from observations Ahyeeh_1 of 2 and Ahyeeh_20f2, sol 33, zcam05106). Below: Portion of the Mastcam-Z landing site mosaic (sol 3, zcam00023) showing disrupted soils and exhumed rocks in the Ahyeeh scour mark (Bayer RGB natural color).
Table 6
Principal Components of Rock Spectra, With Observations From Which the Maximum and Minimum PC Examples in Figure 8 Are Taken

<table>
<thead>
<tr>
<th>PC</th>
<th>% variance</th>
<th>Defining spectral characteristics</th>
<th>Max PC examples</th>
<th>Min PC examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74.93</td>
<td>Overall redness (751 nm/445 nm ratio); NIR slope (754 nm/1,022 nm)</td>
<td>Dourbes_abrasion (sol 255); Garde (sol 207); Pont_du_loup_partial (sol 268)</td>
<td>Bastide (sol 205); Issole (sol 202); Champares (sol 185); Gion (sol 242)</td>
</tr>
<tr>
<td>2</td>
<td>18.31</td>
<td>Reflectance “hump” centered at 754 nm</td>
<td>Guillaumes_abrasion (sol 162); fta_detritus_150 (sol 151); Longon_Madone (sol 342); Séïtah (sol 123)</td>
<td>Pra_Loup_Pra_Balou (sol 327); King_Salmon (sol 421); Robine_Borehole (sol 297)</td>
</tr>
<tr>
<td>3</td>
<td>5.91</td>
<td>Peak reflectance position (677 nm/754 nm ratio); 528 nm band depth</td>
<td>Dourbes_abrasion (sol 255); Rochette_Manior (sol 188); Bellegarde_Abrasion (sol 187); Castillon (sol 159)</td>
<td>Estoublaisse (sol 285); Adsiilii_Wall_Boulders (sol 107); Rourebel (sol 203); Guillaumes (sol 162)</td>
</tr>
<tr>
<td>4</td>
<td>1.62</td>
<td>NIR slope (866 nm/1,022 nm)</td>
<td>Dahazkah (sol 102); Caille (sol 239); Adziilii_356 (sol 356); Taa_tsaadah (sol 112)</td>
<td>Quartier_abrasion (sol 295); Robine_Borehole (sol 297)</td>
</tr>
</tbody>
</table>

more weathered exteriors, the VIS profiles of the basalts and andesites change from negative to positive slopes, with increasing depths of the 528 nm band. The peak reflectance position shifts to longer wavelengths in the more weathered surfaces of all rock types.

Figure 14 shows examples of these pure mineral and natural rock surface laboratory spectra plotted for the parameters that best distinguish Mastcam-Z rock lithologies (677 nm/605 nm ratio vs. 800 nm/1,022 nm ratio; Figure 11). These parameters separate Fe-oxides (e.g., hematite and Mars analog dust) from the mafic rock-forming minerals. Low-Ca pyroxenes and feldspars plot with the bulk of the Mastcam-Z data set, while olivines, basaltic glasses and most high-Ca pyroxenes are distinct (in the lower right). Fe-rich pyroxenes (e.g., hedenbergite) are distinguished from other pyroxenes by 677 nm/605 nm ratios <1.0. Of the natural rock examples, the spectra of all basalt and andesites are most consistent with the low-Ca pyroxenes and feldspars in this parameter space, regardless of the degree of alteration of their surfaces. The dunite surfaces, however, are split into two populations: the less-weathered dunites fall in the lower right of the plot near the olivines, and the more-weathered dunites plot in the upper left with the Fe-oxides.

4. Discussion

4.1. Influence of Dust on Rock Spectra

We observe the influence of dust on the spectra of all soils and natural rock surfaces. PC1 for both soil and rock spectra—which characterizes ~75% of the variance in the Mastcam-Z spectral database—is directly related to the amount of dust. Soil spectra fall on a linear trend in the plot of 528 nm band depth versus “redness” (the 754 nm/442 nm ratio) (Figure 8), which we attribute to dust on the surface of and/or intermixed with the soils. Rock spectra plotted on these parameters (Figure 15) largely fall on the same linear trend as the soils, except for the spectra of “purple” rock coatings, which fall on a separate trend with a steeper slope. These spectral differences are attributed to the addition of Fe-oxides in the coating material (Garczynski et al., 2022). Rock surfaces that we have classified as “dark natural surfaces,” based on qualitative assessments of the images, plot in the lower left corner and exhibit minimal contributions from dust. Rock surfaces with thick dust deposits plot in the upper right with the reddest soil examples.

Notably, rock surfaces within the landing site scour area (Ahyeeh) plot with the soils from the same region (diamonds in Figure 8). These plot on a separate trend that is parallel to the rest of the data set but “redder” than other rocks and soils. The landing event was highly disruptive as the thrusters kicked-up significant amounts of dust and even large grains, some of which settled on the rover's deck (Merusi et al., 2022). If only dust was mobilized and redeposited in the scour region, we would expect both rock and soil spectra from the Ahyeeh observations to plot in the upper corner of the 528 versus 754 nm/442 nm plot (with the dustiest soils and dustiest rock surfaces). However, the “redder” scour spectra imply that some material other than the surface dust was redistributed during the event. We hypothesize that a red, fine-grained component of the soil at depth was excavated and deposited on the surface in the scour region. There is precedent for landing events giving rise to unique surface spectra; in Gale crater, the Goulburn class of Mastcam rock spectra were only seen in the vicinity of Curiosity's landing site (Rice, Seeger, et al., 2022).
Figure 9. Principal component plots for rocks in the multispectral database. Color scale indicates rock surface type.
Figure 10. Example rock spectra with maximum and minimum values of each of the first four principal components. Observation details provided in Table 7.
Figure 11. Spectral parameters that best distinguish (a) Séítah formation rocks from (b) Máaz formation rocks: 677 nm/605 nm ratio versus 800 nm/1,022 nm ratio. Diamond symbols correspond to abraded surfaces and tailings. Points in the lower right of (a) correspond to the olivine-rich Garde and Dourbes abrasion targets; points in the upper right of (b) correspond to hematite-like spectra.
Figure 12. Examples of laboratory mineral spectra convolved to Mastcam-Z bandpasses: (a) oxides; (b) olivines and basaltic glasses; (c) low-Ca pyroxenes; (d) high-Ca pyroxenes; (e) feldspars. Some spectra have been offset for clarity by values shown in the legends. Details of laboratory spectra are provided in Table S3 of Supporting Information S1.
The most disruptive surface event observed after landing was a dust event on sols 314–16, when measurements of atmospheric opacity increased from 0.3 to >2.0 (Lemmon et al., 2022) and significant dust was deposited on the Mastcam-Z caltarget (Merusi et al., 2022). To test if the dust in the atmosphere influenced surface spectra during the event—and/or if the surface reddened from dust settling after the event—we examined the 754 nm/422 nm

Figure 13. Examples of laboratory spectra of rocks with naturally weathered surfaces convolved to Mastcam-Z bandpasses: (a) dunites; (b) basalts; and (c) andesites. All plots include full-resolution laboratory spectra (left) with the shaded region indicating wavelengths beyond Mastcam-Z's spectral range; images of rock surfaces from which spectra were acquired (each 4 cm across) (middle); and spectra convolved to Mastcam-Z wavelengths (right).
Figure 14. Examples of laboratory spectra convolved to Mastcam-Z bandpasses and plotted as the 677 nm/605 nm ratio versus the 800 nm/1022 nm ratio: (a) Pure mineral phases (spectra shown in Figure 10); (b) Naturally weathered rock surfaces (numbers correspond to the spectra shown in Figure 11). Small gray points ("ZCAM Rocks") are the Mastcam-Z spectra from Figure 9.

ratio versus sol (Figure 16). We observed no increase in this parameter in the spectra of rock and soils during or following the event, suggesting that the Mastcam-Z IOF calibration properly corrected for the increased atmospheric opacity and dust settling on the caltarget. Similarly, no increased reddening was observed in Mastcam spectra of rocks and soils following the multiple dust events observed in Gale crater, including the 2018 dust...
storm (Rice, Seeger, et al., 2022). These observations provide confidence that the observed variations in soil and rock spectra presented in the previous sections indicate real compositional variations.

4.2. Definition of Rock Spectral Classes

We identified eight major spectral classes of rocks on the Jezero crater floor from synthesizing the results of PCA, spectral parameter inspections, and comparisons to laboratory spectra. Representative spectra of each of these classes are shown in Figure 17; the spectral properties and occurrences of each spectral class are summarized in Table 7. Class names are interpretive. Class 1 (Dusty) is characterized by a large red/blue ratio, moderate 528 nm band, and flat NIR profiles. These spectra are closely matched by the dust analog JSC-Mars1 (Figure 12a).

Some Dusty class rock spectra have a downturn at 1,022 nm that is not present in pure airfall dust spectra or dusty soil spectra (e.g., Vaughan et al., 2023). We attribute this feature to a narrow absorption near ∼1,000 nm due to hydration and/or hydroxylation (e.g., Rice et al., 2010). Hydration features in alteration minerals are often centered between ∼950 and 980 nm (see Table S1 of Rice, Seeger, et al. (2022)) and result in resolvable 978 nm bands in Mastcam-Z spectra (Figures S1 and S2 in Supporting Information S1). However, the presence of a hydration feature closer to ∼1,000 nm is consistent with some dust observations from Pancam at Meridiani Planum, which exhibited a spectral downturn at 1,009 nm and were interpreted as dust deposits that had undergone minor hydration (Johnson et al., 2021). Similarly, we interpret that some airfall dust coatings on rocks in Jezero crater have undergone some degree of alteration that is observable as minor hydration in Mastcam-Z spectra. However, it is also possible that some hydration absorption features in Dusty class rock spectra may result from bound water in the dust itself. Hydration in Mars' dust has been observed in ground-based telescope spectra (e.g., Bell & Crisp, 1993), orbital observations (e.g., Bandfield et al., 2003), and in situ rover measurements by
and MSL (e.g., Meslin et al., 2013). Laser-induced breakdown spectroscopy and IR observations of dust in Jezero crater by SuperCam also confirm minor hydration (Mandon et al., 2023).

Class 2 (Hematite-like) spectra have absorption bands centered at 528 and 866 nm, consistent with red hematite (Figure 12a). The “V-shaped” profile of the 866 nm feature is consistent with Mastcam spectra of rocks that were confirmed to be hematite-bearing in Gale crater (e.g., Fraeman et al., 2020; Horgan, Johnson, et al., 2020; Jacob et al., 2020). These spectra have been observed sporadically in all members of the Máaz and Séítah formations but most prominently in the Cha’al member of Máaz (particularly in the Alfalfa abrasion patch). Because the 866 nm band depth is detectable even beneath surface dust (as shown via comparisons of dusty surfaces of hematite-rich rocks in Gale crater to adjacent dust-removed surfaces; Rice, Seeger, et al., 2022), we expect that Mastcam-Z’s observations of the Hematite-like class represent an accurate, patchy distribution of hematite along the traverse.

Class 3 (Coated) spectra are similar to the Hematite-like spectra but have weaker 866 nm bands and stronger 528 nm features, which lead to a purple color for these surfaces. This spectral class is exclusively associated with coatings visible on natural rock surfaces, which are patchily distributed on rocks in all members of the Máaz and Séítah formations. Garczynski et al. (2022) attribute these spectral features to Fe-oxides in coatings deposited in aqueous alteration events following the emplacement and partial exhumation of the Jezero crater floor and which have been variably eroded due to ongoing aeolian abrasion. However, the presence of the Class 2 (Hematite-like) spectra in abraded surfaces suggests that Fe-oxides are also present in rock interiors, not only as superficial coatings. This suggests that the hematite may have been the result of oxidation due to surface exposure and weathering, and/or during eruption and emplacement of the lava flow (Horgan et al., 2023).

Class 4 (Low-Ca Pyroxene-like) spectra are prevalent in dark, natural rock surfaces; these are observed in all stratigraphic members but primarily within the Máaz formation. These have broad ∼900 nm absorptions and peak reflectance values near 754 nm, consistent with weak signatures of low-Ca pyroxenes/orthopyroxenes (e.g.,

Figure 16. Variations in “redness” versus sol for rocks and soils across the Jezero crater floor. Diamond symbols indicate abraded surfaces as tailings. The sol 314–316 dust event (gray region) does not appear to have influenced the surface spectra.
Most low-dust rock surfaces in the Bastide and Issole members of the Séítah have Class 5 (Olivine-like) or Class 6 (Weathered Olivine-like) spectra. We observed the most Olivine-like spectra in the Dourbes and Garde abraded surfaces and fresh drill tailings (the points in the lower right corner of Figure 11), which are characterized by steeply negative NIR slopes (high 800 nm/1,022 nm ratios), peak reflectance positions at shorter wavelengths (low 677 nm/605 nm ratios), and no 528 nm bands. These spectra are consistent with olivines of a variety of forsterite compositions, as well as some basaltic glasses and high-Ca pyroxenes (Figures 12 and 14a). We interpret these spectra as being dominated by olivine, consistent with the measured compositions by other instruments (e.g., Farley et al., 2022). The surfaces of natural dunites (Figure 13a) are good spectral analogs to the olivine-rich rocks in Séítah: the Class 5 (Olivine-like) spectra closely match the “tan” dunites (point 3 in Figure 14b), which have undergone some degree of alteration (Curtis, 2022). The Class 6 (Weathered Olivine-like) spectra have shallow NIR slopes and reflectance peak positions shifted to longer wavelengths (near 754 nm), consistent with more extensively weathered “orange” dunite surfaces (point 4 in Figure 14b). We observe no rock surfaces with Mastcam-Z that are consistent with the “green” dunite interiors, consistent with a higher Fe content in the Jezero olivine relative to terrestrial olivine (Brown et al., 2020).

The spectral characteristics that distinguish many dark rock surfaces in the Artuby and Rochette members of the Máaz formation from the rest of the data set are those of Class 7 (Fe-rich Pyroxene-like) spectra: peak reflectance...
Table 7
Summary of Rock Spectral Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Interpretive name</th>
<th>Short description</th>
<th>Defining spectral characteristics</th>
<th>Type examples</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dusty</td>
<td>Red, flat NIR profile, can have 1,022 nm downturn</td>
<td>Large 751 nm/445 nm ratios; Flat NIR profiles; 800 nm/978 nm ratios ≤1.0; 978 nm/1,022 nm ratios ≥ 1.0</td>
<td>Naakib_isaadah (sol 110, zcam03160)</td>
<td>Horizontal rock surfaces with bright, thick dust coatings, prevalent across the traverse</td>
<td></td>
</tr>
<tr>
<td>2 Hematite-like</td>
<td>Red, strong 866 nm band, strong 528 nm band</td>
<td>Large 751 nm/445 nm ratios; Large 528 nm band depths; 800 nm/1,022 nm ratios close to 1.0; Large 866 nm band depths</td>
<td>Bastide_2of2 (sol 205, zcam03227)</td>
<td>Sporadic occurrences in all mems, of the Máaz and Séítah fms., most prevalent within Máaz abrasion patches</td>
<td></td>
</tr>
<tr>
<td>3 Coated</td>
<td>Purple, weak 866 nm band, strong 528 nm band</td>
<td>Large 528 nm band depths; Lower 745/422 nm ratios; Moderate 866 nm band depths</td>
<td>Dourbes_abrasion (sol 255, zcam03253)</td>
<td>Patchily distributed on surfaces of all mems, of the Máaz and Séítah fms.</td>
<td></td>
</tr>
<tr>
<td>4 Low-Ca Pyroxene-like</td>
<td>Gray, Broad ~900 nm band, peak reflectance near 754 nm</td>
<td>Moderate 908 nm band depths; Low 978 nm/1,022 nm ratios; 800 nm/978 nm ratios &gt; 1.0</td>
<td>Rochette_Manior_1of2 (sol 188, zcam03214)</td>
<td>Dark natural surfaces, primarily within the Máaz fm.</td>
<td></td>
</tr>
<tr>
<td>5 Olivine-like</td>
<td>Strongly negative NIR slope, peak reflectance near 677 nm</td>
<td>Very large 800 nm/1,022 nm ratios; Low 677 nm/605 nm ratios; Very large 978 nm/1,022 nm ratios; Very large 800 nm/978 nm ratios</td>
<td>Guillaumes_abrasion (sol 162, zcam03197)</td>
<td>Dark natural surfaces, abraded patches and tailings in the Séítah fm.</td>
<td></td>
</tr>
<tr>
<td>6 Weathered Olivine-like</td>
<td>Negative NIR slope, peak reflectance near 754 nm, 528 nm band</td>
<td>Large 800 nm/1,022 nm ratios; Low 677 nm/605 nm ratios; Large 978 nm/1,022 nm ratios; Large 800 nm/978 nm ratios; Moderate 528 nm band depths</td>
<td>Eoulix (sol 299, zcam03275)</td>
<td>Dark natural surfaces, abraded patches and tailings in the Séítah fm.</td>
<td></td>
</tr>
<tr>
<td>7 Fe-rich Pyroxene-like</td>
<td>Negative NIR slope, peak reflectance near 600 nm</td>
<td>Large 751 nm/445 nm ratios; Positive 1,012 nm/751 nm ratios; no 866 nm band depth</td>
<td>Touyet_Artuby_Ridge (sol 302, zcam03276)</td>
<td>Primarily within the Artuby and Rochette mems. of the Máaz fm.</td>
<td></td>
</tr>
<tr>
<td>8 Dark Oxide-like</td>
<td>Gray, positive VIS and NIR slope</td>
<td>Very low 800 nm/1,022 nm ratios; Moderate 677 nm/600 nm ratios; Weak 528 nm band depths</td>
<td>Garde_abrasion (sol 207, zcam03229)</td>
<td>Limited occurrences in the Bastide member of the Séítah fm.</td>
<td></td>
</tr>
</tbody>
</table>

positions near 600 nm and shallow, negative NIR slopes. These spectra are most consistent with the presence of Fe-rich pyroxenes such as hedenbergite (Figure 14a). Class 8 (Dark Oxide-like) spectra are consistent with dark, spectrally sloped opaque minerals such as Mn-oxides, sulfides, and some Fe-bearing phyllosilicates like greenalite and hisingerite. Of the eight spectral classes defined here, the Dark Oxide-like spectra are the least prevalent, seen only in the Bastide member of the Séítah formation.

Each of these eight spectral classes can be distinguished in the parameter spaces shown in Figure 18. The 677 nm/605 nm ratio versus the 800 nm/1,022 nm ratio (Figure 18a) separates Olivine-like from Weathered Olivine-like spectra, with Fe-rich Pyx-like spectra, Dark Oxide-like spectra, and Hematite-like spectra also separated from the rest of the data set. In the plot of 528 nm band depth versus 754 nm/442 nm ratio (Figure 18b), coated spectra are separated from other rock spectra, including Dusty spectra and the redder Hematite-like spectra. Low-Ca Pyx-like spectra are distinguishable in their small 978 nm/1,022 nm ratios and moderate 800 nm/978 nm ratios compared to other rocks (Figure 18c).

In this parameter space, the Dusty spectra most consistent with hydration (with downturns at 1,022 nm and otherwise flat NIR profiles) are those in the uppermost left corner of the data cloud (with the largest 978 nm/1,022 nm ratios). We acknowledge several limitations in our approach for defining spectral classes, including potential biases in ROI collection, image resolution versus grain sizes, the low spectral resolution of Mastcam-Z, and influence of dust in masking spectra, as elaborated by Rice, Seeger, et al. (2022) for the Mastcam multispectral database. This methodology used geologically trained human eyes, which could introduce biases associated with human error and training inconsistencies. It is possible that other spectrally distinct materials in some scenes were overlooked. In future work, machine learning will be explored for identifying spectral end-members that are geologically distinct within each observation (e.g., Kerner et al., 2020).
4.3. Implications for Origin and Modification of the Jezero Crater Floor

Across the traverse, variations in the 800 nm/1,022 nm ratio can indicate materials that are generally more Olivine-like versus more Hematite-like (Figure 19). The most Olivine-like spectra occur exclusively within the Séítah formation and the most Hematite-like spectra are confined to Máaz formation targets, with the strongest examples of each occurring within abraded surfaces and drill tailings (diamonds in Figure 19). Comparisons of spectral properties in rocks versus soils across the traverse (black dots in Figure 19) can indicate the degree that sediments derived from local outcrops are being incorporated into adjacent soils. The most Olivine-like soil spectra occur within the Máaz formation, where Olivine-like rocks are not observed; these are locations, however, where dark soils appear to have been transported from Séítah to the west onto the overlying Máaz rocks. The soil spectra generally indicate a consistent mineralogy across the traverse but some local contributions to the sediments are also consistent with the Mastcam-Z data (Vaughan et al., 2023).

The occurrences of Olivine-like and Weathered Olivine-like spectra give insights into the alteration history of the Séítah formation. Within the Bastide member, Mastcam-Z spectra show minimal evidence for oxidation or the presence of ferric minerals in the abraded spots at targets Garde and Dourbes (Figure 20), which exhibit the strongest olivine signatures, consistent with the observations of the SuperCam visible and infrared (VISIR) spectrometers (Brown et al., 2022). On the natural surfaces of those rocks, however, the broad ∼1,000 nm olivine absorption is entirely masked by the purple coatings where present on the surface, and by other Fe-oxides on surfaces without coatings. Within the Issole member, the Quartier abrasion target spectra exhibit weaker and more variable olivine signatures than those of Dourbes and Garde (Figure 20), consistent with a higher degree of olivine weathering and/or more ferric oxides. At all core sample locations within Séítah, the spectra from drill tailings are very similar to those of the adjacent abrasion targets, implying that the abraded surfaces are representative of the rock at sampling depth. The alteration observed at the rock surfaces, therefore, is only present in the top few mm of the outcrop, but the alteration observed in the abraded surfaces continues to several cm depth.

Within the Máaz formation, the stratigraphically lower members (Rubion, Artuby, and Rochette) exhibit spectral differences from the other members. These members exhibit more Fe-rich Pyx-like spectra and fewer Fe-oxide spectra, consistent with observations from the SuperCam instrument (Udry et al., 2023). Spectra from the core sample tailings and abraded surfaces in Máaz are nearly identical in all instances, with the exception of at the Guillamares abrasion target in the Rubion member, where differences between the core tailings and adjacent abrasion tailings suggest possible differences in the Fe-bearing mineralogy or a weathering profile (Horgan et al., 2023). The upper members of the Máaz formation are more Hematite-like than the lower members, in spectra from both natural surfaces and abrasion targets (such as the Cha’l abrasion target Alfalfa). Cha’l is the only member in which hematite is observed in CRISM orbital spectra (Horgan, Anderson, et al., 2020), indicating that Fe-oxides are prevalent at the top of Máaz lava flows.

We note that no spectra from dark natural rock surfaces abrasion patches or drill tailings are consistent with spectra of hydrated minerals (e.g., Figures S1 and S2 in Supporting Information S1); no rock spectra in our database have clear 978 nm absorption features, even in abraded surfaces where salts were
observed by other instruments (e.g., Farley et al., 2022). It is possible that weak hydration features are masked by the Fe-oxides and other mafic minerals because the small bright salts in voids are barely resolvable to Mastcam-Z and are not isolated in our ROIs.

4.4. Comparisons to MSL Mastcam Spectral Classes

We have adapted key Mastcam-Z parameters (Table 4) to enable direct comparison to Mastcam parameters, as plotted in Figure 21 for all rocks in the Jezero crater floor and for all rocks in Gale crater (sols 0–2302). Overall, the Mastcam-Z rock spectra are less diverse than the Mastcam data set; they occupy a more limited region of the 866 nm band depth versus 1,022 nm/754 nm ratio parameter space. Comparing the Mastcam-Z data to the nine major classes of Mastcam rock spectra of Rice, Seeger, et al. (2022) (Figure 21, right), we note that there are no Mastcam-Z equivalents to Mastcam Class 5 (the Mn-oxide-bearing layers observed in the Kimberley formation). The Dark Oxide-like spectra in Jezero crater, therefore, are distinct from the Mn-oxide layers observed in Gale crater, indicating that different opaque minerals may be the cause of these spectra observed by Mastcam-Z. Also, the Mastcam-Z rock spectra do not extend into the region Mastcam Class 4 (the strongest hematite absorptions on Vera Rubin ridge), indicating that even the most Hematite-like spectra from the Cha’l member in Jezero crater have weaker 866 nm band depths than the hematite-rich outcrops in Gale crater. This difference could be due to lower abundances of hematite and/or differences in grain size (e.g., Jacob et al., 2020).

We observe no iron meteorites in Mastcam-Z spectra, which would be equivalent to Mastcam Class 8 (negative 866 nm band depths and large 1,022 nm/754 nm ratios; Figure 21). Meteorites have not yet been identified in other Perseverance data sets either. Several meteorites were found along the Opportunity and Curiosity traverses (e.g., Ashley et al., 2011; Johnson et al., 2020; Schröder et al., 2011; Wellington et al., 2018), notably within sedimentary terrains that had potentially long depositional periods (ample time to collect meteorites) and significant erosional histories (from which meteorites may have been left as a lag deposit). It is not surprising, therefore, that Perseverance has not seen meteorites within the igneous Jezero crater floor units. However, we predict that iron meteorites might be more abundant at the Jezero delta, where they can be identified by these parameters in Mastcam-Z multispectral observations.

The only Mastcam-Z rocks with spectra unlike anything seen by Mastcam are the Olivine-like rocks from the Séítah formation. These plot outside of the regions that define Mastcam spectral classes (Figure 21), with very
small 1,022 nm/754 nm ratios (indicating steeply negative NIR slopes), consistent with the spectra of olivines and weakly weathered ultramafic rocks. Some olivine-bearing sands in Gale crater have similar spectra to these (such as those of the Bagnold dune field), but Mastcam has not seen such spectra in outcrop. Some Gale crater rocks do have similarly negative NIR slopes (namely dark layers within the Sutton Island member of the Murray formation; Mastcam Class 3) but their 866 nm band depths are more consistent with nontronite than with olivine (Rice, Seeger, et al., 2022). Spectral equivalents to the Mastcam-Z Olivine-like class have not been seen by the Spirit or Opportunity Pancams either (e.g., Farrand et al., 2008, 2013). Although olivine-bearing rocks within the Columbia Hills of Gusev crater have similar mineral compositions to those of the larger Nili Fossae region (Ruff et al., 2022)—which includes Jezero crater—Pancam spectra of those rocks (the “Seminole class” of Farrand et al., 2008) have shallower NIR slopes than the Mastcam-Z Olivine-like class, with flat or positive slopes from ~930 to ~1,010 nm and ~530 nm absorptions. Therefore, the Mastcam-Z Olivine-like class represents a new spectral class from multispectral observations at Mars.
5. Conclusions

Perseverance has acquired an extensive data set of multispectral images with its Mastcam-Z instrument over its first 380 sols of exploration in the floor of Jezero crater. These observations document the mafic lava flows of the Máaz formation and the ultramafic cumulates of the Séítah formation, both of which have undergone small degrees of aqueous alteration and are variably covered by coatings, dust, and/or soil deposits. From 311 full-filter observations, we compiled a database of ∼2400 representative Mastcam-Z spectra. Our analyses of principal components, spectral parameters and comparisons to laboratory spectra of pure minerals and natural rock surfaces reveal the following:

1. The variability of soil spectra in the Jezero crater floor is controlled primarily by the amount of dust and indicates a largely consistent soil mineralogy across the traverse;
2. During Perseverance’s landing event, a fine-grained component of the soil at depth—spectrally distinct from the ubiquitous airfall dust—was excavated and deposited on the surface in the scour region;
3. Spectra of some thick dust coatings on rocks indicate hydration, but no other Mastcam-Z rock spectra are consistent with hydrated minerals;
4. The variability of rock spectra in the Máaz and Séítah formations can be described by eight major classes: Dusty, Hematite-like, Coated, Low-Ca Pyroxene-like, Olivine-like, Weathered Olivine-like, Fe-rich Pyroxene-like, and Dark Oxide-like;
5. The lower members of the Máaz formation are spectrally dominated by Fe-rich pyroxenes, while the upper members have more Fe-oxides;
6. Séítah formation rock spectra show weakly altered olivine in abraded surfaces and drill tailings, although superficial coatings and/or alternation rinds can mask the presence of olivine in natural surface spectra;
7. Rocks on the Jezero crater floor are generally less spectrally diverse than those encountered in Curiosity’s traverse in Gale crater, but the Olivine-like rocks within the Séítah formation represent a new spectral rock class in Mars surface exploration.

These analyses provide a baseline to interpret future observations along the Perseverance traverse. As Mastcam-Z continues its investigation at the Jezero delta and beyond, we predict new spectral classes of rocks to be encountered in the sedimentary units and marginal deposits, where phyllosilicate and carbonate mineralogies have been documented from orbit.
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