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Spectral Diversity of Rocks and Soils in Mastcam Observations Along the Curiosity Rover’s Traverse in Gale Crater, Mars

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Abstract The Mars Science Laboratory Curiosity rover has explored over 400 m of vertical stratigraphy within Gale crater to date. These fluvio-deltaic, lacustrine, and aeolian strata have been well-documented by Curiosity’s in situ and remote science instruments, including the Mast Camera (Mastcam) pair of multispectral imagers. Mastcam visible to near-infrared spectra can broadly distinguish between iron phases and oxidation states, and in combination with chemical data from other instruments, Mastcam spectra can help constrain mineralogy, depositional origin, and diagenesis. However, no traverse-scale analysis of Mastcam multispectral data has yet been performed. We compiled a database of Mastcam spectra from >600 multispectral observations and quantified spectral variations across Curiosity’s traverse through Vera Rubin ridge (sols 0–2302). From principal component analysis and an examination of spectral parameters, we identified nine rock spectral classes and five soil spectral classes. Rock classes are dominated by spectral differences attributed to hematite and other oxides (due to variations in grain size, composition, and abundance) and are mostly confined to specific stratigraphic members. Soil classes fall along a mixing line between soil spectra dominated by fine-grained Fe-oxides and those dominated by olivine-bearing sands. By comparing trends in soil versus rock spectra, we find that locally derived sediments are not significantly contributing to the spectra of soils. Rather, varying contributions of dark, mafic sands from the active Bagnold Dune field is the primary spectral characteristic of soils. These spectral classes and their trends with stratigraphy provide a basis for comparison in Curiosity’s ongoing exploration of Gale crater.

Plain Language Summary The Curiosity rover’s Mastcam instrument is a pair of cameras that take images in visible and near-infrared wavelengths. Mastcam spectra can distinguish between different types of iron-bearing minerals. During Curiosity’s traverse through a variety of sedimentary rock types in Gale crater, Mars, the rover has acquired more than 600 Mastcam multispectral observations, but no previous studies have analyzed the full data set. In this study, we compiled a database of Mastcam spectra from the first 2302 sols (Martian days) of Curiosity’s mission and analyzed spectral trends across the traverse. We define nine classes of spectra for rocks and five classes of spectra for soils, and we observe that different classes occur in different locations. The major spectral differences are due to the mineral hematite and other iron oxides. By comparing the trends in rock spectra to nearby soils across the traverse, we find that the soils are not made of the same minerals as the local rocks, but are dominated by sands from the active Bagnold Dune field. These spectral classes and their trends will be a basis of comparison for Curiosity’s ongoing exploration of Gale crater.

1. Introduction

The Mars Science Laboratory (MSL) Curiosity rover has traversed more than 26 km and gained over 400 m in elevation since landing in Gale crater in 2012. Across this traverse, Curiosity has encountered a wide variety of sedimentary units within the crater floor and Aeolis Mons (informally called Mt. Sharp), which have been divided into stratigraphic formations within three major groups: the Bradbury Group (Grotzinger et al., 2013; Rice et al., 2017), the Siccar Point Group (Banham et al., 2018; Fraeman et al., 2016), and the Mt. Sharp Group...
Mastcam is unique among Curiosity's scientific payload in that it can quickly acquire spectral information over broad spatial areas. At distances of a few meters, Mastcam multispectral images can document spectral diversity over the wavelength interval 440–1020 nm across a given outcrop in combination with textural information such as grain size, sedimentary structures, diagenetic features, and contact geometries. At distances of up to several kilometers, Mastcam observations correlated with the larger-scale stratigraphy can enhance mineralogical and stratigraphic maps made from orbiter data, such as from the Mars Reconnaissance Orbiter (MRO) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) and High Resolution Imaging Science Experiment (HiRISE) instruments (McEwen et al., 2007; Murchie et al., 2007).

Each Mastcam camera is mounted ~1.9 m above the Martian surface on the rover's mast and utilizes an 8-position filter wheel in front of a 1,600 × 1,200 pixel Bayer-patterned charge-coupled device (CCD) (Malin et al., 2017). When images are acquired through multiple filter positions with both cameras at the same pointing, each pixel in the resulting multispectral observation includes visible to near-infrared (VNIR) reflectance data at up to 12 unique wavelengths, including the Bayer red, green and blue (RGB) broadbands. Mastcam's filter set has direct heritage from the Imager for Mars Pathfinder (IMP) (Bell et al., 2000; Smith et al., 1997), the Mars Exploration Rover (MER) Panoramic Camera (Pancam) instruments (Bell et al., 2003, 2006), and Phoenix's Surface Stereo Imager (SSI) (Smith et al., 2008). However, Mastcam multispectral analyses are inherently different from those of previous imagers in two ways: the addition of the Bayer filters on the CCD (which each set of narrowband wavelengths must “see through”) and the different focal lengths of the two cameras (34 mm for Mastcam left and 100 mm for Mastcam right, which produce significantly different fields of view).

On their own, Mastcam spectra do not provide unique mineral identifications, but they can broadly distinguish between differences in iron mineralogies and/or oxidation states. In combination with chemical and mineralogical data from Curiosity's other instruments, Mastcam spectra can help constrain mineralogy, depositional origin, and diagenesis. In observations from the first part of Curiosity's traverse, through the fluvio-deltaic sequences within the Bradbury Group (Vasavada et al., 2014) and the fluviolacustrine mudstones and siltstones of lower Murray Formation of the Mt. Sharp Group (Grotzinger et al., 2013), Mastcam spectra of soils and rock targets are largely consistent with basaltic materials with variable coatings of nanophase ferric oxide from airfall dust (Wellington et al., 2017). Outcrop targets where the Dust Removal Tool (DRT) and/or drill were used, however, show more spectral diversity (Wellington et al., 2017). Mastcam spectra of bright, fracture-filling veins within the Bradbury Group, in combination with measurements of elevated Ca and S by ChemCam and APXS (e.g., Nachon et al., 2014), are consistent with hydrated Ca-sulfate phases in some occurrences (Vaniman et al., 2014). At locations where high-Mn concentrations have been observed by ChemCam LIBS, such as in the Kimberley formation (Rice et al., 2017), Mastcam spectra are very dark and flat, consistent with Mn-oxides (Lanza et al., 2016). Rocks identified as meteorites exhibit distinct spectral profiles characterized by both relatively low overall reflectance as well as positive spectral slope throughout the Mastcam wavelength range (Wellington et al., 2018, 2019).

Further along Curiosity's traverse through the Murray formation, Mastcam spectra of specific outcrops near Marias Pass, where DAN measurements predicted high-SiO$_2$/low-FeO bedrock, are consistent with opaline silica, leading to their interpretation as a silicic volcanlastic layer (Czarnecki et al., 2020). Observations of active aeolian sand deposits at the Bagnold Dunes are consistent with the mafic compositions observed from orbit by CRISM (Lapotre et al., 2017) with variable contributions of Fe-oxide-bearing sands (Johnson et al., 2017, 2018). At the Sutton Island outcrops, Mastcam spectral variations have been attributed to Fe/Mg-smectites in lacus-

(Edgar et al., 2020; Stack et al., 2019). The chemical and mineralogical compositions of these units have been studied in detail using remote sensing observations from the Chemistry and Camera (ChemCam) Laser Induced Breakdown Spectroscopy (LIBS) instrument, subsurface observations from the Dynamic Albedo of Neutrons (DAN) instrument, in situ observations from the Alpha Particle X-Ray Spectrometer (APXS), and laboratory measurements from the Sample Analysis at Mars (SAM) and Chemistry and Mineralogy (CheMin) investigations. In addition to these quantitative composition techniques, Curiosity's Mast Camera (Mastcam) multispectral instrument can help to constrain mineralogy and extend the mapping of compositional units beyond where other instrument measurements have been acquired.
Table 1: Mastcam RGB Bayer and Geology Filters Effective Center Wavelengths ($\lambda_{\text{eff}}$) and Half-Widths at Half-Maximum (HWHM), After Bell et al. (2017)

<table>
<thead>
<tr>
<th>Mastcam left (M34)</th>
<th>Mastcam right (M100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter position</td>
<td>$\lambda_{\text{eff}}$ ± HWHM (nm)</td>
</tr>
<tr>
<td>L0 (Red Bayer)</td>
<td>640 ± 44</td>
</tr>
<tr>
<td>L0 (Green Bayer)</td>
<td>554 ± 38</td>
</tr>
<tr>
<td>L0 (Blue Bayer)</td>
<td>481 ± 37</td>
</tr>
<tr>
<td>L1</td>
<td>527 ± 7</td>
</tr>
<tr>
<td>L2</td>
<td>445 ± 10</td>
</tr>
<tr>
<td>L3</td>
<td>751 ± 10</td>
</tr>
<tr>
<td>L4</td>
<td>676 ± 10</td>
</tr>
<tr>
<td>L5</td>
<td>867 ± 10</td>
</tr>
<tr>
<td>L6</td>
<td>1012 ± 21</td>
</tr>
</tbody>
</table>

*The blue Bayer band center wavelengths differ from those reported by (Bell et al., 2017), see text for details.

The Mastcam multispectral analyses summarized above have all focused on isolated geographic regions along Curiosity’s traverse and/or specific types of surface features. No studies to date have synthesized Mastcam multispectral observations for the entire data set across the traverse. However, understanding how outcrop properties vary with lithology and elevation throughout the full stratigraphy is key to interpreting the depositional history of Gale crater and the complex history of diagenesis. Indeed, such systematic analyses of chemical variations with stratigraphy (chemostratigraphy), as derived from by ChemCam (e.g., Frydenvang et al., 2020) and APXS (e.g., Thompson et al., 2020) data, have been critical to contextualizing individual outcrops within the larger geologic history of fluviolacustrine activity, diagenetic alteration, and subsequent erosion in Gale crater. Thus, this work is motivated by the need for a comprehensive analysis of the full Mastcam multispectral data set. Our objectives are to identify the predominant Mastcam spectral classes encountered to date, to analyze their distributions across Curiosity’s traverse, and to correlate the observed spectral variations with trends in the stratigraphy.

To this end, we analyzed the full suite of Mastcam multispectral images and compiled a comprehensive multispectral database from surface observations up to sol 2302 (through Curiosity’s exploration of Vera Rubin ridge). In the following sections, we describe a systematic analysis of Mastcam spectra from all regions, rock types, and soils across the rover’s extended traverse. This comprehensive approach allows us to develop “best practices” for analyzing Mastcam multispectral observations and to establish conventions for working with the data set, taking into account the complicating presence of Bayer filters and separate fixed focal lengths. We generate “spectro-stratigraphic” columns that document spectral variations across the traverse by plotting spectral parameters versus elevation, which we qualitatively compare to changes in lithology and quantitatively compare to laboratory measurements of mineral spectra. We also leverage principal component analysis (PCA) to identify the major components of spectral variability in the database, which we use to identify the major rock and soil spectral classes that Curiosity has encountered to date. Ultimately, we synthesize these observations to present a holistic view of the Mastcam spectral diversity in Gale crater.

2. Methods

2.1. Mastcam Filter Set

The Mastcam instrument is a pair of cameras referred to as M34 (left camera) and M100 (right camera). Each camera obtains images through a Bayer pattern of broadband RGB filters and telecentric microlenses bonded onto the charge-coupled device (CCD) (Malin et al., 2017). The cameras’ eight-position filter wheels enable the collection of spectra in 12 unique wavelength bands centered between 445 and 1013 nm (Table 1; Figure 1) (Bell et al., 2017). Each filter wheel includes a broadband filter with a near-infrared cutoff for Bayer RGB images, six narrowband geology filters (three of which are nearly identical in the left and right cameras for stereo imaging), and a solar filter for atmospheric monitoring (e.g., tau measurements) and certain astronomical observations (solar transits of Phobos and Deimos). We have adopted 481 and 483 nm as the center wavelengths of the blue Bayer filter for the left and right eye, respectively (Table 1), as opposed to the 493 and 495 nm used by Bell et al. (2017). The change incorporates information learned during the pre-flight radiometric calibration of Mastcam-Z on the Mars-2020 mission Perseverance rover (Hayes et al., 2021), as detailed in the Supplemental Information (Text S1 and Figure S1 in Supporting Information S1).
When displaying full-filter spectra in this work, we always scale spectra in both cameras to the average at L6 (1012 nm) and R6 (1013 nm); this convention best reproduces the expected band profiles in Mastcam spectra targets of known mineralogy, as detailed in the Supplemental Information (Text S2, Figures S2, and S3 in Supporting Information S1). We use caution when evaluating the shape of full spectra where the filters alternate between the two Mastcams (751–908 nm), especially when “sawtooth” patterns are present in the scaled spectra (e.g., Figure S3 in Supporting Information S1). In quantitative analyses, we also use filters exclusively from the left- or right-Mastcam when calculating band parameters (Table 4), obviating the effects of absolute reflectance offsets.

2.2. Mastcam Image Calibration

We calibrated Mastcam observations to radiance using pre-flight calibration coefficients from radiance products available via the NASA Planetary Data System (PDS) (Bell et al., 2017). We converted radiance to radiance factor (I/F, or “IOF,” where I is equal to the measured scene radiance and πF is the solar irradiance received at the surface at the time of the observation) using associated observations of the Mastcam calibration target. To correct for the effects of airfall dust on the calibration target, we used two-stream radiative transfer models (Kinch et al., 2015). We converted radiance factor to relative reflectance (R*) (Reid et al., 1999), also known as the “reflectance factor” (Hapke, 1993), by:

$$R^* = \frac{IOF}{\cos(i)}$$

where $i$ is the solar incidence angle (provided in the observation metadata, see Section 2.4). This procedure was first developed from the MER Pancam calibration pipeline (Bell et al., 2006). Absolute calibration accuracy for Mastcam’s filter set is 10%–15% or better (Bell et al., 2017).

Images calibrated to R* are partially “atmospherically corrected” because observations of the Mastcam calibration target also include near-simultaneous measurements of the Mastcam sky illumination component of the scene radiance (Bell et al., 2017; Kinch et al., 2015). However, the calibration of Mastcam images to R* assumes that all illumination comes from a point source at the position of the Sun, and that the scene is perfectly flat and parallel to the calibration target (and therefore the solar incidence angle remains constant within an image).

To minimize uncertainties that arise from these assumptions, the Curiosity team typically acquires Mastcam multispectral observations as close to local noon as possible; routine exceptions are photometry observations.
which are intentionally acquired at multiple times of sol to document the same surface under multiple illumination geometries (e.g., Johnson et al., 2013).

2.3. Compilation of a Mastcam Multispectral Database

Curiosity has acquired Mastcam multispectral observations within all major stratigraphic units (Table 2) and across most elevation intervals over the traverse (Figure 2b). We compiled a comprehensive database of Mastcam spectra that sample the diversity observed across Curiosity’s traverse (Figure 3), including a total of 624 observations as described below. This tally excludes 38 multispectral observations acquired between sols 0–2302 because of extensive shadowing, failed image execution, incomplete downlink, and/or complicated mosaic acquisition (which pose challenges to our multispectral analysis tools and have been deferred to future analyses) (Table S2 in Supporting Information S1).

For each Mastcam multispectral observation, we characterized the spectral variability in the scene by manually identifying color end members through a visual inspection of the approximate true color (ATC) images, false color images and decorrelation stretch (DCS) products (Gillespie et al., 1986) (e.g., Figure 4). We produced false color and DCS composites from combinations of Mastcam filter images that produced the largest color contrasts for each observation. While the specific filter combination that produces the most variability in false color and DCS images is not necessarily the same for each scene, we found that R1/R2/R6 and L1/L2/L6 produced the best color contrast in most observations. We identified end members as groupings of pixels that exhibit distinct colors in the false color and DCS products and also represent geologically-distinct surfaces (as identified in the ATC images). We took care to identify color end members corresponding to different geologic materials, and to distinguish these from color variations that may result from small differences in local viewing geometry (e.g., the multiple facets of a homogenous rock). In instances of variable dust cover on an otherwise homogenous surface, we selected end members on both the most- and least-dusty regions. We generally excluded regions where color

<table>
<thead>
<tr>
<th>Group</th>
<th>Formation</th>
<th>Member</th>
<th>Elevation range (m)</th>
<th>Sol range</th>
<th>Number Mastcam observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt. Sharp</td>
<td>Murray</td>
<td>Jura</td>
<td>−4.174.7—−4.139.9</td>
<td>1866–1302</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pettigrove Point</td>
<td>−4.200.1—−4.155.4</td>
<td>1812–2153</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blunts Point</td>
<td>−4.280.5—−4.180.6</td>
<td>1688–1807</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sutton Island</td>
<td>−4.371.2—−4.286.2</td>
<td>1475–1682</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Karasburg</td>
<td>−4.410.8—−4.360.8</td>
<td>1417–1492</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hartmann's Valley</td>
<td>−4.435.6—−4.410.4</td>
<td>1355–1405</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pahrump Hills</td>
<td>−4.461.3—−4.419.9</td>
<td>758–1276</td>
<td>86</td>
</tr>
<tr>
<td>Siccar Point</td>
<td>Stimson</td>
<td>Beagle*</td>
<td>−4.450.4—−4.379.5</td>
<td>943–1462</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dillinger*</td>
<td>−4.479.2—−4.456.7</td>
<td>614–626</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liga*</td>
<td>−4.479.2—−4.478.7</td>
<td>582–620</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Square Top*</td>
<td>−4.478.7—−4.582.7</td>
<td>581–582</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sheepbed*</td>
<td>−4.521.0—−4.520.3</td>
<td>133–298</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gillespie*</td>
<td>−4.520.5—−4.518.2</td>
<td>116–301</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glenelg*</td>
<td>−4.519.3—−4.516.6</td>
<td>53–323</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Unclassified)</td>
<td>−4.520.5—−4.456.7</td>
<td>13–728</td>
<td>66</td>
</tr>
</tbody>
</table>

Note. Some dedicated soil observations include no rocks in the field of view and are not listed here; some observations tallied here include rocks from multiple members. Descriptions of stratigraphic units can be found in Grotzinger et al. (2013), Rice et al. (2017), Stack et al. (2019), and Edgar et al. (2020).

*Not shown on the stratigraphic column in Figure 2.
Figure 2. Frequency of Mastcam multispectral images acquired along Curiosity’s traverse: (a) Time of day (Local True Solar Time) for all multispectral surface observations (excluding photometry sequences). Assumptions in the calibration pipeline do not apply at low Sun angles, so we generally restrict our analyses to observations acquired 10:30–13:30 LTST (range indicated by horizontal dashed lines); (b) Rover elevation versus sol for each multispectral surface observation (details provided in Table 2). Red points indicate the locations of low-dust targets (including those brushed by the Dust Removal Tool (DRT), broken rocks and drill fines). Approximate elevation intervals of stratigraphic members (Table 2) are marked by dashed horizontal lines.
end-members were present only in the M34 images but not in the M100 images, such as the magenta/orange hues seen in the left of Figure 4c, except for targets of particular geologic interest (e.g., candidate meteorites) or significance to the mission (e.g., drill tailings).

We extracted a representative spectrum of each end member by manually selecting pixels from regions of interest (ROIs) in the right and left camera images separately. All spectra are available in Rice (2022). In selecting ROIs, we adhered to a system of “best practices” to ensure the extraction of geologically meaningful spectra with minimal noise:

1. We used a minimum ROI size of 30 unsaturated pixels in the M34 images, with rare exceptions for very small features (e.g., narrow veins).
2. We generally collected spectra from contiguous regions, but occasionally selected ROIs from non-contiguous regions of the same spectral endmember (as could be identified in DCS images) to increase the total pixel count.
3. Where possible, we extracted spectra from near-horizontal surfaces near the center of the image to best match the assumptions made in the Mastcam calibration pipeline (Bell et al., 2017).
4. 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.
5. We avoided surfaces exhibiting specular reflections, shadows, and/or rover hardware.

Multiple people (2–4) inspected each observation to verify that the selected ROIs corresponded to end members within the scene and consistently followed the best practices procedures. Locations of ROIs are documented in Rice (2022) (shown overlain on DCS images for each multispectral observation).

Figure 3. Maps of Curiosity’s traverse and locations of Mastcam multispectral observations for (a) sols 0–750 in the Bradbury Group, and (b) sols 750–2302 in the Mt. Sharp Group, with observations within the Murray formation labeled (Siccar Point Group targets occur throughout this sol range, see Table 2).
We flagged pixels with 11-bit data number (DN) values greater than 2,000 in raw images as “saturated” and excluded them from ROI averages on a per-filter basis. In the spectra shown, we represent "error bars" in $R^*$ as the standard deviation among the selected ROI pixels; this is a measure of the homogeneity of the pixel values within the ROI, and is generally much larger than the instrumental error (Bell et al., 2017).

Figure 4. Example of region of interest (ROI) selection of color endmembers in a full-filter Mastcam multispectral observation of the Hex River Dust Removal Tool (DRT) spot (sol 1885, mcarn09853): Bayer red, green and blue (RGB) composites from the (a) L0 image and (b) R0 image; Decorrelation stretch (DCS) images, with ROI positions overlain, made with filters (c) L1, L2 and L6, and (d) R1, R2 and R6; (e) Spectra extracted from ROIs (with left- and right-eye spectra scaled to 1012 nm and stereo filters averaged). The DRT spot size is ~4.5 cm in diameter.

2.4. Compilation of Relevant Metadata

Each endmember spectrum was compiled with relevant metadata. Observation-level and ROI-specific metadata are included with the spectral database (Rice, 2022). A number of the metadata fields specific to each observation were taken directly from the Mastcam images’ Planetary Data System version 3 (PDS3) headers, including: the Mastcam sequence identifier (seq ID); target name; day of the mission (sol); time of day measured as the local true solar time (LTST) at the start of the observation; camera focal distance; site index and rover drive number (which resets after each site index increment, so that site index and drive number together give a unique rover position). We also included metadata for the season in the form of solar longitude ($L_s$), which is the Mars-Sun angle measured from the Northern Hemisphere spring equinox. Atmospheric optical depth was also included for each observation, given as $\tau$ (“tau”) (Guzewich et al., 2019; Lemmon et al., 2019); interpolated values were used for times when direct measurements were not available.

Geographic information was taken from localization data provided for each rover position in the PDS, including: latitude, longitude, total traverse distance (odometry), and rover elevation. Depending on the observation geometry, the elevation of the targets in the scene may be significantly different from the rover’s elevation; however, most multispectral observations are of workspace targets that are close to the same elevation as the rover (<1 m
difference), and more distant targets are identified by the camera focal distance in the PDS3 image headers. When making spectro-stratigraphic plots of parameters versus elevation, we exclude distant targets with large uncertainties in their elevations.

Observation geometries were calculated using instrument data in the PDS3 headers: the incidence angle \( i \) was calculated from the site frame SOLAR_ELEVATION field minus 90°, and the emission angle \( e \) was taken as the INSTRUMENT_ELEVATION plus 90°. The phase angle \( \gamma \) is defined as the angle between the incidence and emission vectors, which is given by:

\[
\cos \gamma = \cos i \cos e + \sin i \sin e \cos(\Delta \phi)
\]

(2)

where \( \Delta \phi \) is the angle between the projection of the incidence vector \( \phi_i \) and emission vector \( \phi_e \) on the surface, given as the difference between the two absolute azimuths, or \( \Delta \phi = |\phi_i - \phi_e| \) (e.g., Shepherd, 2017). The incidence vector is taken directly from the SOLAR_AZIMUTH header value in the PDS3 images, and the emission vector is the INSTRUMENT_AZIMUTH value plus 180°. For our metadata, we recorded the geometries for the center of the image at the start of the observation (from the headers of the first filter acquired, usually L0).

Each spectrum was assigned one of the geologic “feature types” listed in Table 3. We classified all rock spectra in our multispectral database as either “in-place” or “float” (not attached to outcrop). Float rocks can either be eroded components of bedrock or allochthonous material (e.g., impact ejecta or meteorites). Rocks that were not clearly distinguishable as float rocks or in-place outcrop (e.g., partially-buried rocks) were classified as “in-place.” In observations with both in-place and float rocks with the same textural and color properties, we preferentially extracted spectra from the in-place rock.

We assigned specific lithology information (group, formation, and member) from the stratigraphic column of Edgar et al. (2020) (Table 2). Using the multispectral database and these metadata, we examined how key spectral parameters vary with stratigraphy and other aspects of geology and geography. In the spectro-stratigraphic plots and parameter space analyses presented here, we restrict our analyses to observations acquired between 10:30 and 13:30 LTST (local noon ± 1.5 hr), as some assumptions in the calibration pipeline break down at lower Sun angles. Figure 2a shows the starting LTST of Mastcam multispectral observations in our database (excluding photometry sequences); only a small subset of observations falls outside this range, mostly from early in the mission.

2.5. Quantification of Spectral Parameters

To study variations in Mastcam spectra, we quantified a variety of spectral parameters specific to the Mastcam filter set (Table 4). Band depths were calculated using the definition from Clark and Roush (1984):

\[
D = 1 - \frac{R_b}{R_c}
\]

(3)
Where $R_b$ is the reflectance at the band center $\lambda_b$ and $R_c$ is the reflectance of the continuum at the same wavelength as $R_b$, defined as a straight line passing through two “shoulder” positions on either side of the absorption feature. For left and right shoulder reflectance values $R_L$ and $R_R$ at wavelength positions $\lambda_L$ and $\lambda_R$, the reflectance of the continuum is:

\[ R_c = x R_L + y R_R \]  \hspace{1cm} (4)

where

\[ x = \frac{\lambda_R - \lambda_b}{\lambda_R - \lambda_L} \]  \hspace{1cm} (5)

and

\[ y = 1 - x \]  \hspace{1cm} (6)

To characterize broad spectral profiles (e.g., from unresolved bands at the short- or long-wavelength ends of the Mastcam spectrum), previous multispectral analyses have used slope and ratio parameters interchangeably (e.g., Farrand et al., 2008). Here, we exclusively use ratio parameters (Table 4), based on an evaluation of slope versus ratio parameters detailed in Text S3 and Figure S4 in Supporting Information S1.

### 2.6. Comparisons to Laboratory Spectra

We performed an analysis of laboratory spectra as a baseline for comparison to and interpretation of Mastcam spectra. We used a representative subset of minerals with prominent Fe$^{2+}$ and/or Fe$^{3+}$ absorptions for a Mastcam

<table>
<thead>
<tr>
<th>Camera</th>
<th>Parameter</th>
<th>Formula</th>
<th>Possible mineralogic indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>L6 (1012 nm)/L3 (751 nm) ratio</td>
<td>$R_{1012}^* / R_{751}^*$</td>
<td>Used as a proxy for NIR profile; values &lt;1.0 are consistent olivine, clinopyroxene, and basaltic glasses; values &gt;1.05 can be indicative of iron meteorites</td>
</tr>
<tr>
<td>Left</td>
<td>L1 (527 nm) band depth</td>
<td>$1 - R_{327}^* (0.645 R_{445}^* + 0.355 R_{676}^*)$</td>
<td>Larger value can indicate higher degree of Fe oxidation (e.g., Farrand et al., 2008)</td>
</tr>
<tr>
<td>Left</td>
<td>L3 (751 nm)/L2 (445 nm) ratio</td>
<td>$R_{751}^* / R_{445}^*$</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 (751 nm)/L1 (527 nm) ratio</td>
<td>$R_{751}^* / R_{527}^*$</td>
<td>A modified version of the “red/blue ratio”; values &gt;1.0 are consistent with iron meteorites (e.g. Wellington et al., 2018)</td>
</tr>
<tr>
<td>Left</td>
<td>L3 (751 nm)/L4 (676 nm) ratio</td>
<td>$R_{751}^* / R_{676}^*$</td>
<td>Indicates the location of the reflectance maximum between 600 and 800 nm; values &gt;1.0 have peak positions closer to 751 nm, consistent with ferric phases; values &lt;1.0 have peak positions closer to 676 nm, more consistent with ferrous phases</td>
</tr>
<tr>
<td>Left</td>
<td>L5 (867 nm) band depth</td>
<td>$1 - R_{867}^* (0.556 R_{751}^* + 0.444 R_{1012}^*)$</td>
<td>Largest values are consistent with presence of fine-grained, red crystalline hematite, and smaller positive values consistent with other Fe-oxides. Negative values indicate a convex NIR profile more consistent with olivine, pyroxenes and nontronite (e.g. Horgan et al., 2020)</td>
</tr>
<tr>
<td>Right</td>
<td>R3 (805 nm)/R5 (937 nm) ratio</td>
<td>$R_{805}^* / R_{937}^*$</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 (937 nm)/R6 (1013 nm) ratio</td>
<td>$R_{937}^* / R_{1013}^*$</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 900–1000 nm absorptions (e.g., olivines, pyroxenes). Values &lt;1.0 are more consistent with 800–900 nm absorptions (e.g., hematite).</td>
</tr>
</tbody>
</table>

Table 4

Summary of Spectral Parameters Used to Characterize Mastcam Spectra

RICE ET AL.
band parameter analysis (Figure 6), following Horgan et al. (2020), with additional meteorite spectra from Cloutis et al. (2010). We convolved the high-resolution laboratory spectra of these minerals to the Mastcam spectral bands with the algorithm described by Rice et al. (2010).

The spectral region covered by Mastcam's geology filters is particularly sensitive to iron-bearing primary basaltic minerals (e.g., Adams, 1974), secondary iron oxide and oxyhydroxide minerals (e.g., Morris et al., 1985; Singer, 1982); ferric sulfates, ferric carbonates, and iron-bearing clays (e.g., Sherman et al., 1982). The VNIR spectral properties of ferrous iron (Fe$^{2+}$) and ferric iron (Fe$^{3+}$) in various minerals have been extensively documented (e.g., Clark et al., 1990), and key spectral parameters can help distinguish between iron oxidation states, which we have adapted to the Mastcam filter set (Table 4). The L1 (527 nm) band depth parameter quantifies the depth of an absorption near 530 nm which, together with the L3 (751 nm)/L2 (445 nm) ratio (indicating a steep “red” profile from ~440 to 700 nm) can characterize relative amounts of Fe-oxides.

A broad spectral “hump” near 600 nm is consistent with ferrous phases, while most ferric phases have local maxima closer to 750 nm (Figure 6); these distinctions can be quantified as L3 (751 nm)/L4 (676 nm) ratios less than or greater than 1.0, respectively (Table 4). L3 (751 nm)/L4 (676 nm) ratios <1.0 together with broad absorptions centered near 1000 nm (quantified as L6 (1012 nm)/L3 (751 nm) ratios <1.0) are consistent with olivine, clinopyroxene or basalt glass (Figure 6). Ferric minerals typically have L6 (1012 nm)/L3 (751 nm) ratios >1.0, indicative of broad absorptions between 800 and 900 nm. Red, fine-grained hematite spectra exhibit particularly large L6 (1012 nm)/L3 (751 nm) ratios and strong bands centered at 867 nm; other ferric phases, in addition to orthopyroxene, exhibit deep absorption bands centered at 908 nm.

We also analyzed a representative suite of hydrated and/or hydroxylated minerals, including borates, carbonates, chlorides, halides, hydroxides, perchlorates, phyllosilicates, other hydrated silicates, ices, sulfates and zeolites (Cloutis et al., 2006; Crowley, 1991; Kokaly et al., 2017; Rice et al., 2013). From this survey of library spectra, we identified 49 minerals with H$_2$O and/or OH absorptions in Mastcam's wavelength range, which have generally narrow absorption bands centered from 949 to 1020 nm (Table S1). Example spectra of minerals with a range of band centers, depths and widths are shown in Figure 7. Generally, the depth of the band correlates with the amount of hydration (e.g., Rice et al., 2010). However, not all hydrated and/or hydroxylated minerals exhibit related absorption features that are detectable in this wavelength range; for example, this weak overtone feature is easily masked by more prominent absorptions centered between 900 and 1000 nm in many iron-bearing minerals, such as nontronite (see Fe$^{3+}$ smectite in Figure 5).

In the Mastcam-convolved spectra, the depth of the narrow hydration absorption at R6 (1013 nm) is strongly dependent on the band center and width of the feature (Figure S5 in Supporting Information S1). Mastcam is only able to detect this band at a threshold of $>$1% for minerals with absorptions centered longward of ~980 nm (e.g., epsomite, bischofite, ulexite, and gypsum; Figure 6). The position of the H$_2$O and/or OH feature in the majority of hydrated and hydroxylated minerals, however, is centered between ~950 and 980 nm. For minerals with narrow bands centered in this range, the hydration is invisible to Mastcam (e.g., analcime, brucite; Figure 6). Therefore, the depth of the R6 (1013 nm) feature in Mastcam spectra (Table S1) does not necessarily correlate with amount of H$_2$O and/or OH; while the presence of the band can indicate the presence of hydrated and/or hydroxylated minerals, the absence of an R6 (1013 nm) band does not indicate an absence of hydration and/or hydroxylation. Also, for absorptions centered closer to 950 nm, such as in saponite (Figure 6) and other phyllosilicates (Figure S5 in Supporting Information S1), the band may be detectable by Mastcam's R5 (937 nm) filter.

Spectral parameters that characterize minerals with potential >980 nm absorptions are the R5 (937 nm)/R6 (1013 nm) ratio and the R3 (805 nm)/R5 (937 nm) ratio (Table 4), which quantify the absorption at R6 (1013 nm) and the broad NIR profile (which is flat or slightly positively-sloping in most hydrated minerals). Distinguishing between the hydrated and/or hydroxylated phases that exhibit these characteristics is not possible using Mastcam spectra alone. However, in combination with chemistry data from other Curiosity instruments (such as elevated Ca and S in fracture-filling veins, as indicated by ChemCam and APXS), the presence of these spectral features in Mastcam spectra can help refine mineralogic interpretations (e.g., gypsum vs. anhydrite or bassanite for calcium sulfates).

### 2.7. Spectral Classification

We visually inspected Mastcam spectra for VNIR features associated with iron-bearing mineralogy and/or hydration, and quantified key parameters for all spectra as shown in Table 4. In order to maximize the variance within
the Mastcam spectral data set, we also used PCA, a dimensional reduction technique in which a linear orthogonal transformation transforms a data set into a new coordinate space (e.g., Davis, 1973). We represented the data as a linear sum of orthogonal principal components, which were chosen in the PCA process to be in order of decreasing variance. To exclude noisy spectra from the analysis (which may result from ROIs with very few pixels, image misregistration, or accidental inclusion of shadowed regions), we filtered the data set by the size of their average error bars, excluding spectra with average pixel standard deviation greater than 0.02 reflectance units. Because several non-mineralogical factors can darken or brighten Mastcam spectra (e.g., averaging of shadowed pixels on textured surfaces, or uncertainties in the $R^*$ correction), we elected to remove the overall albedo from the PCA. We normalized spectra to 1.0 at their peak reflectance prior to performing the PCA so that the components would represent variance in spectral shape independent of overall albedo. However, we did include albedo in our interpretations of spectral classes that could be consistent with dark phases such as magnetite.

We used the Scikit-learn Python package (https://scikit-learn.org/stable/about.html; Pedregosa et al., 2011) to perform PCA on two subsets of the Mastcam multispectral database: rocks and soils (Table 3). We plotted the contributions of the various PCs to each spectrum against one another to represent Mastcam spectra in component space, where unique spectral endmembers were identified by their separation from the rest of the data cloud. We examined the shapes of the spectra with the largest and smallest values of each PC to infer the specific spectral features that contribute to the components. This general approach was previously applied to identify spectral classes from Pancam dataset along the Spirit and Opportunity rover traverses (e.g., Farrand et al., 2006, 2008, 2013).

We defined spectral classes by synthesizing PCA results (Section 3.4) with spectro-stratigraphic plots and visual inspections of spectra across the traverse (Sections 3.1 and 3.2). We identified these classes based on similar
spectral characteristics that are compositionally meaningful and which are less likely to result from calibration uncertainties, overall brightness of the scene, and/or effects of scaling the two Mastcam spectra (as discussed in Text S2 in Supporting Information S1). To that end, we avoided defining classes based on albedo alone, or based on the relative reflectance values of adjacent filters between the two Mastcams (e.g., the L5 (867 nm) versus R4 (908 nm) values). We do not define classes based on any single outlier spectrum; in order to be defined as a class, we require that the same spectral features be observed in multiple Mastcam observations.

3. Results

3.1. Rock Spectral Variability

3.1.1. Trends With Stratigraphy and Dust Cover

Where Curiosity’s DRT had been employed, we extracted spectra from the resulting dust-cleared rock surface, as well as spectra from adjacent, dusty rock surfaces (e.g., Figure 7). Direct comparisons of dusty and dust-cleared targets demonstrate that dust consistently masks rock spectra, resulting in higher reflectance (especially at longer wavelengths), muted absorption features, and smaller L3/L2 (751 nm/445 nm) ratios, approaching the spectrum of optically-thick dust (black spectrum in Figure 7). Across the entire data set, dust-cleared rocks tend to exhibit greater L5 (867 nm) band depths than dusty rocks, particularly on Vera Rubin ridge. They also exhibit consist-

Figure 6. Examples of hydrated mineral spectra from existing libraries plotted over the Mastcam wavelength range (black lines), with reflectance values convolved to Mastcam bandpasses (gray points). All spectra are offset for clarity (offset values shown next to mineral names). Epsomite, bischofite, ulexite and gypsum are examples of minerals with Mastcam “R6 hydration band” depths ≥1.0%. Analcime, brucite and saponite are examples of minerals with hydration bands that are not detectable by Mastcam’s R6 filter. Spectral libraries are listed in Table S1.
ently lower \( L_3/L_2 \) (751 nm/445 nm) ratios, especially in the lower Murray formation where \( L_1 \) (527 nm) band depths are also shallower for dust-cleared rocks.

Like dust-cleared sections of rock, drill targets can provide even more insight into the rocks’ spectral properties. Drill tailings (Table 3) have grain sizes <1 mm, with most of the material generally <150 μm (Anderson et al., 2012) and >5 μm in diameter (Rampe, Bristow, et al., 2020). Although variable in their size fractions, tailings are largely dust-free and offer a bulk rock sample from depths of up to 5 cm (Anderson et al., 2012).

Although the middle interval of the Murray formation has sparse drill samples due to time needed to develop new drilling techniques after the drill feed mechanism failure, every stratigraphic member (Edgar et al., 2020) was still sampled. Spectra from drill fines present similar advantages as DRT spots for investigating rock spectral properties, and they have little to no dust cover, although they are texturally different than intact rock surfaces. For example, in the Big Sky observation on sol 1118, we extracted spectra from drill tailings, an adjacent DRT spot, and typical dusty bedrock surface (Figure 8). The drill tailings spectrum is much flatter than the others, with a lower \( L_3/L_2 \) (751 nm/445 nm) ratio and generally deeper absorption features than the dustier counterparts, particularly in the NIR.

In the traverse through the Bradbury Group and into the lower Murray formation (below the Sutton Island member), spectra from drill fines are consistent with corresponding DRT spectra in \( L_5 \) (867 nm) band depth but tend to have lower \( L_3/L_2 \) (751 nm/445 nm) ratios and shallower \( L_2 \) (527 nm) absorption features (Figure 10). In these strata, we observe a clear progression of decreasing redness (lower \( L_3/L_2 \) (751 nm/445 nm) ratios) from dusty rock surfaces to DRT targets to drill fines at the same elevations. However, these relationships are more complicated within and stratigraphically above the Sutton Island member, where some drill fines are redder than adjacent DRT targets, with deeper \( L_2 \) (527 nm) absorptions. These trends have been attributed to the presence of hematite in the Murray formation, which is redder at fine grain sizes than in outcrop (Horgan et al., 2020; Jacob et al., 2020).

Overall, drill fines are more spectrally diverse in their \( L_3/L_2 \) (751 nm/445 nm) ratios than dust-cleared and dusty targets. Juxtaposing spectra from these three feature types demonstrates the degrees to which dust masks the spectra.
and highlights which spectral features are most useful in the dusty rock spectrum to reflect the actual spectral signature of the underlying rock. Specifically, the L5 (867 nm) band depth is the most consistent across all target types (Figure 9), indicating that this band is the least influenced by surface dust. Indeed, laboratory studies have shown that thin covers of dust simulants have stronger masking effects on VIS than NIR spectral features (e.g., Johnson & Grundy, 2001).

3.1.2. Float Versus In-Place Rock Spectra

It is rare to encounter large, cohesive bedrock outcrops in Gale crater; rather, most of Curiosity’s traverse has been across an expansive, broken pavement. Our multispectral database includes 1,102 in-place rock spectra and 556 float rock spectra. Float rocks are distributed throughout the stratigraphic sequence but are comparatively sparse in the Blunts Point member (Figure 10). In general, float rocks are spectrally consistent with proximal in-place targets, as would be expected for rock fragments weathering out of local outcrop. Only float rocks found in the Sutton Island and Jura members are spectrally distinct from their in-place counterparts at equivalent elevations (Figure 10), interpretations for which are given in Section 4.

Several anomalous float rocks were noted in previous studies as being candidate meteorites or meteorite fragments (based on morphology, chemistry and/or spectral properties). Those that have been confirmed as meteorites with chemical measurements have dark grayish colors and distinct positive NIR slopes in Mastcam spectra (Wellington et al., 2018). These spectral properties can be quantified with low L3/L2 (751 nm/527 nm) ratios and high L6/L3 (1012 nm/751 nm) ratios, respectively. In the parameter space shown in Figure 11, candidate meteorites plot in the lower right corner, separately from all other rock targets. The five points with L6/L3 (1012 nm/751 nm) ratios greater than 1.1 include float rock spectra from: Lebanon (sols 640 mcam02729; sol 641 mcam02718), Cottonwood (sol 1032, mcam04511), Mustards Island (sol 1821, mcam09401), and Newburgh (sol 2255, mcam12069). Each of these has previously been reported as a candidate meteorite (Johnson et al., 2020; Wellington et al., 2018, 2019); therefore, we do not identify any new meteorite candidates in our multispectral...
database but confirm the utility of these parameters for searching for meteorites along Curiosity's ongoing traverse.

### 3.1.3. Fracture-Filling Veins

We searched the multispectral database for hydration absorptions at R6 (1013 nm), as have been associated with Ca-sulfate veins at Meridiani Planum (Farrand et al., 2013; Squyres et al., 2012) and with opaline silica at Gusev crater (Rice et al., 2010; Ruff et al., 2011), and found no features that are clear indicators of hydration and/or hydroxylation in vein or other rock spectra. In locations where CheMin has confirmed the presence of phyllosilicates (e.g., Rampe, Bristow, et al., 2020, Rampe, Lapotre, et al., 2020), Mastcam spectra of the drill tailings exhibit no detectable H$_2$O and/or OH absorptions in the R5 (937 nm) filter that are expected for minerals such as saponite (Figure 6) and other phyllosilicates (e.g., Figure S5 in Supporting Information S1).

The parameter space in Figure 12 indicates where minerals with hydration features (Table S1) occur when present as pure phases. Spectra with positive R5/R6 (937 nm/1013 nm) ratios (indicative of $a > 980$ nm absorption) and R3/R5 (805 nm/937 nm) ratios close to 1.0 (indicative of otherwise flat NIR profiles) are consistent with—but not unique signatures of—some hydrated minerals (e.g., gypsum and epsomite, Figure 6). These spectral characteristics are also easily masked in mixtures with other phases, so detecting hydration in Mastcam spectra is expected to be challenging.

Vaniman et al. (2014) reported possible hydration in veins near the landing site, and ChemCam H data suggest the calcium sulfate veins are predominantly bassanite, with some gypsum and anhydrite (Nachon et al., 2014; Rapin...
Figure 11. Identification of iron meteorites in Mastcam float rock spectra. (a) Parameters that distinguish candidate meteorites (colored circles) from the rest of the float rock data set (red diamonds), with values for lab spectra of iron meteorites shown as black triangles (full lab spectra shown in Figure 6). (b) Mastcam spectra of the five iron meteorite candidates shown in the gray region in (a), images of which are shown in Figure 10.
et al., 2016). We do not find evidence for hydration in Mastcam spectra of the veins to be widespread across the traverse. We find that spectra of light-toned, fracture-filling veins (yellow diamonds, Figure 12) do not cluster within the region of the parameter space that is consistent with hydrated minerals, which we would expect if the veins were dominated by hydrated phases such as gypsum. Rather, vein spectra have a spread of values, indicating variability within these features. While some vein spectra do exhibit R6 (1013 nm) absorptions, which may be consistent with hydration, these spectra were collected from ROIs containing only a few pixels and therefore suffer from high uncertainty due to the factors discussed above. The multispectral database only includes spectra from a subset of vein targets, owing to their small sizes and the difficulty in extracting spectral averages; however, adding more of the narrow veins to the database and classifying their textures (such as thin, thick, boxwork, subparallel, or “chickenwire”; e.g., Minitti et al., 2017) will be part of ongoing database development.

3.2. Soil Spectral Variability

Soils across Curiosity’s traverse show notable spectral trends with elevation (Figure 13). For spectral parameters related to iron-bearing phases and ferric materials, the soil variability across the traverse does not follow the vari-

Figure 12. (a) Spectral parameters that can distinguish minerals with hydration absorptions >980 nm, shown for lab spectra of hydrated minerals convolved to Mastcam bandpasses (pink circle, full spectra shown in Figure 6), Mastcam vein targets (yellow diamonds), and all other rock targets (blue dots). The gray region indicates where hydrated minerals fall in this parameter space; (b) Example Mastcam spectra from a variety of vein morphologies (note that the Measles Point observation only included filters R0345); (c) Mastcam R0 images of veins, spectra were extracted from region of interests (ROIs) within the yellow circles.
ability seen in adjacent rocks. At the landing site and Yellowknife Bay, the soils are remarkably redder and have deeper L1 (527 nm) band depths than the rocks, a trend that reverses later in the traverse. At low elevations, the L1 (527 nm) band depth, L3/2 (751 nm/445 nm) ratio, and L6/L3 (1012 nm/751 nm) ratio parameters increase from the landing site through the Bradbury Group and into the lower Mount Sharp Group members. At elevations above −4,450 m (in the Karasburg member and above), these parameters remain low, including in regions where the rock spectra vary considerably in the Sutton Island, Pettegrove Point and Jura members. Anomalously low L6/L3 (1012 nm/751 nm) ratios are seen at specific elevations within the Hartmann’s Valley (−4,430 m) and Sutton Island members (near −4,300 m), corresponding with Curiosity’s exploration of the Bagnold Dune field in these locations. The low red/blue ratio and L6/L3 (1012 nm/751 nm) ratios at these elevations are spectrally consistent with olivine (see Section 4).

The L5 (867 nm) band depth in soils is less variable than other parameters across the full traverse (Figure 13), with values restricted between −0.04 and +0.05 (compared to the range of −0.06 to +0.17 in rock spectra). At lower elevations, this band depth parameter is slightly negative, then slightly positive from the Karasburg to Pettegrove Point members, after which values are near zero. In the Blunts Point and Jura members, where the deepest L5 (867 nm) band depths are observed in rock spectra, the soils consistently have flat NIR profiles (e.g., Figure 13).

### 3.3. Influence of Atmospheric Opacity

To investigate the potential influence of atmospheric events on the spectral trends presented above, we searched for correlations between atmospheric dust opacity (tau) and a variety of spectral parameters. Figure 14 shows the “redness” as the L3/L2 (751 nm/445 nm) ratio for dusty soil and rock spectra across the traverse (which should be less spectrally variable than disturbed soils, DRT targets and drill fines, due to the masking effects of dust), with regions highlighted where tau exceeded 1.0. If redder illumination from atmospheric dust loads had influenced Mastcam spectra, we would expect to see enhanced reddening in the spectra of both soils and rocks during high-tau periods. However, we do not observe increased L3/L2 (751 nm/445 nm) ratios corresponding to the high-tau excursions, including the Mars Year 34 (2018) global dust storm.

The 2018 dust storm originated around sol 2060, reached Gale crater 15 sols later, and did not decline to climatological values until ~sol 2157 (Guzewich et al., 2019). Dust storms of this magnitude periodically sweep the surface of Mars, and during the preceding 2007 event, MER Opportunity observed albedo increases in Pancam’s...
broadband (L1 filter) observations due to the resulting redder illumination conditions (Rice et al., 2018). However, the Mastcam observations acquired during similar high-tau conditions were not systematically brighter or redder than during low-tau periods (Figure 14), suggesting that Mastcam's radiometric calibration mitigates the influence of redder illumination. Comparisons of spectra of the same rock targets before and after the dust storm also show no significant changes (Jacob et al., 2020). These observations provide confidence that the observed variations in soil and rock spectra, as discussed in Sections 3.1 and 3.2 above, are due to real compositional variations.

3.4. Principal Components Analysis

Table 5 summarizes results of the PCA for rock and soils. In the resulting principal component (PC) coordinate spaces, the greatest variance lies along the first principal component (PC1), the second greatest variance lies along PC2, etc. The majority of spectra have low values of all PCs, and spectra with the highest versus lowest PC values are representative of the spectral characteristics that define the highest-order variability of the data set. Below we discuss the characteristics of spectral endmembers identified in these analyses (Table 5), which we use to help identify spectral classes (as discussed in Section 4.1).

3.4.1. Rocks

In our rock analysis, 72% of the variance lies in PC1, 18% in PC2, 6% in PC3, 2% in PC4, and 2% in all remaining components (Table 5). Coordinate spaces for the first four components are shown in Figure 15, with each point representing a single rock spectrum from the database, color-coded by stratigraphic member. Some trends with lithology are immediately apparent: the Stimson DRT targets and drill fines are distinct from the rest of the data set in PC1 versus PC2, and have positive values of PC3. Also, the Kimberley DRT targets and drill fines all have negative values of PC3 and positive values of PC4, distinct from the rest of the data set.

![Figure 14. Comparison of atmospheric dust opacity (tau) to the redness of dusty rocks and soils across the traverse. Above: tau versus sol, showing the MY34 global dust storm as the spike around sol 2060. Below: 751 nm/445 nm ratio for dusty rocks and undisturbed soils across the traverse. Gray regions indicate sol ranges where tau > 1.0.](image-url)
Figure 16 includes examples of spectra with minimum and maximum component values for PCs 1–4. Based on these representations, PC1 corresponds to the overall “redness” of rock spectra, and the distinguishing metric for these spectra is the L3/L2 (751 nm/445 nm) ratio. PC2 characterizes the peak NIR position, which occurs closer to 751 nm in the maximum PC2 examples and longward of 900 nm in the minimum PC2 examples. The brightness of the blue filters contributes to this component as well, as the minimum PC2 values all have high reflectance values at 445 and 438 nm. We find these short wavelength “upticks” exclusively in drill fines (see minimum PC2 and maximum PC1 examples), and they may be related to previously-reported “blue artifacts” of unknown origin (Wellington et al., 2017).

The maximum and minimum examples of PC3 (Figure 16) show that this component is related to the shape of the NIR profile: the maximum PC3 examples have the strongest L5 (867 nm) absorption bands, while the minimum PC3 examples have convex NIR profiles (negative L5 (867 nm) band depths). The spectral contributors to PC4 are difficult to identify in their end member spectra, although the spectra in the maximum versus minimum PC4 examples share common positions for peak NIR reflectance at L3 (751 nm) versus R3 (805 nm), respectively.

### 3.4.2. Soils

In our soil analysis, 79% of the variance lies in PC1, 13% in PC2, 3% in PC3, 2% in PC4, and 3% in all remaining components (Table 5). Coordinate spaces for the first four components are shown in Figure 18, with each point representing a single rock spectrum from the database color-coded by elevation. The component space for PC2 versus PC1 shows clear trends with elevation: spectra from soils at the very lowest elevations have the smallest PC1 values. Soil spectra from a broader range of elevations below −4,400 m have low PC3 values, and those

### Table 5

Principal Components of Rock and Soil Spectra, With Observations From Which the Maximum and Minimum PC Examples in Figures 16 and 20 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>Rocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>72.06</td>
<td>Overall redness (751 nm/445 nm ratio)</td>
<td>Big Sky Post Sieve Pile (sol 1138); Quoddy Quimby (sol 1608); Lubango Full Drill (sol 1321); Greenhorn Full Drill (sol 1138)</td>
<td>Perry (sol 1610); Quoddy Quimby (sol 1608); Ailsa Craig Drill Tailings (sol 2123); Belle Lake DRT (sol 1587)</td>
</tr>
<tr>
<td>2</td>
<td>17.84</td>
<td>Relative blue reflectance (527 nm/445 nm ratio); position peak NIR reflectance between 751 and 937 nm</td>
<td>Sutton Island Manset (sol 1524); Zephyr Ledges (sol 1790); Benbecula (sol 1964)</td>
<td>Confidence Hills Drill Tailings (sol 762); Confidence Hills Dump Pile (sol 782); Oudam Drill Tailings (sol 1363); Inverness Drill Tailings (sol 2171)</td>
</tr>
<tr>
<td>3</td>
<td>5.91</td>
<td>867 nm band depth and 527 nm band depth</td>
<td>Walls Peninsula Stereo (sol 2007); Britt Stereo (sol 2036); Voyageurs Drill Tailings (sol 2113); Woodhill (sol 2255); Stranraer DRT (sol 2007)</td>
<td>Gariep (sol 1314); Meob DRT (sol 1349); Askival (sol 2016); Windjana DRT (sol 626)</td>
</tr>
<tr>
<td>4</td>
<td>1.62</td>
<td>Position of peak NIR reflectance at 751 versus 805 nm</td>
<td>Windjana Dump Pile (sol 705); Seely (sol 999); Durness Stereo (sol 1996); Sutton_Inlier (sol 174)</td>
<td>Blinkberg Stereo (sol 1850); Gometra (sol 2259); Marinha Drill Tailings (sol 1421)</td>
</tr>
<tr>
<td>Soils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>79.35</td>
<td>Overall redness (751 nm/445 nm ratio)</td>
<td>Ekwr (sol 150); Wernecke (sol 172); John Klein Dill Tailings (sol 183); Pearson (sol 66)</td>
<td>Kobabeb Dump Pile (sol 1229); Hildreths (sol 1637); Zephyr Ledges (sol 1790); Hoanib (sol 1182)</td>
</tr>
<tr>
<td>2</td>
<td>13.23</td>
<td>Position of peak NIR reflectance at 751 versus 805 nm; concavity of NIR profile</td>
<td>Matagamon (sol 1603); Ogunquit (sol 1652); Greening Island (sol 1571)</td>
<td>Kubib (sol 1183); Aubures (sol 1368); Ile Damour (sol 1749)</td>
</tr>
<tr>
<td>3</td>
<td>3.31</td>
<td>638–805 nm concavity; filter-to-filter NIR variability</td>
<td>Duck Brook Bridge DRT (sol 1682); Winter Harbor DRT (sol 1737); Fort Brown DRT (sol 1876); Belle Lake DRT (sol 1587)</td>
<td>Jemtland (sol 1608); Mark Island (sol 1729); Inverness (sol 2217); Telegraph Peak Tailings (sol 909)</td>
</tr>
<tr>
<td>4</td>
<td>2.14</td>
<td>527 nm band depth; 908 nm band depth</td>
<td>Broad Cove (sol 1703); Fernald Point wheel track (sol 1728); Long-dist VRR (sol 1745); Eddie Brook (sol 1688)</td>
<td>Goulburn (sol 13); Copper Canyon wheel track (sol 728); Hoanib (sol 1182)</td>
</tr>
</tbody>
</table>
Figure 15. Principal component plots for rocks in the multispectral database. Large circles are low-dust surfaces (drill fines, DRT targets and broken rocks), and small circles are dusty rocks. Colors indicate formations within the Bradbury Group (Yellowknife Bay, Kimberley and others) and Mt. Sharp Group (Stimson and Murray).
Figure 16. Example rock spectra with maximum and minimum values of each of the first four principal components. Observation details provided in Table 5.
with the highest PC4 values are from elevations above -4,300 m. Spectra from soils on Vera Rubin ridge, at the highest elevations in the data set, mostly have values near zero for all PCs.

Figure 19 shows examples of spectra exhibiting minimum and maximum component values for PCs 1–4. Based on these representations, PC1 corresponds to overall “redness” of soil spectra (similar to PC1 for rock spectra), as characterized by large L3/L2 (751 nm/445 nm) ratios versus flat spectral profiles. PC2 relates to the position of the peak NIR reflectance (closer to 751 nm for maximum PC2 vs. 805 nm for minimum PC2) and the concavity of the NIR profile. The contributing spectral features to PCs 3 and 4 are less clearly identified from maximum and minimum end member spectra. PC3 may be related to the concavity of the NIR profile between 638 and 805 nm and a “sawtooth” pattern in the NIR bands (likely an artifact from joining the left- and right-Mastcam spectra, see Section 2.7). PC4 may be related to the L1 (527 nm) band depth and R4 (908 nm) band depth (exemplified in example spectra from Goulburn for minimum PC4).

4. Discussion

4.1. Mastcam Spectral Classes

4.1.1. Rock Classes

Synthesizing the results above, we propose nine major spectral classes for rock targets within the Mastcam multispectral database (Table 6). Figure 20 shows type examples of these rock spectral classes, with class names given for notable rock targets (either DRT targets, drill targets, or the first target of the class that Mastcam observed). Class numbers correspond to the prevalence of spectra in our database. The most common spectral class across the traverse is Class 1 (Neutral/Dusty), characterized by moderate to large red ratios and flat NIR profiles. These spectra do not have any of the extreme endmember spectral characteristics of the PCs in Figure 16. The redder Neutral/Dusty Class spectra are consistent with dust (e.g., see the nanophase hematite spectrum in Figure 6), and the variability of spectra within this class likely corresponds to different amounts of dust cover above rock surfaces with generally featureless NIR spectra. Thus, the Neutral/Dusty Class includes rocks with a range of compositions and origins. In addition to very dusty surfaces, some spectra of dust-cleared rocks and drill fines from each stratigraphic member fall into this class as well, including all DRT targets within the Stimson formation. Spectra of fracture-filling, Ca-sulfate veins, which are high-albedo with generally flat NIR profiles and red VIS profiles (e.g., Figure 12), fall within the Neutral/Dusty class as well.

Class 2 (Marimba) spectra are defined by moderate red ratios and weak absorptions at L5 (867 nm), consistent with varying contributions of hematite and/or other Fe-oxides. Class 3 (Sutton Island Manset) spectra are associated with dark diagenetic features, one of three spectral types within Sutton Island noted by Haber al. (2020) (the other two of which, based on our classification schemes, would be grouped within the Marimba and Hexriver Classes identified here). Class 4 (Hexriver) spectra exhibit the strongest L5 (867 nm) and L1 (527 nm) band depths, consistent with red fine-grained hematite. These four most abundant classes encompass the majority of rock spectra within the Sutton Island member and at higher elevations in the traverse.

At lower elevations, Mastcam observed several spectral classes that are largely confined to specific stratigraphic members and have rarely been encountered since. Class 5 (Windjana Class) targets include dark rocks and drill fines in the Kimberley formation, where Mn-oxides occur as subparallel fracture fills (Lanza et al., 2016). These dark oxides are the likely cause of this class’ defining spectral characteristics (Table 6), most notably the straight, flat to positively sloping profiles out to 908 nm. Class 6 (Big Sky) spectra are remarkably flat across the full Mastcam wavelength range. The predominant targets within this class are drill fines within the Stimson formation, corresponding to sandstone rock interiors with little Fe-oxides. Class 7 (Glenelg) spectra are characterized by flat and positively-sloping NIR profiles.

Class 8 (Lebanon) includes candidate meteorites, as defined by their positively sloping spectral profiles across the full wavelength range (as defined by the parameters shown in Figure 13). The meteorites detected by Curiosity are dominantly iron-nickel and stony iron types, which may be more abundant, more resistant to erosion, and/or more easily spotted than chondritic meteorites (Wellington et al., 2018). Stony meteorites may also not be spectrally distinguishable from other rocks in Gale crater, and if present may be lumped into another of the rock spectral classes. The least abundant rock spectral class, Class 9 (Confidence Hills), is specific to drill fines
Figure 17. Principal component plots for soils in the multispectral database. Large circles are disturbed surfaces (e.g., wheel tracks), and small circles are dusty soils. Color scale indicates elevation along the traverse, with lighter shades corresponding to lower in the stratigraphic section (earlier in the mission), and darker shades corresponding to higher in the section (later in the mission). Labeled points indicate spectra included in Figure 19.
Figure 18. Example soil spectra with maximum and minimum values of each of the first four principal components. Observation details provided in Table 5.
and DRT targets near Confidence Hills. We identified this class as distinct from other spectra by their minimum values of PC2, which are defined by large L2 (527 nm) band depths and flat NIR profiles.

The spectral parameters that best separate these classes are the L5 (867 nm) band depth and the L6/L3 (1012 nm/751 nm) ratio. Figure 20b shows the distribution of all rock spectra in this parameter space, with regions that each rock class occupies shown in 21c. Note that the defining spectral characteristics of Class 6 (Big Sky) and Class 9 (Confidence Hills) are not captured by these parameters, so they overlap with the Class 1 (Dusty/Neutral) region in this parameter space. In comparison to the distribution of convolved laboratory spectra in this parameter space (Figure 21a), we interpret that Class 3 (Sutton Island Manset) spectra are most consistent with nontronite and/or olivine phases, Class 5 (Hexriver) spectra are consistent with red hematite, and reaffirm that Class 8 (Lebanon) spectra are consistent with iron meteorites. We note that no rock spectra in the database fall within the lower left corner of this parameter space, indicating that no spectral class is dominated by clinopyroxenes or other phases with convex NIR profiles.

The distribution of spectral classes with elevation (Figure 21) reveals that some—but not all—spectral rock classes are associated with specific formations in the stratigraphy. The Neutral/Dusty Class is the only class that Curiosity has encountered at nearly every elevation interval; this is unsurprising, given that this class lumps together a variety of feature types (e.g., dusty rocks, DRT targets, diagenetic veins) and compositions that lack distinguishing spectral characteristics to Mastcam. The Lebanon Class occurs at punctuated elevation intervals, and indeed we would expect a seemingly-random distribution of iron meteorites throughout the stratigraphy. The remaining seven rock classes, however, tell a story of changing spectral characteristics across Curiosity's traverse.

Figure 19. Representative spectra from each of the nine rock spectral classes. Spectra are from observations listed in Table 6.
Collectively, these correlations with stratigraphy show that many of the rocks that Curiosity studied within the Bradbury Group are spectrally distinct from those of the Mt. Sharp Group; the Fe-oxides influencing the positively-sloping NIR profiles of the Glenelg Class spectra are different from those causing the pronounced L5 (867 nm) bands in the Marimba and Hexriver Classes (red hematite). Within the Mt. Sharp Group, the Stimson formation drill tailings lack any spectral indication of Fe-oxides and are spectrally distinct from the Murray formation drill tailings and other rocks. The confinement of the Hexriver Class to the Sutton Island, Pettegrove Point and Jura members of the Murray formation indicates that rocks in these intervals are most strongly influenced by the presence of fine-grained red hematite (which is also supported by CRISM observations; Fraeman, Johnson, et al., 2020). Within the Sutton Island member, the predominance of the Sutton Island Manset Class at some elevations indicates an increasing influence of dark, possibly nontronite-bearing diagenetic features (Haber et al., 2020), which return in Blunts Point.

<table>
<thead>
<tr>
<th>Class</th>
<th>Name</th>
<th>Short description</th>
<th>Defining spectral characteristics</th>
<th>Type examples</th>
<th>Distribution</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Neutral/dusty</td>
<td>Red, flat NIR profile</td>
<td>Moderate 751 nm/445 nm ratios; Small values of 1012 nm/751 nm ratio; Flat NIR profiles</td>
<td>sol 183, mcam00993</td>
<td>Consistent throughout the traverse</td>
<td>Variable amounts of dust upon rocks with neutral spectra</td>
</tr>
<tr>
<td>2</td>
<td>Marimba</td>
<td>Red, shallow 866 nm band</td>
<td>Large 751 nm/445 nm ratios; Small values of 1012 nm/751 nm ratio; Positive 867 nm band depths</td>
<td>sol 1425, mcam07034</td>
<td>Prevalent in the Murray formation, mostly above the Hartmann's Valley member</td>
<td>Rocks bearing some red hematite and/or nontronite</td>
</tr>
<tr>
<td>3</td>
<td>Sutton Island Manset</td>
<td>Gray, Negative NIR slope</td>
<td>Peak reflectance at 751 nm; Small 1012/751 nm ratios; Positive 867 nm band depths</td>
<td>sol 1524, mcam0770</td>
<td>Primarily within the Sutton Island member</td>
<td>Dark, diagenetic features, possibly nontronite-bearing</td>
</tr>
<tr>
<td>5</td>
<td>Hexriver</td>
<td>Red, deep 866 nm band</td>
<td>Large 867 and 527 nm band depths</td>
<td>sol 1885, mcam09853</td>
<td>Mostly within the Sutton Island and Jura members, with significant local variability</td>
<td>Strongly diagenetically-altered rocks containing red hematite, nontronite and/or ferric phases</td>
</tr>
<tr>
<td>5</td>
<td>Windjana</td>
<td>Gray, convex NIR profile</td>
<td>Straight, flat to positively sloping profiles to 908 nm; 908 nm/1013 nm &lt; 1.0</td>
<td>sol 626, mcam02676</td>
<td>Primarily within the Kimberley formation and Pahrump Hills member</td>
<td>Rocks with variable contributions of dark Fe- and/or Mn-oxides</td>
</tr>
<tr>
<td>6</td>
<td>Big Sky</td>
<td>Gray, flat NIR profile</td>
<td>1012 nm/751 nm ratios close to 1.0; blue/red ratios positive or close to 1.0</td>
<td>sol 1120, mcam04990</td>
<td>Drill fines, mostly within the Stimson formation</td>
<td>Rock interiors with minimal spectrally neutral phases (e.g., crystalline SiO2, magnetite)</td>
</tr>
<tr>
<td>7</td>
<td>Glenelg</td>
<td>Red, positive NIR slope</td>
<td>Large 751 nm/445 nm ratios; Positive 1012 nm/751 nm ratios; no 867 nm band depth</td>
<td>sol 069, mcam00486</td>
<td>Only seen within the Bradbury Group</td>
<td>Thick dust cover on rock surfaces</td>
</tr>
<tr>
<td>8</td>
<td>Lebanon</td>
<td>Gray, positive VIS and NIR slope</td>
<td>1012 nm/751 nm ratios &gt;1.1; 741 nm/527 nm ratios 1.0–2.0</td>
<td>sol 640, mcam02718</td>
<td>Isolated float rocks, found sporadically at all elevations</td>
<td>Iron meteorites</td>
</tr>
<tr>
<td>9</td>
<td>Confidence Hills</td>
<td>Gray, peak at 908 nm</td>
<td>Large 527 nm band depth; flat NIR profile</td>
<td>sol 758, mcam03257</td>
<td>Only seen within the Pahrump Hills member</td>
<td>Dark Fe-oxide, possibly coarse-grained hematite</td>
</tr>
</tbody>
</table>

Table 6
Summary of Rock Spectral Classes
4.1.2. Soil Classes

Based on PCA and spectral parameter analyses, we have identified five spectral classes of soils in the multispectral database. Type examples of these classes shown in Figure 22, and their spectral characteristics are summarized in Table 7. Classes are numbered in order of decreasing “redness” (Class 1 having the largest L3/L2 (751 nm/445 nm) ratios), and class names are given for the region of the traverse where each soil class is most prevalent. Class 1 (Yellowknife Bay) soil spectra are also distinct in their positively-sloping NIR profiles, which are consistent with Fe-oxides. While similar to Goulburn Class soil spectra (Figure 22), the Yellowknife Bay Class soil spectra are generally redder (larger L3/L2 (751 nm/445 nm) ratios) and have larger L6/L3 (1012 nm/751 nm) ratios. Class 2 (Bradbury) spectra are characterized by flat NIR profiles, similar to the Dusty/Neutral Class of rock spectra, but generally redder in VIS wavelengths. These spectra are consistent with nanophase hematite (e.g., Figure 5).

Class 3 (Goulburn) spectra are red and defined by prominent R4 (908 nm) band depths, and L6/L3 (1012 nm/751 nm) ratios close to 1.0, consistent with orthopyroxene spectra (e.g., Figure 5) or some clinopyroxenes (e.g., pigeonite). Goulburn Class spectra only occur at the Bradbury Landing, within the scour marks where soil was disturbed by the retrorockets during the landing event, which generated significant local winds and mobilization of surface fines, extreme temperatures, and contamination by hydrazine exhaust. The unique soil spectra here may result from the landing event having cleared dust from the surface soils, potentially revealing the pyroxene signature of dust-free grains. This seems unlikely, however, given that we do not see the R4 (908 nm) band depth in any other low-dust, disturbed soils (e.g., wheel tracks) along the traverse. Alternative explanations are that the extreme heating resulted in highly localized mineralogic phase changes and/or differences in the IOF calibration for these earliest observations of the mission (which were the only ones to use images of a near-dust-free calibration target). Throughout most of the traverse, Class 4 (Mt. Sharp) is the most prevalent class of soil spectra. These are less red than the Bradbury class, with flat to slightly negatively sloping NIR profiles (L6/L3 (1012 nm/751 nm) ratios ≤1.0). Class 5 (Bagnold) soil spectra are dark gray with low L6/L3 (1012 nm/751 nm) ratios and concave NIR profiles. This class includes soils within and near the Bagnold Dune Field, a collection of dark, active mafic sands (Rampe et al., 2018).

We have identified two parameter spaces that best distinguish the soil classes: (a) those that clearly separate Fe-oxide from other minerals (redness vs. L1 (527 nm) band depth; Figure 23) and (b) those that broadly separate olivines and pyroxenes from other minerals (L6/L3 (1012 nm/751 nm) ratio versus L3/L4 (751 nm/676 nm) ratio; Figure 24). In both parameter spaces, the full data set of soil spectra falls on a mixing line, with soils from early in the traverse toward the upper right (light-toned symbols) and soils from near the Bagnold Dunes in the lower left. Figure 24c shows the distribution of soil spectral classes in the “olivine” parameter space, ordered from 1 to 5 in the upper-right to lower-left. The only class that does not occupy a unique region in this space is the Goulburn Class, which overlaps with the Bradbury and Mt. Sharp Classes (which both have L6/L3 (1012 nm/751 nm) ratios close to zero). We interpret that the vast majority of the spectral diversity among soils in Gale crater, therefore, is due to the relative contributions of olivine-bearing sands versus Fe-oxides from airfall dust and/or other sources.
We observe distinct trends in distributions of these soil classes with elevation across the traverse (Figure 25). At the lowest elevations, within the Yellowknife Bay formation, the soil spectra are dominated by the Yellowknife Bay and Bradbury Classes, which are the most red and most consistent with large contributions of Fe-oxides. Across the rest of Curiosity’s traverse in the Bradbury Group, the Bradbury Class spectra are most prominent (with the exception of the landing site at −4,501 m, which is the only location with Goulburn Class soils). The Mt. Sharp Class becomes increasingly more frequent after the contact with the Mt. Sharp Group strata and is the dominant soil spectral class at most higher elevations.

Near the two locations where Curiosity investigated the Bagnold Dune sands (a two-part campaign at elevations indicated in Figure 25), we observe the Bagnold Class spectra at targets within the Bagnold Dunes themselves, and at other dark soil deposits which likely have contributions of the dune sands. Seelos et al. (2014) identified variations in CRISM mafic mineral signatures at the Bagnold Dunes attributed to variable contributions of olivine and high-calcium pyroxene and showed that these spectral variations correlate with dune type and grain sorting (especially olivine enrichment on the upwind margin of the dune field). These observations were corroborated by Curiosity’s observations of the dune field, where it found that the zones of stronger olivine signatures were qualitatively correlated with zones of inferred lower dust cover and higher rates of sand motion (Lapotre et al., 2017).

The Bagnold Class is the only soil spectral class observed at the base of Vera Rubin ridge (immediately below the Pettegrove Point member), suggesting that the dark soils at this location are related to the Bagnold Dunes, and may be active aeolian deposits trapped against the base of the ridge. At a high level, these observations suggest that soils encountered early in the mission were largely inactive and spectrally dominated by dust and/or other Fe-oxides, whereas those later in the traverse are significantly less red and are spectrally dominated by contributions from the active, mafic dune fields.

Figure 21. Distribution of rock spectral classes with elevation across Curiosity’s traverse (omitting the Neutral/Dusty class, which is included in Figure S6 in Supporting Information S1). Data are binned to 10 m elevation intervals. Percentage values indicate proportions of rock spectra belonging to each class within the elevation bin (numbers of spectra provided in Table S4 in Supporting Information S1).
4.1.3. Caveats

We acknowledge several limitations in our approach to define the spectral classes outlined above. Binning spectra into classes is a matter of judgment, and what we present here are not unique solutions for the data set. There are degrees of variability lumped within each of our proposed classes, which could be reasonably split into subclasses. We also recognize that these classes are not exhaustive; there may be other spectral classes that are not included here because they were not included in our ROI selections (e.g., very small-scale features) or were only encountered once along the traverse.

Our database of end-member spectra is representative of the color diversity within each observation, but it also is not exhaustive. There may be spectrally distinct materials that have been overlooked because they do not appear distinct in the false-color and/or DCS composites used to identify the end-members. Our approach relies on a geologically trained human eye to identify the distinct color end members that are also geologically distinct, but judgment calls are often required, so we introduce biases associated with human error, training, and convention. An algorithm could perhaps be trained to identify such end-members, and similar attempts have been successful for novelty detection in Mastcam multispectral data (e.g., Kerner et al., 2020) and for identifying geologically-distinct materials in Navcam imagery (e.g., Francis et al., 2017). The training and implementation of such techniques is beyond the scope of this effort but will be explored in future work.

Figure 22. Representative spectra from each of the five soil spectral classes. Spectra are from observations listed in Table 7.
4.2. Comparison to Pancam Multispectral Observations

The Pancam multispectral stereo imaging systems (Bell et al., 2003) provided VNIR spectra of rocks and soils across the MER Spirit and Opportunity traverses. Farrand et al. (2006, 2008, 2013) established spectral classes of rocks at both sites using a combination of PCA, clustering techniques, and spectral parameters (e.g., band depths at 535, 864, and near 900 nm, visible and near-infrared spectral slopes, and peak reflectance positions). For Spirit, Plains Basalts rocks were interpreted to be among the least altered based on weak 535 and 904 nm band depths, low albedo, and relative reflectance maxima near 673 nm, whereas those from West Spur and Watchtower classes in the Columbia Hills were the most altered (strong 535 nm band depths, with convex spectral shapes near 600 nm). Variations in the peak reflectance position and absorptions centered near 900–930 nm suggested variations in pyroxene contents across the Husband Hill region. At Home Plate, the presence of an upturn from 934 to

| Table 7 | Summary of Soil Spectral Classes |
|---|---|---|---|---|---|---|
| Class | Name | Short description | Defining spectral characteristics | Type examples | Distribution | Interpretation |
| 1 | Yellowknife Bay | Red, positive NIR slope | Large 751 nm/445 nm ratios; Large 527 nm band depths; Large 1012 nm/751 nm ratios | Pearson, sol 66, mcam00478 | Only seen near the landing site and in Yellowknife Bay | Strong influence of nanophase Fe-oxides and/or red hematite |
| 2 | Bradbury | Red, flat NIR profile | Large 751 nm/445 nm ratios; 1012 nm/751 nm ratio close to 1.0 | Sparkle, sol 514, mcam02022 | Prevalent throughout the Bradbury Group after leaving Yellowknife Bay | Spectra dominated by dust |
| 3 | Goulburn | Red, 908 nm band | Large 751 nm/445 nm ratios; 1012 nm/751 nm ratios close to 1.0; Large 908 nm band depth | Goulburn, sol 013, mcam00012 | Only seen within scour marks at Bradbury Landing | Disturbance due to landing event |
| 4 | Mt. Sharp | Gray, flat to negative NIR slope | Small 751 nm/445 nm ratios; 1012 nm/751 nm ratio <1.0 | Benbecula, sol 1964, mcam10270 | Prevalent throughout the Mt. Sharp Group | Increasing contribution of mafic sand |
| 5 | Bagnold | Gray, strongly negative NIR slope | Peak reflectance at 751 nm; Small 1012/751 nm ratios; Positive 867 nm band depths | Ogunquit, sol 1652, mcam08558 | At and near the Bagnold Dunes | Olivine-bearing dark sands with very little dust |

Figure 23. Spectral parameters that distinguish Fe-oxides from other mineral phases are the 751 nm/445 nm ratio versus 527 nm band depth, shown for: (a) Laboratory spectra of minerals convolved to Mastcam bandpasses: ferrous alteration phases (green triangles); pyroxenes (purple diamonds); olivines and basaltic glass (purple squares); ferric alteration phases (orange diamonds); iron meteorites (black circles), and hydrated minerals (white circles). Full spectra shown in Figures 5 and 6. The gray shaded region in the upper right is only Fe-oxide minerals; (b) All Mastcam soil spectra, color coded by rover elevation, showing the interpretation of increasing Fe-oxide contributions in the upper right (changing grain sizes may also contribute).
1009 nm distinguished two classes, perhaps attributable to variations in thin dust coatings. Five major exposures of sulfate-rich soils were excavated by Spirit’s wheels from depths of ~10 cm, and their peak reflectances near 673 nm and variable absorptions near 800–900 nm indicated Fe-sulfates. Light toned soils and nodules containing near-pure amorphous silica compositions in the Eastern Valley of the Home Plate region were characterized by a negative 934–1009 nm slope attributable to hydration and/or hydroxylation (e.g., Rice et al., 2010).

Along the Opportunity traverse, two basic spectral units were found in the Burns formation. Yellow/buff-colored rocks exhibited larger 482–535 nm (and 535–601 nm) slopes compared to red/purple-colored outcrop. Ubiquitous hematite-bearing spherules exhibited strong 900 nm bands. Along the rim of Endeavor crater, distinct classes of dominantly basaltic rocks were characterized by variations in 535, 864, and/or 900 nm band depths related to differences in primary pyroxene mineralogy and surface oxidation state (hematite), with possible minor contributions from smectites or ferric sulfates. Dark red rock coatings with featureless Pancam spectral slopes were attributed to Mn-oxides, and other dark, featureless spectral slopes were observed for iron meteorites. Opportunity also observed light-toned veins with high Ca and S, as determined by the rover’s APXS, and with negative

Figure 24. The spectral parameters that best distinguish olivine from other mineral phases is the 1012 nm/751 nm ratio versus 751 nm/676 nm ratio, shown for: (a) Laboratory spectra of minerals convolved to Mastcam bandpasses: ferrous alteration phases (green triangles); pyroxenes (purple diamonds); olivines and basaltic glass (purple squares); ferric alteration phases (orange diamonds); iron meteorites (black circles), and hydrated minerals (white circles). Full spectra shown in Figures 5 and 6. The gray shaded region in the lower left is where olivine maps in this parameter space. The region bounded by the dashed line is that shown in (b–c); (b) All soil spectra, color coded by rover elevation; (c) Soil spectral classes (Table 7).
934–1009 nm slopes in Pancam spectra; together, these observations indicated that the veins are composed of gypsum. Light-toned coatings on the overturned rocks Pinnacle and Stuart Island had similar Pancam spectra as the veins but APXS showed enrichments in Mg and S, indicating hydrated Mg-sulfates such as kieserite (e.g., Farrand et al., 2016).

Comparing these to the Mastcam spectral classes defined in Section 4.1, we note that Pancam and Mastcam have observed materials with many similar spectral characteristics. Specifically, Mastcam's Neutral/Dusty, Marimba, Sutton Island Manset, Windjana, Lebanon and Confidence Hill rock classes have clear spectral analogs at the Spirit and Opportunity sites. We note differences between Mastcam's Hexriver Class spectra and the Pancam spectra of hematite-bearing rocks along the Opportunity traverse, as the Mastcam absorption at 867 nm is much narrower than the equivalent Pancam hematite feature. However, the hematite observed by Pancam was coarse-grained gray hematite (e.g., Farrand et al., 2016), while that observed by Mastcam has more fine-grained red hematite (e.g., Jacob et al., 2020) and is associated with other phases that can influence the shape of the 867 nm band (e.g., nontronite, jarosite and/or akageneite, as described in Section 4.3).

The Big Sky Class rock spectra observed by Mastcam are “bluer” than any rocks previously documented by Pancam; spectra with such high 445 nm reflectances and relatively flat VIS profiles were not observed at the Spirit or Opportunity sites. The Glenelg Class rock spectra also have no clear analogs in the Pancam data set. We also observe that multiple classes of Pancam spectra have not yet been seen by Mastcam; neither spectra with ~900 nm absorptions (consistent with Fe-sulfates) nor spectra with prominent ~1010 nm downturns (consistent with hydration and/or hydroxylation in amorphous silica, gypsum, or Mg-sulfates) have yet been observed by Mastcam in Gale crater.

Figure 25. Distribution of soil spectral classes with elevation across Curiosity's traverse. Data are binned to 10 m elevation intervals. Percentage values indicate proportions of the soil spectra belonging to each class within the elevation bin.
4.3. Comparison to APXS and CheMin Observations

DRT targets allow for a direct comparison of Mastcam spectra to APXS chemical compositions, with minimal obscuration by surface dust. In our Mastcam multispectral database (Rice, 2022), 73 spectra of DRT targets have been categorized as Neutral/Dusty Class, Marimba Class, Hexriver Class, Sutton Island Manset Class, Windjana Class, or Big Sky Class (no Glenelg Class, Lebanon Class, nor Confidence Hills Class rock spectra have been acquired from DRT targets). Comparing these to APXS elemental abundances from Thompson et al. (2016, 2020), we find that the rock spectral classes are not isochemical (Table 8). The total alkalis (Na₂O + K₂O) versus SiO₂ plot shows a spread of silica compositions within each class (Figure 26a). Unfortunately, we only have one DRT target example from each of the Sutton Island Manset Class and Big Sky Class rocks, and thus cannot evaluate the range of APXS compositions for these classes.

The finding that Mastcam spectral classes are not isochemical is not surprising, given that VNIR spectra are much more sensitive to secondary alteration minerals and iron oxidation than to TAS igneous rock compositions. Previous studies comparing Pancam spectral parameters to compositional data from the MER APXS compositions also found only weak correlations between these datasets (Anderson & Bell, 2013). In an examination of various APXS element oxides within each spectral class, we find that FeO and MnO provide the clearest distinctions between some classes (Figure 26b). While the Marimba Class and Neutral/Dusty Class rocks span a range values, the Hexriver Class rocks have consistently higher Fe and low Mn, while the Windjana Class rocks exhibit generally lower Fe and higher Mn. These trends are consistent with the Hexriver Class rocks containing more fine-grained red hematite, and the Windjana Class rocks being influenced by Mn-oxides (Table 6).

In all, the comparisons to APXS support an interpretation that the Mastcam spectral classes are distinguished primarily by small differences in red hematite and other oxides. Comparisons of Mastcam drill tailings spectra to CheMin mineralogy measurements from Rampe, Blake, et al. (2020) further support this interpretation. Although CheMin and Mastcam do not observe the exact same materials (CheMin samples are taken from ~2 to 6 cm beneath the surface, while Mastcam observes pulverized rock mixed from the full drill depth; Anderson et al., 2012), the comparisons provide useful constraints on the mineral phases that influence Mastcam spectra (e.g., Wellington et al., 2017). We have assigned Mastcam spectral classes to the drill tailings and/or dump piles associated with each CheMin sample (Table 9). Curiosity has not sampled targets with spectral characteristics of the Sutton Island Manset, Lebanon and Glenelg rock classes, nor the Yellowknife Bay and Goulburn soil classes.

Within specific Mastcam spectral classes, CheMin samples exhibit some key similarities in their mineralogies (Figure 27). Samples from the Marimba spectral rock class all contain abundant phyllosilicates (5–28 wt.%),

<table>
<thead>
<tr>
<th>Table 8</th>
<th>APXS Compositional Data From Thompson et al. (2016, 2020) Averaged for Each Mastcam Spectral Rock Class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neutral/dusty</td>
</tr>
<tr>
<td>N</td>
<td>28</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.60 ± 0.23</td>
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<tr>
<td>MgO</td>
<td>5.30 ± 0.92</td>
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<tr>
<td>Al₂O₃</td>
<td>9.13 ± 1.15</td>
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<tr>
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<tr>
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<td>Cr₂O₃</td>
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<td>MnO</td>
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</tr>
<tr>
<td>FeO</td>
<td>16.65 ± 4.23</td>
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</table>

Note. Number of APXS DRT targets within each Mastcam class are given as N. All compositions are reported wt. % (with standard deviation for targets with N > 1).
crystalline hematite (5–28 wt.%) and Ca-sulfates (3–12 wt.%), with low relatively abundances of pyroxenes (<5 wt.%) and negligible magnetite (<0.7 wt.%). In contrast, samples within the Windjana, Big Sky and Confidence Hills spectral rock classes all have significant concentrations of magnetite (3–18 wt.%), which likely contribute

Figure 26. Comparisons of Mastcam spectral classes from DRT targets to APXS elemental compositions from Thompson et al. (2016, 2020): (a) Total alkalis versus silica plot (Le Maitre et al., 2002); (b) Plot of FeO versus MnO, showing that Hexriver Class rocks are generally higher Fe and lower Mn, while Windjana Class rocks are typically lower Fe and higher Mn. High-Si targets associated with alteration halos are labeled.
to their flat NIR profiles in Mastcam spectra (Figure 5). The Big Sky Class is distinguished by a lack of phyllosilicates and, for some samples, significant amounts of crystalline SiO$_2$. The Rock Hall CheMin sample has low crystalline hematite (3 wt.%) compared to the other lacustrine mudstones within the Murray formation; however, Rock Hall drill tailings spectra are within the Hexriver spectral rock class, with the deepest 867 nm absorptions of all CheMin samples. These Mastcam spectra may be influenced by the akageneite and jarosite present in these rocks (Jacob et al., 2020), which also have absorptions centered near 867 nm (Figure 5).

The Neutral/Dusty Class of rocks is the only spectral class with a large diversity of CheMin mineral abundances (Figure 27). This heterogeneity is not unexpected, given that the generally red VIS slopes and flat NIR profiles that characterize Neutral/Dusty Class spectra can be attributable to many spectrally-neutral phases (e.g., Figure 5). The neutral spectrum of the Oudam drill tailings is distinct from the spectra of other Murray formation samples with similar mineralogies, which all have 867 nm absorptions and fall in the Marimba Class. Although Oudam had some of the highest crystalline hematite abundances of any CheMin sample (14 wt. %), this is likely coarser-grained gray hematite, and not the fine-grained red hematite seen elsewhere (Jacob et al., 2020). Compared to the Marimba Class rocks, the Oudam sample has relatively low abundances of other phases with 800–900 nm absorptions (nontronite, jarosite, akageneite), and is interpreted to have a different depositional environment (reworked aeolian and fluvial, as opposed to lacustrine) (Table 9).

The soil samples observed by CheMin are mineralogically similar (Rocknest, Gobabeb and Ogunquit Beach; Table 9), with larger abundances of olivine (10–17 wt.%) than observed in any rock samples. We note that the phyllosilicate in the Ogunquit Beach sample is from contamination in the CheMin funnel from the previous sample (Sebina) (Rampe, Blake, et al., 2020). The Rocknest soil was scooped from an inactive bedform, while

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>CheMin sample</th>
<th>Sol(s)</th>
<th>Formation</th>
<th>Depositional environment</th>
<th>Mastcam spectral class</th>
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<td>RN</td>
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<td>Windjana</td>
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<td>Hexriver</td>
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Table 9
Summary of CheMin Samples (Rampe, Blake, et al., 2020) and the Mastcam Spectral Classes Assigned to Their Associated Drill Tailings and/or Dump Piles
Figure 27. Mineral abundances of CheMin samples (Rampe, Blake, et al., 2020) grouped by Mastcam spectral class. Sample name abbreviations are defined in Table 9. Mastcam spectral classes are based on spectral features of the drill tailings and/or dump piles from each sample. Note that the phyllosilicate in the Ogunquit Beach (OG) sample is from contamination in the CheMin funnel from the previous sample Sebina (SB).
Gobabeb was scooped from an active ripple crest on the Namib Dune, and Ogunquit Beach was scooped from a ripple trough in the active Mount Desert Island sand patch. Other Curiosity measurements have shown that ripple crests concentrate olivine grains, while troughs concentrate felsic grains (e.g., Johnson et al., 2017), which is consistent with Gobabeb having a higher CheMin abundance of olivine and having Bagnold Class spectral properties. Rocknest has a similar olivine abundance as Gobabeb, but its Mastcam spectra are consistent with the Bradbury Class and do not exhibit the NIR slopes characteristic of olivine. The olivine in Rocknest and other soils from early in the traverse is likely masked in Mastcam spectra by the large amounts of dust on this inactive feature (Rampe, Blake, et al., 2020).

4.4. Implications for Erosion and Transportation of Sediments in Gale Crater

By comparing the spectral variations of soils and rocks across the traverse (Figure 14), and by examining the distributions of soil and rock spectral classes (Figures 21 and 25), we can test specific hypotheses about the origin of soils in Gale crater. If ongoing erosion of outcrops is contributing to the makeup of local soils, we would expect trends in spectral parameters for rocks and soils to parallel each other, which is not what we observe (Figure 17). If local mixing plays no part in soil composition, and if Gale crater soils are spectrally consistent with a “global Mars” soil and dust composition (e.g., Berger at al., 2016; Yen et al., 2005), we hypothesize that the soil spectral parameters would be near-uniform across the traverse, independent of rock spectral trends. We do not observe this pattern either, as soils do exhibit similar levels of spectral variability to the rocks, although with different trends (the exception being the L5 (867 nm) band depth, which has a much narrower spread of values than the rocks; Figure 17).

At the start of the traverse, where the Yellowknife and Bradbury Classes were encountered, the soil spectra were redder and had stronger L1 (527 nm) band depths than adjacent rock spectra, indicating increased levels of Fe-oxidation in soils relative to that observed on rock surfaces. These parameters likely correspond to large concentrations of dust in the soils near the beginning of Curiosity's traverse, consistent with CRISM data (Seelos et al., 2014) and dust cover indices from the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) (Ruff & Christensen, 2002), in-situ observations of inactive soils near the landing site (e.g., Minitti et al., 2013), and APXS observations of dust thicknesses on rock surfaces generally decreasing along the traverse (Schmidt et al., 2018). The elevated Fe-oxidation parameters decrease with elevation (Figures 17 and 25), and Mt. Sharp Class soils are consistently less red than the rocks, with consistently negative NIR profiles (L6/L3 (1012 nm/751 nm) ratios <1.0), with Bagnold Class soils representing the end member of these spectral characteristics, and also the highest olivine abundances in CheMin data (Figure 27). No soils observed within the Mt. Sharp Group share spectral characteristics of the Marimba or Hexriver Class rocks in the region. Although the Sutton Island Manset Class rocks are spectrally similar to Bagnold Class soils (both have reflectance maxima at 751 nm and negative NIR slopes), we do not interpret a direct relationship between these rocks and soils because Sutton Island Manset Class spectra are associated with diagenetically-altered intervals in Murray formation mudstones, which are volumetrically too small and also too fine-grained to be the source of the Bagnold Class sands. Furthermore, CheMin samples from Murray formation rocks indicate no olivine and little pyroxene, although these minerals are primary contributors in all soils observed by CheMin (Figure 27). Collectively, these observations imply that variable amounts of dark, mafic sands from the Bagnold Dunes—which are active in the modern aeolian environment—are the primary driver of spectral variability of soils throughout the Mt. Sharp Group. We find no spectral evidence for a contribution of sediments derived from local bedrock.

Erosion of local rocks in the modern environment is certainly ongoing, however, as evidenced by the prevalence of active sands (e.g., Baker et al., 2018; Day & Kocurek, 2016), wind-sculpted textures (e.g., Bridges et al., 2014), cobble- and pebble-sized float clasts with spectra equivalent to adjacent outcrop (Figure 16). However, the Mastcam spectra show no indication of sand-sized or finer grains derived from local rocks that are mixing with nearby soils, at any point in the traverse. This is not unexpected, however, as the most spectral variability in the rocks of both groups occurs within the mudstones (grayer spectra due to a lack of oxidation in the Yellowknife Bay mudstones, redder spectra due to fine-grained hematite and other ferric phases in the Murray mudstones), which erode into silt- to mud-sized grains that are more easily transported away by winds. Microscopic images of soils by the MAHLI instrument support the a winnowing of the find-sediment fraction (e.g., Minitti et al., 2013), and
CheMin measurements of soils show only trace amounts of hematite, Ca-sulfate, crystalline SiO$_2$ or other minerals likely to be sourced from adjacent Murray formation rocks (Rampe, Blake, et al., 2020).

If local bedrock is eroding into cobble- and pebble-sized float clasts, which are being left as a surface lag, we hypothesize that float rocks can predict lithologies at higher elevations, as we might expect to encounter the same materials in outcrops further up in the section. We can test this hypothesis by comparing trends in float rock spectra to those of in-place outcrop in the multispectral database. We do not observe clear instances of float rock spectral parameters preceding the same parameters in overlying outcrop spectra; however, we observe the reverse phenomenon in the Sutton Island member. At elevations near −4,330 m, outcrop spectra have 1012 nm/751 nm ratios that are lower than had been observed previously in the mission, indicating negatively-sloped NIR profiles, and defined above as the Sutton Island Manset Class. In subsequent Mastcam observations, from elevations near −4,310 m, a population of float rocks have this same NIR profile, although it is not seen in outcrop (Figure 16). This spectral class is associated with dark diagenetic features that are resistant to erosion (Haber et al., 2020), which may be the only parts of the overlying −40 m of Sutton Island rocks in the section that remain as a cobble-sized lag of float rocks at this elevation.

5. Conclusions

We compiled a comprehensive database of Mastcam spectra for sols 0–2302 and quantified spectral variations across Curiosity's traverse in Gale crater through Vera Rubin ridge. As part of this effort, we adopted a number of conventions for analyzing Mastcam spectra, including: revised L0 and R0 Bayer blue band center wavelengths of 481 and 483, respectively; scaling the left- and right-cameras to their average value of the L6 (1012 nm) and R6 (1013 nm) filters; calculating spectral parameters exclusively from left- or right-camera filters; and opting to quantify spectral parameters as ratios instead of slopes.

In comparing dust-cleared surfaces (DRT targets and drill fines) to dusty rocks surfaces, we find that dust consistently masks rock spectra, resulting in higher reflectance (especially at longer wavelengths), muted VIS absorption features, and redder spectra (larger 751 nm/445 nm ratios). However, the 867 nm band depth (which is consistent with fine-grained red hematite) is more consistent between dusty and dust-cleared surfaces within the same rock units; therefore, the 867 nm band depth in dusty rock spectra reflects the actual spectral signature of the underlying rock. We find no evidence for atmospheric opacity (tau) influencing Mastcam spectra of surface rocks and soils, giving confidence that observed spectral trends across the traverse indicate real mineralogic variations.

Based on PCA and an examination of spectral parameters across the entire traverse, we identified 9 rock spectral classes and 5 soil spectral classes. Rock classes are dominated by spectral differences attributed to hematite versus other oxides, and are mostly confined to specific stratigraphic formations, except for the Dusty/Neutral Class (seen everywhere) and the Lebanon Class (iron meteorites punctuated across the traverse). Soil classes fall along a mixing line between spectra dominated by fine-grained Fe-oxides and those dominated by olivine-bearing sands. Like the rock classes, soil classes occur in specific sections of Curiosity's traverse, with the reddest soils seen at the lowest elevations and darker, more mafic spectral signatures increasing with proximity to the Bagnold Dunes. The only soil spectral outlier class is the Goulburn Class, seen at Bradbury Landing, where the soils had been influenced by the landing event. Comparisons of rock and soil spectral trends have implications for the erosion of and transportation of sediments in Gale crater. The trends in soil spectra with elevation do not follow the trends observed in rock spectra, indicating that locally derived sediments are not significantly contributing to the spectra of soils. Rather, varying contributions of dark, mafic sands from the active Bagnold Dune field is the primary spectral characteristic of soils.

These spectral classes and their trends with stratigraphy through Vera Rubin ridge will provide a basis for comparison as Curiosity continues its ongoing ascent of Mt. Sharp. Based on orbital observations, which identified minerals such as Mg-sulfates and opaline silica at higher elevations along the traverse (Milliken et al., 2010; Sheppard et al., 2020), we anticipate that Mastcam will encounter new spectral classes of rocks and/or soils as Curiosity explores these units. While detecting hydrated minerals with Mastcam is challenging, given the spacing of its longest-wavelength filters, our analyses of laboratory spectra suggest that Mastcam spectra can distinguish between mono-hydrated versus poly-hydrated Mg-sulfate phases (e.g., kieserite vs. epsomite). Therefore, combined with chemical data from other Curiosity instruments, we expect that Mastcam spectra can play a key role interpreting mineralogy during the next stages of Curiosity's exploration.
Data Availability Statement

All of the Mastcam multispectral image data used in this manuscript are freely available through the Planetary Data System Cartography and Imaging Sciences node (https://pds-imaging.jpl.nasa.gov/volumes/msl.html). Our Mastcam multispectral database and ROI context images are available in Rice (2022).

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