Bagnold Dunes campaign Phase 2: Visible/near-infrared reflectance spectroscopy of longitudinal ripple sands

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Key Points:
- Bagnold Phase 2 sands exhibit higher 535 nm band depths and red/blue ratios, and lower 600/700 nm ratios than Bagnold Phase 1 sands
- Phase 2 sands contain a greater amount of redder, ferric materials, likely owing to minor hematite contamination from nearby bedrock
Abstract
As part of the Phase 2 Bagnold Dune campaign at Gale Crater, Mars, constraints on the geochemistry, mineralogy, and oxidation state of pristine and disturbed linear sand ripples were made using visible/near-infrared spectral observations for comparison to Phase 1 spectra of the barchan dunes to the north. Spectra acquired by the ChemCam and Mastcam instruments (400-1000 nm) at four Phase 2 locations revealed similar overall spectral trends between the two regions, but most Phase 2 sands were redder in the visible wavelengths. The majority of targets exhibited lower red/infrared ratios, higher ~530 nm band depths, and higher red/blue ratios than Phase 1 samples, suggesting a greater proportion of redder, fine-grained, ferric sands in Phase 2 samples. This is consistent with the slightly greater proportion of hematite in Phase 2 samples as determined from CheMin analyses of the Ogunquit sands, which may reflect contamination from the surrounding hematite-bearing Murray formation bedrock.

1 Introduction
Understanding the provenance and evolution of windblown sands on Mars requires a combination of regional and local analyses of their geochemical and mineralogical diversity. During Phase 1 of the Bagnold Dune campaign conducted by the Mars Science Laboratory Curiosity (Sols 1181-1254) the barchan dunes in the Namib and High Dune areas were investigated (Bridges and Ehlmann, 2018; Ehlmann et al., 2017). Phase 2 of the campaign (Sols 1601-1653) studied ripple fields and linear dunes in the Mount Desert Island and Nathan Bridges Dune regions 2 km to the south and ~100 m higher in elevation (Lapôtre and Rampe, 2018). Both campaigns acquired visible/near-infrared (400-1000 nm) reflectance spectra of pristine, disturbed, and sieved sands using Mast Camera (Mastcam) multispectral imaging (445–1013 nm) and Chemistry and Camera (ChemCam) passive point spectroscopy (400–840 nm). Johnson et al. (2017) reported that the Phase 1 dune sands were distinct from other martian dusty sands and typically exhibited low relative reflectance, weak ~530 nm absorption bands, an absorption band near 620 nm, and a decrease in spectral reflectance longward of ~685 nm. These characteristics were consistent with dominantly olivine-bearing sands, with likely contributions from high-calcium pyroxene (cf. Lapôtre et al., 2017). However, variations were observed between the finer and coarser-grained sands. Fine sands exhibited higher 535 nm absorption band depths and lower 600/700 nm spectral ratios, consistent with a combination of ferric materials (e.g., hematite, magnetite, nanophase and/or
amorphous oxides). Conversely, the coarsest grains (in ridge crests, lee slopes) were the darkest and bluest, with strong reflectance downturns in the near-infrared, higher 600/700 nm ratios (flatter spectra in this region) and near-zero 535 nm band depths, consistent with greater proportions of mafic silicate minerals.

We report here analyses of Mastcam and ChemCam reflectance data acquired during the Phase 2 campaign, which comprised four stops along the rover traverse (Figure 1). The first three of these stops (Mapleton, Sandy Point Beach, and Southern Cove) sampled locations on the eastern margin of Nathan Bridges Dune (Figures S1-S4). The fourth stop was on the western edge of Mount Desert Island at Ogunquit Beach (Figure S5), where scooped sands were sieved for onboard analyses (Rampe et al., 2018; Stern et al., 2018). The pre-sieved (>150 µm) and post-sieved (<150 µm) samples were kept onboard the rover until they were dumped on Sol 1968 and analyzed with Mastcam and ChemCam shortly thereafter (Figure S6).

2 Methodology

2.1 ChemCam passive spectra

The ChemCam instrument is used for laser-induced breakdown spectroscopy (LIBS) in which light from a laser-generated plasma is dispersed onto three spectrometers to detect elemental emission lines at high spectral resolution (< 1 nm) (Wiens et al. 2013, 2015). Relative reflectance spectra (400-840 nm) can be collected in passive mode (i.e., without using the laser) for each sunlit location to provide information on variations in ferrous and ferric components (Johnson et al., 2015, 2016, 2017). For materials near the rover (~2-7 m) the 0.65 mrad field of view of each point measurement sampled areas 1.3-4.5 mm. Each LIBS measurement included a 3 msec exposure passive (“dark”) measurement used to subtract ambient light from the LIBS spectrum. Because the laser shock wave creates pits in the sands, passive measurements shown here were acquired prior to its use to avoid pit shadows. Passive measurements at 30 msec exposures were acquired for specific targets to increase the signal to noise ratio (SNR). Data acquired on Sol 76 at 12:52 Local True Solar Time (LTST) of the white ChemCam calibration target holder were used to minimize dark current variations between scene and calibration targets. Raw data were converted to radiance (Johnson et al., 2015), with an estimated absolute 6-8% calibration uncertainty. The ratio of the scene and Sol 76 calibration target radiance was multiplied by the laboratory reflectance
of the calibration target material (Wiens et al. 2012) to provide relative reflectance. Images from the Remote Micro-Imager (RMI) were acquired to provide accurate positions for raster locations (Wiens et al. 2012, 2015; Maurice et al. 2012, 2016; Le Mouélic et al. 2015) (Figure S6).

We calculated spectral parameters using ±5 nm averages around a central wavelength. Near-infrared ratios (e.g., 600/700 nm) and peak reflectance wavelengths are indicative of the strength of iron absorptions from mafic minerals, and 600/440 nm (red/blue) ratios are sensitive to oxidation state and/or dust deposition. The 535 nm band depth (calculated using shoulders at 500 nm and 600 nm) is sensitive to the presence of crystalline ferric oxides (e.g., Morris et al. 1997, 2000; Bell et al, 2000).

2.1 Mastcam passive spectra

The Mastcam system includes two cameras (M100, 100 mm focal length; M34, 34 mm focal length) that use 1600x1200 pixel Bayer-patterned CCDs. Each uses 6 narrow band (±10 nm) filters to characterize the 445-1013 nm reflectance spectra of surface targets. One filter position has a broadband infrared-cutoff filter for RGB color imaging using a Bayer pattern bonded directly to the detectors (Wellington et al., 2016). The two cameras provide twelve center wavelengths for multispectral analysis, including the three RGB Bayer bands (which have ± 40 nm bandwidths). Wellington et al. (2017) and Bell et al. (2003, 2017) describe conversion of raw Mastcam data to radiance (W/m²/nm/sr) and to radiance factor (I/F) using observations of the onboard Mastcam calibration target (Kinch et al., 2015; Wellington et al., 2016; He et al. 1991; Bell et al. 2003). Radiance factors were divided by the cosine of the solar incidence angle to provide relative reflectance (R*), an approximation of the reflectance factor defined in Hapke (1993, 2012). Relative reflectance spectra presented here are average values derived from manually defined regions selected of the same region in the M34 and M100 images. M100 filter values were scaled to the left eye at the 1013 nm wavelength (which is least affected by uncertainties in the dust correction) and averaged with the M34 values at overlapping wavelengths to produce a combined spectrum. The absolute radiometric accuracy for Mastcam is estimated to be 10-20%, with a filter-to-filter uncertainty of <5% and pixel-to-pixel variation of <1% (Bell et al. 2003, 2017; Wellington et al. 2016).

Mastcam spectral parameters were calculated using wavelengths similar to the ChemCam spectral parameters. Parameters sensitive to ferric crystallinity, oxidation state
and/or dust deposition included the band depth at 527 nm (calculated using shoulders at 494 nm and 639 nm), the peak reflectance position, and the 639/446 nm ratio. Near-infrared parameters (676/751 nm ratio) are sensitive to mafic silicate minerals.

3 Data sets used

Table 1 lists the ChemCam and Mastcam data sets acquired at each Stop that were used in this analysis. At Stop 1, Mastcam observations were acquired of undisturbed and Alpha Particle X-Ray Spectrometer (APXS)-disturbed ripple sands at Matagamon, and two locations on pristine and rover wheel-disturbed sands in the Scarboro area (Figures S1-S2). ChemCam data were acquired at Mapleton. At Stop 2, Mastcam imaging at Macworth documented rover tracks and pristine sands (Figure S3), while ChemCam observations sampled the edge of a rover track (Macworth) and ripple crests (Towow, Leighton, Carrassett, Swanback). Between Stops 2 and 3 ChemCam observed the ripple crest Mattawamkeag. At Stop 3, Mastcam targeted the pristine and disturbed sands at Hildreths (Figure S4), while ChemCam observed disturbed sands at Greenvale Cove and the ripple crests Ripogenus (Figure S7) and Spragueville (acquired twice owing to shadows obscuring raster locations 7-10 during the first attempt). At Stop 4, Mastcam observed pristine and rover-disturbed sands near Ogunquit (Figure S5), and ChemCam acquired spectra on a rover scuff wall (Tumbledown Mountain), the base of that wall (Elephant Mountain) and on the scuff floor (Canoe Point). Undisturbed sand was observed at North Brother, and ripple crests of different sizes were sampled at Hamlin Peak (small), Avery Peak (medium), and Baxter Peak (large; Figure S7). Unused portions of the Ogunquit sand samples were kept onboard until Sol 1970, when the post-sieve (<150 μm) and pre-sieve (>150 μm) samples were dumped onto bedrock while the rover was on Vera Rubin Ridge (VRR) and analyzed by Mastcam and using dedicated passive and active ChemCam methods (Figures S6, S8-S10).

4 Results

4.1 ChemCam and Mastcam spectra

Representative Chemcam passive and Mastcam relative reflectance spectra from the four stops are shown in Figure 2. Spectral differences among disturbed, undisturbed, and ripple crest/trough sands are marked by changes in the visible spectral slope, maximum reflectance position, and the steepness of the near-infrared slope. These are due to variations in the relative abundance and/or grain size of mafic minerals (olivines, pyroxenes) versus finer-grained, more ferric, oxidized materials, particularly in the disturbed sands, modulated by the
effects of amorphous components (e.g., Achilles et al., 2017; Rampe et al., 2018). In the Mapleton and Towow areas, ChemCam spectra are typical of reddish sands observed elsewhere throughout the traverse (Johnson et al., 2015, 2016). The crest of the Ripogenus ripple exhibited reflectance maxima at shorter wavelengths than the flank, consistent with more ferrous materials on the crest (cf. Figure S7). The spectral shapes of nearby Spragueville sands were nearly identical to the Ripogenus flank. The Baxter Peak ripple target’s crest showed the strongest near-infrared downturn, consistent with more ferrous sands compared to the trough (cf. Figure S7). In enhanced Mastcam color images, the coarser disturbed sands in the Hildreths area appear bluish (Figure S4). The corresponding Mastcam spectra in Figure 2b show a maximum reflectance near 675 nm compared to a maximum reflectance position near 750 nm associated with redder sands of Macworth and Ogunquit. Similar shorter-wavelength maxima were observed for bluer regions at the Ogunquit area and the ripple crest target Scarboro in the Mapleton area. For comparison, redder sands in the troughs of scuff areas and flanks of ripples in the Scarboro area exhibited longer-wavelength maxima. In summary, ripple crests (e.g., Ripogenus, Baxter Peak, Scarboro) and collections of coarser grains in disturbed soils (e.g., Hildreths, Ogunquit) tend to exhibit reflectance peaks at shorter wavelengths, steeper near-infrared downturns, and weak to nonexistent ~530 nm band depths, consistent with more ferrous materials compared to the redder, more ferric ripple flanks or troughs.

The Ogunquit pre- and post-sieve dumped samples exhibited very similar ChemCam passive and Mastcam relative reflectance spectra (Figures 3, S6), with ~530 nm and 867 nm absorption bands in both samples. Nearby background sand exhibited similar Mastcam spectra, albeit with some variations in the strength of the 867 nm band. This is evident in the Mastcam 867 nm band depth image (Figure S8) in which the dumped samples and background sands are essentially indistinguishable. However, the 527 nm band depth images showed that the dumped samples were slightly brighter than the background sands (Figures S8-S10), and the decorrelation stretch images manifest this with more purple hues in the dump piles. This spectral behavior suggests a greater proportion of ferric oxides in the Ogunquit sieved sands. Rampe et al. (2018) discuss the possible contamination of this sample by remnants of the previously drilled, hematite-rich sample Sebina. However, they
did not estimate hematite contamination and concluded from Chemistry and Mineralogy (CheMin) data that minor (1.2 wt%) hematite is likely present in the crystalline+amorphous portion of the Ogunquit < 150 μm sample.

4.2 Spectral parameters
Spectral parameters computed from ChemCam spectra are shown in Figure 4, where the 600/700 nm (red/infrared) ratio is compared to the 535 nm band depth and 600/440 nm (red/blue) ratio. Parameters from representative Phase 1 targets are shown for comparison (square symbols). Phase 2 samples were redder (higher 600/440 nm ratios) than most Phase 1 samples, with lower red/near-infrared ratios. Exceptions were the bluer portions of ripple crests with higher red/infrared ratios (e.g., Baxter Peak, Ripogenus), which transitioned into redder, more ferric materials along the flanks or troughs of the ripples, as shown schematically by the orange arrows in Figure 4. The Ogunquit dump samples exhibited high 535 nm band depths but were among the least red Phase 2 samples, similar to the Dump E (< 150 μm) sands from Phase 1.

Figure 5 shows similar spectral parameters computed from Mastcam spectra from both campaign Phases, where the 676/751 nm (red/infrared) ratio is compared to the 527 nm band depth and the 639/446 (red/blue) ratio. Nearly all Phase 2 samples were redder with stronger 527 nm band depths than Phase 1 sands, with low red/infrared ratios closer to the < 150 μm Phase 1 sieved samples. The exceptions were the bluer, coarser disturbed sands from Hildreths, Ogunquit, and Matagamon, which exhibited the weakest 527 nm band depths and highest red/infrared ratios, transitioning to finer, redder sands as shown schematically by the arrows (cf. Figures S1-S5). The Ogunquit samples were much less red than other Phase 2 samples and most similar to Phase 1 sands. However, their 527 nm band depths and red/infrared ratios were similar to the other Phase 2 sands.

5 Discussion and Conclusions
Based on their higher ~530 nm band depths and red/blue ratios and lower red/infrared ratios, we interpret that most of the Phase 2 sands contained greater proportions of redder, fine-grained, ferric materials than Phase 1 sands. However, several of the bluer, coarser-grained Phase 2 ripple crests were similar to Phase 1 sands, and some exhibited higher red/infrared ratios for a given red/blue ratio than Phase 1 sands (e.g., Hildreths, Baxter Peaks’ crest in
Figure 5b). This likely resulted from the more active wind regime in this region (cf. Baker et al., 2018; Lapôtre et al., 2018), which limited dust contamination and exposed more ferrous sands. Indeed, APXS analyses suggested low dust content (implied from low S, Cl and Zn concentrations), particularly for the more mafic ripple crests which contained relatively greater amounts of Mg and Ni, compared to enrichments in Ti and Cr in off-crest sands (O’Connell-Cooper et al., 2018). By comparison, the sieved Ogunquit samples exhibited strong ~530 nm band depths but an overall less red appearance than other Phase 2 sands even though APXS analyses suggested higher dust contributions. We conclude that Phase 2 sands contained minor, detrital, hematite-rich particles sourced from the surrounding bedrock of the Murray formation in addition to relatively lower proportions of mafic minerals. Analyses by Rampe et al. (2018) suggested lower olivine and higher plagioclase abundances in the crystalline portion of the < 150 μm Ogunquit fraction than in the Phase 1 Gobabeb samples, along with ~2 wt% hematite. The proportion of crystalline hematite was likely larger in the Phase 2 sands, and/or the grain size distribution of hematite was smaller, in order to account for their stronger ~530 nm bands. In addition, images from the Mars Hand Lens Imager (MAHLI) suggested the presence of reddish outcrop fragments < 500 mm in size, although the average grain size was smaller in the Phase 2 dune sands than Phase 1 (Weitz et al., 2018). Analyses of sands along the rest of the Curiosity rover traverse will continue to document compositional and mineralogical variations and potential bedrock contributions from the stratigraphy of Mt. Sharp.
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Table 1. ChemCam and Mastcam sequences used.

| Target         | Stop # | Sol  | Sequence ID       | LTST (start) | Raster Size column x row |
|----------------|--------|------|-------------------|--------------|--------------------------|
| Mapleton       | 1      | 1602 | ccam1602          | 12:11        | 5x1                      |
| New Sweden     | 2      | 1617 | ccam1617          | 10:26        | 1x5                      |
| Macworth       | 2      | 1618 | ccam3618          | 10:44        | 1x10                     |
| Towow          | 2      | 1618 | ccam1618          | 10:18        | 5x1                      |
| Leighton       | 3      | 1623 | ccam2623          | 12:30        | 10x1                     |
| Carrasset      | 3      | 1625 | ccam1625          | 11:43        | 10x1                     |
| Swanback       | 3      | 1627 | ccam1627          | 11:42        | 1x10                     |
| Mattawankeag   | 2/3    | 1630 | ccam2630          | 12:45        | 1x5                      |
| Ripogenus      | 3      | 1637 | ccam2637          | 10:35        | 1x10                     |
| Spragueville   | 3      | 1637 | ccam1637          | 10:06        | 1x10                     |
| Spragueville_2 | 3      | 1638 | ccam02638         | 12:12        | 1x10                     |
| Greenvale Cove | 3      | 1639 | ccam1639          | 11:49        | 1x7                      |
| Tumbledown Mountain | 4   | 1652 | ccam1652          | 11:18        | 5x1                      |
| Elephant Mountain | 4    | 1652 | ccam2652          | 11:32        | 5x1                      |
| Canoe Point    | 4      | 1652 | ccam3652          | 11:48        | 5x1                      |
| North Brother  | 4      | 1653 | ccam1653          | 11:04        | 10x1                     |
| Avery Peak     | 4      | 1653 | ccam2653          | 11:19        | 10x1                     |
| Baxter Peak    | 4      | 1653 | ccam3653          | 14:15        | 10x1                     |
| Ogunquit       | --     | 1970 | ccam5968          | 12:27        | 5x1                      |
| Ogunquit       | --     | 1971 | ccam1971          | 13:24        | 5x1                      |
| Ogunquit       | --     | 1971 | ccam2971          | 13:33        | 5x1                      |
| Ogunquit       | --     | 1972 | ccam1972          | 12:53        | 5x1                      |
| Matagamon      | 1      | 1603 | mcam08177         | 12:40        | --                       |
| Scarboro       | 1      | 1603 | mcam08179         | 12:50        | --                       |
| Macworth       | 2      | 1618 | mcam08273         | 11:28        | --                       |
| Hildreths      | 3      | 1637 | mcam08465         | 11:12        | --                       |
| Ogunquit       | 4      | 1652 | mcam08558         | 10:50        | --                       |
| Ogunquit dump  | --     | 1970 | mcam10306         | 12:07        | --                       |
Figure 1. HiRISE orbital color scene of Phase 2 region, showing rover traverse (white) and four stops made during the campaign. Background image is HiRISE ESP_035772_1755.
Figure 2. (a) ChemCam passive reflectance spectra of representative samples acquired at the four stops of the Phase 2 campaign. Legend shows Sol number and raster location number in parentheses. Gap between 468-478 nm represents region between ChemCam detectors. Each spectrum includes a 50-channel average line overlain; only this average is shown in the 400-500 nm region owing to low SNR in this region. (b) Mastcam relative reflectance spectra of representative samples acquired at the four stops. Error bars represent standard deviation of region of interest selected (see Figures S1-S5 for locations from which spectra were extracted).
Figure 3. (a) ChemCam passive reflectance spectra of Ogunquit pre-sieves (150 >μm) and post-sieves (<150 μm) dumped samples. (b) Mastcam relative reflectance spectra of Ogunquit dumped samples (extracted from same area sampled by ChemCam raster, cf. Figure S6) compared to spectra of background sands in the same scene.
Figure 4. ChemCam spectral parameters for Phase 2 (circles) and representative Phase 1 samples (squares) (cf. Johnson et al., 2017). (a) 535 nm band depth versus 600/700 nm ratio; (b) 600/440 nm ratio vs. 600/700 nm ratio. Orange arrow points from coarser, more ferrous sands on larger ripple crests to finer, more ferric sands on smaller ripple crests.
Figure 5. Mastcam spectral parameters for Phase 2 (circles) and representative Phase 1 samples (squares) (cf. Johnson et al., 2017). (a) 527 nm band depth versus 676/751 nm ratio; (b) 639/446 nm ratio vs. 676/751 nm ratio. Black arrows point from coarser, bluer, more ferrous sands on larger ripple crests to finer, more red, ferric sands on smaller ripple crests.