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Note

Evidence for a widespread basaltic breccia component in the martian low-albedo regions from the reflectance spectrum of Northwest Africa 7034

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ABSTRACT

Northwest Africa (NWA) 7034 is the first breccia meteorite from Mars, and unlike the shergottite, nakhlite, and chassignite (SNC) martian meteorites, it matches the estimated chemical composition of martian crust. Here we show that the visible-infrared reflectance spectrum of NWA 7034 is unique compared to other SNCs and is more similar than them to remotely sensed data from Mars, suggesting the martian regolith may contain significant brecciated material produced during heavy bombardment of the crust.

1. Introduction

The shergottite, nakhlite, and chassignite (SNC) meteorites were previously the only samples of Mars available for laboratory studies (e.g., McSween, 1994); however, these igneous rocks may not be chemically or texturally representative of the bulk martian crust (McSween et al., 2009). It is therefore not surprising that there has been limited success in using spectral data to link SNC meteorites to the martian surface (Hamilton et al., 2003; Ody et al., 2014). Results of these efforts show that spectral matches to SNCs occur as patchy areas on Mars, and that most of the low-albedo (dust-poor) regions are not spectrally consistent with the SNCs. Specifically, SNC spectra are brighter with greater spectral contrast at visible/near-infrared (VNIR) wavelengths than remote measurements of low-albedo regions (McFadden and Cline, 2005; Poulet et al., 2009), and there are strong vibrational absorptions in the reststrahlen region (1200–800 cm^{-1}) in SNC spectra rather than the muted boxy shape seen in orbital thermal emissivity data (Bandfield et al., 2000; Hamilton et al., 2003; Rogers and Christensen, 2007).

Northwest Africa (NWA) 7034 – also known as "Black Beauty" – and its pairings are the first martian samples that match the estimated chemical composition of the martian crust (Agee et al., 2013). NWA 7034 has been classified as a basaltic breccia by Agee et al. (2013), and its pairing NWA 7533 as a regolith breccia by Humayun et al. (2013). These meteorites contain clasts of multiple igneous rock types (Santos et al., 2013), fragments of andesine, low-Ca pyroxene, pigeonite, augite, and a variety of accessory phases (Agee et al., 2013), impact spherules, and potential sedimentary clasts (McCubbin et al., 2014), all set in a holocrystalline fine-grained matrix of mostly pyroxene, plagioclase and magnetite (Muttik et al., 2014a,b). Zircons in NWA 7533 are dated to 4.4 Ga (Humayun et al., 2013), and phosphate U–Pb ages of 1.35 Ga may represent the final assembly of the breccia (Bellucci et al., 2014). These meteorites might therefore record crustal formation, impact melting, brecciation, volcanism, and sedimentary transport for billions of years near the martian surface. These processes operated in concert to form the martian regolith, particularly that exposed in the ancient southern highlands. Therefore it is expected that breccias like NWA 7034 and particulate material eroded from them may be a significant component in the martian regolith, mixed on varying spatial scales with more intact basaltic flows and pyroclastics. The objectives of this work are to compare the spectral properties of NWA 7034 to SNC meteorites, and to remote orbital investigations of the martian surface.

2. Material and methods

We investigated an unpolished 0.99 g chip sawn off of NWA 7034, loaned from the Institute of Meteoritics (see Fig. 2). Reflectance spectroscopy was performed at: (1) the Keck/NASA Reflectance Experiment Laboratory at Brown University (RELAB; Mustard and Pieters, 1987), with the custom-built UV–VIS–NIR bidirectional spectrometer (BDR) and with a Nicolet Nexus Fourier Thermal Infrared (FTIR) spectrometer, and at (2) Headwall Photonics, Inc., with two high-efficiency hyperspectral VNIR imaging systems. The BDR in RELAB covers 0.3–2.6 μm with a 5 nm sampling, and the FTIR spectrometer covers 0.8–50 μm (12,500–400 cm^{-1}) with a 4 cm^{-1} sampling. Kirchhoff's law (emissivity = 1-reflectance) does not strictly apply to the biconical geometry of our FTIR measurements of solid samples (Salisbury et al., 1994), but these spectra can still be used to qualitatively compare to emissivity data from Mars. The imaging spectrometers cover 0.4–1.0 μm with 1.785 nm sampling, and 0.95–2.5 μm with a 12.066 nm sampling. All VNIR measurements were corrected to reflectance using dark current measurements and by normalizing to Spectralon® as a white reference, followed by a correction with an independently measured spectrum of Spectralon® to achieve absolute reflectance values. FTIR measurements were normalized to a diffuse gold standard. To confirm that the absolute reflectance values obtained by hyperspectral imaging are accurate, we

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benchmarked regions of interest in the hyperspectral data against independent matching spot measurements (~1 mm circles) from the BDR.

NWA 7034 spectra were compared with other SNC spectra measured previously from solid chips at RELAB using the same instrumental set-up. To compare with martian low-albedo regions, we used regional averages (Milliken, 2006; Bandfield et al., 2000) from the Observatoire pour la Mineralogie, L'Eau, les Glaces et L'Activité (OMEGA) spectrometer (Bibring et al., 2004), and the Thermal Emission Spectrometer for Mars (TES, Christensen et al., 1992). OMEGA is a moderate spatial resolution reflectance spectrometer with nearly global coverage of the martian surface from 0.38 to 5.1 µm with 7–20 nm sampling. TES is a low spatial resolution Thermal Emission Spectrometer, also with nearly global coverage from 6 to 50 µm (1650–200 cm^{-1}) with 10 or 5 cm^{-1} sampling.

3. Results

NWA 7034 has unique spectral properties compared to all other SNC meteorites measured to date (Fig. 1). It has the lowest reflectance (mean = 0.076 from 0.3 to 2.6 µm) of all measured SNC chips, a negative concave-up spectral slope across the VNIR, and a weak Fe^{2+} crystal field absorption feature near 1 µm. Fig. 1a shows hyperspectral imaging spectra of NWA 7034, including the mean of the entire chip and two 3 × 3 pixel regions of interest (see Fig. 2) of the matrix material and a low-Ca pyroxene clast/fragment. The low-Ca pyroxene spectrum shows that there is material within NWA 7034 that has similar reflectance values and spectral contrast to SNCs, and that measurement techniques are not responsible for the very low reflectance and low spectral contrast of the bulk chip. The spectral similarity between the bulk chip and the matrix suggests that the spectral properties of the matrix dominate the spectral signature of the entire sample, and cause the spectral characteristics described above. Hyperspectral maps support this view (Fig. 2), and identify the matrix as the source of the dominant low reflectance, low spectral contrast component in NWA 7034, although some clasts appear to be darker than the matrix.

At mid-infrared wavelengths NWA 7034's spectrum is again distinct from other SNCs and is more similar than them to orbital measurements of martian low-albedo areas, particularly in the wavenumber region from 1240 to 1100 cm^{-1} (Fig. 1b). The reststrahlen region of NWA 7034 shows a boxy shape without pronounced mineral bands, similar to that of surface type 1 (ST1) low-albedo regions on Mars that are usually interpreted as unaltered basalt (Christensen et al., 2000). However, there are discrepancies in spectral shape at lower wavenumbers (~500 cm^{-1}) between all the martian meteorites (including NWA 7034) and the TES data.

4. Discussion

The unique spectral properties of NWA 7034 are likely caused by its high magnetite content (~7–8%, Rochette et al., 2013) and by its very fine-grained matrix, with average grain sizes on the order of 0.2 µm (Muttik et al., 2014a). In general, reflectance values in the VNIR increase with decreasing particle diameter (D) until a critical value, where reflectance then drops dramatically and absorption bands are strongly attenuated (Mustard and Hays, 1997). Mustard and Hays (1997) defined this critical diameter for particulate samples as $D_c = 2\lambda/\pi(n-1)$, where λ is the wavelength of light and n is the real part of the complex index of refraction. Setting $n = 2$ as a realistic value for silicate minerals in the VNIR, D_c varies from 0.19 µm at $\lambda = 0.3$ µm to 1.59 µm at $\lambda = 2.5$ µm, such that the mean NWA 7034 matrix grain size is near or below the critical value for the entire VNIR range. This may explain the very low reflectance and low spectral contrast of NWA 7034. D_c is not strongly dependent on the imaginary part k of the refractive index, such that all mineral components of the matrix can contribute to darkening the meteorite. However, as magnetite has exceptionally strong k values in the VNIR, the high magnetite content of NWA 7034 likely amplifies its low reflectance. It is also possible that trace amounts of carbon from exogenic chondritic sources (Humayun et al., 2013) play a role in darkening NWA 7034. Particle sizes on the order of the wavelength of light can cause negative (blue) spectral slopes (Brown, 2014), possibly explaining this feature of NWA 7034's VNIR spectrum. Brown (2014) found that maximum bluing occurs in the VNIR for $0.5 < X < 1.2$, where the size factor $X = 2\pi D/\lambda$. For the matrix of NWA 7034 ($D \sim 0.2$ µm), $X \sim 0.9$ µm in the VNIR which is within the range of maximum bluing. It is interesting to note that negative spectral slopes in low-albedo regions on Mars were previously attributed to dust coatings (e.g., Singer and Roush, 1983; Fischer and Pieters, 1993), but fine-grained brecciated material offers an alternative (or synergistic) explanation for this ubiquitous spectral characteristic of the martian surface.

Mars is punctured by over 400,000 impact craters greater than 1 km in diameter (Robbins and Hynek, 2012). Because brecciation is a natural consequence of impacts, it is expected that material similar to NWA 7034 has accumulated on Mars over time. This is consistent with other planetary bodies: 90% of lunar meteorites are breccias (database maintained at http://meteorites.wustl.edu/lunar/), and the surface of the Asteroid 4 Vesta is almost entirely covered with material that is spectrally similar to the polymict breccia Howardites (Ammannito et al., 2013). The other major components in the martian regolith are expected to be physically eroded basaltic lava flows and shallow intrusives emplaced after the end of heavy bombardment (i.e., SNC material), ashes and ignimbrites from explosive volcanism

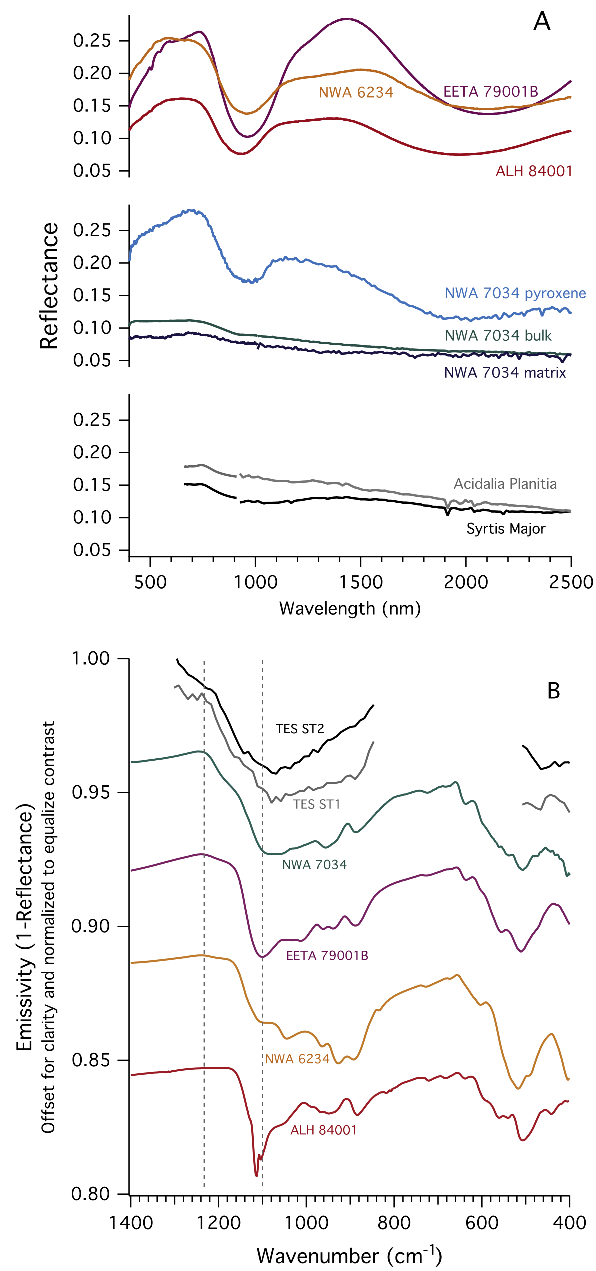

Fig. 1. (A) Visible/near-infrared reflectance spectra of representative SNC meteorite chips measured by the RELAB BDR (top) compared to: (middle) NWA 7034 pyroxene clast (3 × 3 pixel average), whole-rock average, and matrix (3 × 3 pixel average) from hyperspectral imaging (Fig. 2), and to (bottom) martian low-albedo regional spectral averages from the OMEGA instrument (Milliken, 2006). Hyperspectral data were joined at 1.01 µm by scaling the NIR detector data by ~+7%. RELAB IDs for SNC measurements (data available from http://www.planetary.brown.edu/relabdata/): MT-JLB-004 (EETA 79001B), MT-JFM-226 (NWA 6234), MT-TXH-002 (ALH84001). (B) Mid-infrared emissivity spectra of average surface type 1 and type 2 terrains from the TES instrument (ASU spectral library; Bandfield et al., 2000), compared to 1-reflectance spectra of NWA 7034 and representative basaltic (EETA 79001B) and olivine-phyric (NWA 6234) shergottite meteorites, and ALH 84001. The clipped area in the TES spectra is a region of major CO_2 absorption in the martian atmosphere.

(e.g., Bandfield et al., 2013), and distal impact glasses from large Hesperian impacts (Schultz and Mustard, 2004; Wrobel and Schultz, 2007). A mixture of these components (as well as minor dust) is a plausible make-up for the low-albedo regions of Mars. The ~30% amorphous component identified in rocks and soils at Gale Crater (Vaniman et al., 2014) may be mostly basaltic glass (Dehouck et al., 2014), representing an input from impact materials into the regolith. Certain dark regions in the northern plains may host more of this glass, explaining their enigmatic spectral shapes (Horgan and Bell, 2012). Martian orbital spectra have traditionally been

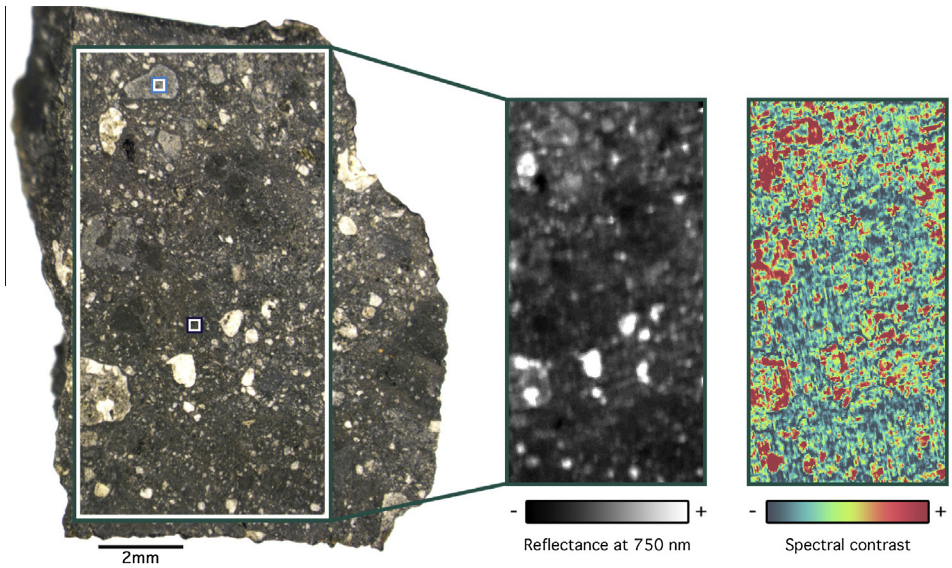

Fig. 2. Optical micrograph of the NWA 7034 chip analyzed in this study, showing a variety of light and dark clasts set in a fine-grained dark-toned matrix. Large green box is the region from which the bulk spectrum in Fig. 1a was obtained, and small colored boxes show the locations of the pyroxene clast and matrix spectra from Fig. 1a. Zoom-in shows hyperspectral maps of reflectance at 750 nm, and spectral contrast, calculated as the mean relative deviation from a linear regression through the VNIR sensor spectrum at each pixel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

interpreted in terms of minerals and not rocks (as opposed to in the lunar spectroscopy community), and this mindset may have hindered proper identification of what the chemically basaltic material in the low-albedo regions of Mars actually is. We suggest here that impact processes have been fundamental in creating and modifying the regolith of Mars, and that the low-albedo regions are not simply eroded lava flows. Further laboratory measurements, observational work, and modeling will help constrain the abundances and distribution of these various components (breccia, basalt, and glass) across the martian surface.

5. Conclusions

NWA 7034 is spectrally distinct from all other SNC meteorites measured to date. It has a very low reflectance, low spectral contrast and a negative spectral slope across the VNIR, resembling OMEGA measurements of the dark plains (Poulet et al., 2009; Horgan and Bell, 2012). In the MIR NWA 7034 has a boxy reststrahlen region resembling TES measurements of ST1 low-albedo surfaces. All these characteristics are more consistent with the average martian low-albedo regions than the SNCs, as determined by remotely sensed data. Low-albedo (dust-poor) regions on Mars are likely composed of a mixture of basaltic breccia, basalt, and basaltic glass that are all physically weathered on the surface to varying grain sizes. If this interpretation is correct then impacts have played a core role in shaping the martian regolith, as expected for heavily-cratered bodies lacking in plate tectonics and Venus-style global resurfacing.

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