Preserved glass-rich impactites on Mars

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ABSTRACT

Quenched glass formed by hypervelocity impacts can encapsulate and preserve biosignatures on Earth, demonstrating the fossilization potential of glass-rich impactites on Mars. However, definitive spectral signatures of impact glass have not been identified on the martian surface from orbital remote sensing. Here we present a remote compositional survey of probable impactites in well-preserved craters, using data from the Compact Reconnaissance Imaging Spectrometer for Mars. These units are composed of mafic glasses mixed with crystalline phases including olivine and pyroxene, determined by radiative transfer Hapke modeling followed by spectral mixture analysis. This glassy material likely formed from impact-induced melting of the target rock with rapid quenching and minor subsequent devitrification or chemical alteration. The metastable glass has been preserved by the cold and dry martian climate during the Amazonian period, and this preservation—as confirmed here across the planet—provides a means to trap signs of ancient life on the accessible martian surface. Our results lend concrete support to theoretical arguments suggesting that impact glass has formed in abundance on Mars, both inside of craters and as spherules in distal strewnfields. Contrary to previous ideas, martian impact products are not destroyed by interaction with volatiles during the impact process.

INTRODUCTION

Hypervelocity impacts of asteroids and comets melt target rocks on planetary surfaces; this is a fundamental process in the solar system (e.g., Melosh, 1989; French, 1998). Resulting silicate liquids mix with pulverized, unmelted, shocked rock to various degrees, cooling to form impactites including breccias and impact glass (Stöffler and Grieve, 1994). The liquid component of these mixtures rapidly quenches if exposed to cold air and rock, and quenching is likely enhanced on Mars because of differential scaling between impact melt and crater volumes (Grieve and Cintala, 1997), a colder surface environment, and volatile-rich sedimentary targets that limit the extent of thick clast-poor melt sheets (Kieffer and Simonds, 1980; Pope et al., 2006; Boyce et al., 2012; Tornabene et al., 2012). On Mars, impactites should have mafic to ultramafic compositions, and it is expected that copious melt products formed from 4.5 Ga to 3.0 Ga when impact rates were much higher than at present (Newsom, 1980; Lorenz, 2000; Schultz and Mustard, 2004; Wrobel and Schultz, 2007; Schultz and Wrobel, 2012). Possible glassy impact spherules have been imaged by landed campaigns (Minitti et al., 2013), and martian impact melts and breccias have been identified from orbit based on their morphology (Tornabene et al., 2010; Osinski et al., 2011; Skok et al., 2012). However, the spectral signature of glass has not been uniquely identified in these materials. Identifying a quenched glass component would be significant because these amorphous phases can preserve biosignatures (Howard et al., 2013; Schultz et al., 2014) and serve as a substrate for microbial life (Izawa et al., 2010; Sapers et al., 2014). Partially glassy impactites on Mars may have been strongly eroded or chemically altered (Newsom, 1980; Tornabene et al., 2013), or simply may not have been detected from orbit because of the subtle spectral signature of mafic glasses at visible and near-infrared (VNIR) wavelengths.

METHODS

We investigated VNIR spectral signatures of geologic units inside impact craters across Mars. Targeted units are located in well-preserved craters, and we focused on those with excellent spectral exposures (i.e., low dust cover from manual inspection of spectral data) and strong geomorphic evidence for an impact origin. Some of the criteria used to identify these impactites included high nighttime temperatures, smooth textures, and entrained breccia blocks visible with orbital imagery from the High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007). These deposits are commonly associated with crater central uplifts, and they show evidence for draping topography, ponding, and flow features. In some cases these specific geologic units have been previously mapped as impact melt rocks or melt breccias (e.g., Tornabene et al., 2010; Osinski et al., 2011), especially those at Alga Crater (Skok et al., 2012), Ritchey Crater (Marzo et al., 2010; Sun and Milliken, 2014), and Toro Crater (Marzo et al., 2010). Without petrographic analysis it is difficult to confidently classify these units (i.e., impact melts versus suevites; Stöffler and Grieve, 1994) so the non-specific "impactite" is used here, although impact breccias can be recognized with HiRISE imagery (e.g., Tornabene et al., 2012).

We determined the mineralogical composition of the impactite units using reflectance data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; Murchie et al., 2007) onboard the Mars Reconnaissance Orbiter spacecraft. Many primary and secondary minerals have been identified with CRISM data based on the presence of their diagnostic absorption features (e.g., Mustard et al., 2008; Skok et al., 2012), but not mafic glasses. The spectral signature of these glasses at VNIR wavelengths is broadly similar to that of other Fe-bearing phases like pyroxene and olivine: they have wide crystal field absorptions near 1.15 µm and 2.0 µm, and unaltered glass has a positively sloped spectral continuum. The presence of glass in a VNIR spectrum can be obscured when pyroxene and olivine are also present because of highly nonlinear mixing behavior; therefore, we used the Hapke radiative transfer model (Hapke, 1981) to account for nonlinearity by converting CRISM data to single-scattering albedo. We then unmixed spectra of the impactite units using a set of spectral end members to determine the presence of mafic glass based on its diagnostic spectral shape (see the GSA Data Repository[1] for additional details on the modeling). Model outputs are relative spectral fractions of each spectral end member, including mafic glass. We mapped the spatial distribution of modeled glass, then targeted apparent glass-rich areas to investigate their spectral signatures and their detailed morphology with HiRISE imagery. Our methods differ from those of previous studies that have inferred the possible presence of glass (e.g., Skok et al., 2012) based qualitatively on how it modifies absorption band shapes/positions in a given spectrum. Importantly, the model can be used to spatially map the strength of the glass signature across a CRISM scene.

RESULTS

We find mafic glass modeled at many craters with spectral fractions approaching 15% or higher; type examples are shown in Figure 1 (see Fig. DR1 in the Data Repository for additional examples). Mapped glass-rich regions are spatially coherent, in some cases with remarkably sharp edges demarcating geomorphic units interpreted as impactites. For example, strongly modeled glass signatures in Alga Crater (Fig. 1A) are found in dark clast-rich units and around the margins of putative impact melt flows on the central uplift (Skok et al., 2012),

[1]GSA Data Repository item 2015222, spectral modeling details and validation, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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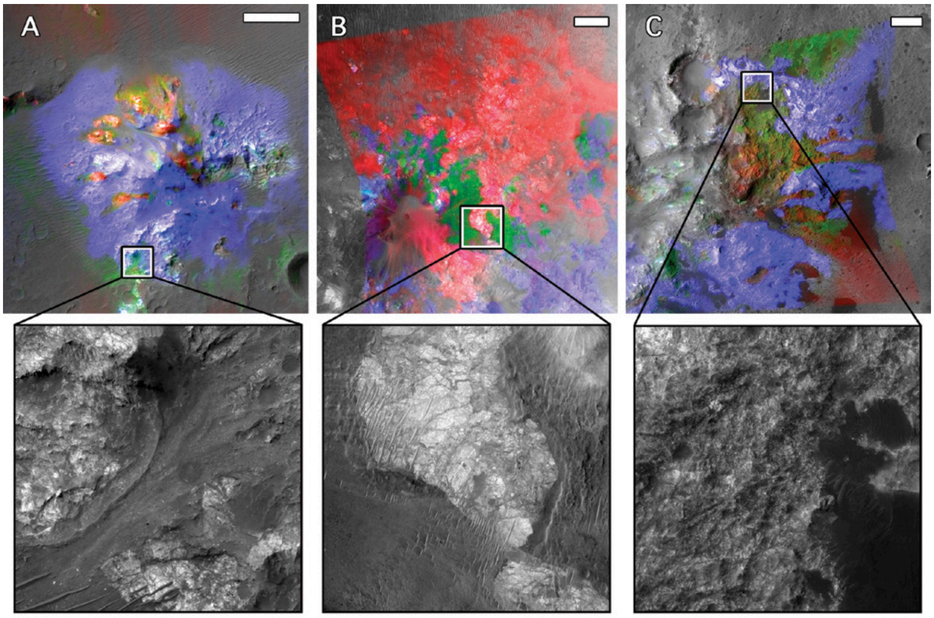

Figure 1. Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) maps of modeled mineralogy (olivine [sum of two end members] in red; mafic glass in green; pyroxene [sum of five end members] in blue) projected over Context Camera (CTX) imagery and smoothed with a 5 × 5 box filter. Linear color stretches are from 0.01 to 0.1 (spectral fraction) for all minerals, and scale bars are 1 km. Zoomed regions show High Resolution Imaging Science Experiment (HiRISE) imagery of modeled glass-rich areas. A: Alga Crater (CRISM ID: FRT00006415). B: Toro Crater (FRT0000B1B5). C: Ritchey Crater (FRT00007C34). See additional examples in Figure DR1 (see footnote 1).

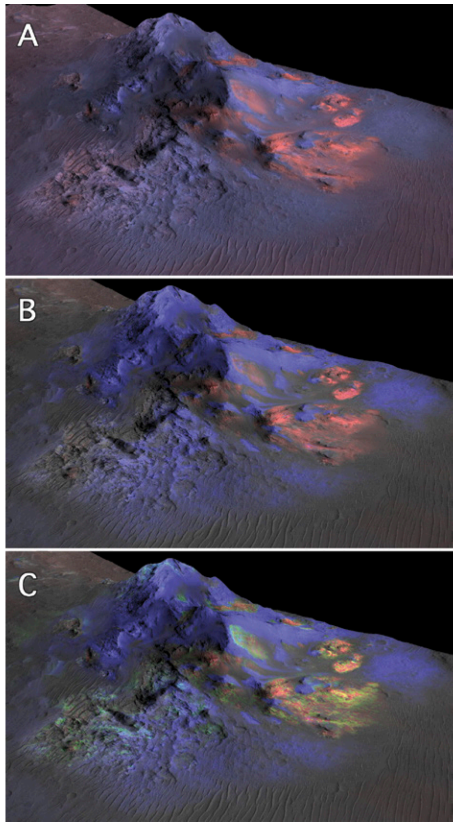

Figure 2. Comparison between modeled mineral spectral fractions and standard Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) spectral parameters (Viviano-Beck et al., 2014) in Alga Crater from CRISM scene FRT00006415, overlaid on High Resolution Imaging Science Experiment (HiRISE) imagery with topography from HiRISE digital terrain model. A: Olivine (OLINDEX3) parameter in red, and pyroxene (LCPINDEX2 + HCPINDEX2) in blue. B: Modeled spectral fraction of total olivine in red, and of total pyroxene in blue. C: Same as B, but with modeled mafic glass fraction in green. Vertical exaggeration is 2×.

and glass modeled in Toro Crater (Fig. 1B) corresponds to a mapped clast-poor melt unit (Marzo et al., 2010). Similarly, modeled glass regions in Ritchey Crater (Fig. 1C) are tightly confined to a unit interpreted as a thin draping of impact melt (Marzo et al., 2010; Sun and Milliken, 2014). Glass is not strongly modeled outside of the impactite units, for example on crater floors covered by younger fill or outside crater rims (Fig. DR1). Modeled glass-rich areas in different craters have a similar set of textures in HiRISE imagery (Fig. 1): they are dark toned, and either clast rich with entrained light-toned breccia blocks visible from orbit, or smooth textured (i.e., no large blocks visible at HiRISE resolutions of 25 cm/pixel).

Modeled olivine and pyroxene distributions can be verified by comparing them to standard CRISM mineral parameters (Viviano-Beck et al., 2014) designed to identify those two minerals based on spectral algebra. Figure 2 shows that our modeled mineralogy from part of Alga Crater's central uplift is highly consistent with the CRISM spectral parameters; modeled mineral signatures of olivine, pyroxene, and mafic glass (for which no CRISM parameter exists) were further validated by manually inspecting CRISM calibrated reflectance spectra (Fig. 3). The position and shape of the crystal field absorptions in these spectra are consistent with the dominant modeled phase, i.e., spectra from modeled olivine-rich pixels have diagnostic absorptions matching those of laboratory studies of olivine (Fig. 3). The same is true for pyroxene and mafic glass. The suitability of our modeled spectral end members is evaluated by the root-mean-square error between the measured and modeled spectra and by visually inspecting the modeled fit and the associated residuals (Fig. 3).

We used the modeled glass spectral fraction maps to identify regions with the purest glass signatures, then extracted individual spectra from these areas and subtracted (in single-scattering albedo space) all other end member spectra except mafic glass, in their modeled proportions. The resulting isolated signatures (Fig. 4) show broad crystal-field absorptions near 1 μm and 2 μm and a positive continuum slope. Comparing these spectra to laboratory spectra of olivine, pyroxenes, and mafic glass shows that they are entirely consistent with glass and not any other common primary (or secondary) minerals detected or suspected on Mars (Fig. 4).

DISCUSSION

Some of the glass-bearing impactite units appear to co-occur with hydrated secondary phases, and it is possible that these were derived from the glass-rich material (Tornabene et al., 2013). Narrow vibrational absorption features at 1.9 μm and 2.1–2.3 μm are diagnostic of hydrated silicate minerals detected on Mars (e.g., Mustard et al., 2008), and such features are present in many of the CRISM scenes studied. However, by closely inspecting HiRISE imagery we found that regions appearing to host both mafic glass and hydrated silicates are mostly made up of separate materials: either the glass-bearing impactites form a thin veneer over light-toned rock that contains the hydrated minerals (and usually olivine), or the impactite units have embedded light-toned clasts that could host these alteration phases. These findings are consistent with previous work (Marzo et al., 2010; Tornabene et al., 2013; Osinski et al., 2013).

The glass-rich impactites do not seem to be pervasively altered, but they may still have reacted with water after they formed. Individual CRISM spectra from modeled glassy areas—ratioed to bright dust-rich neutral regions in the same detector column—have negative spectral slopes, similar to signatures of more widespread (volcanic?) glass detected in the northern martian plains (Horgan and Bell, 2012). These spectral slopes may be caused by fluids stripping cations out of the Si-Al-O backbone of the

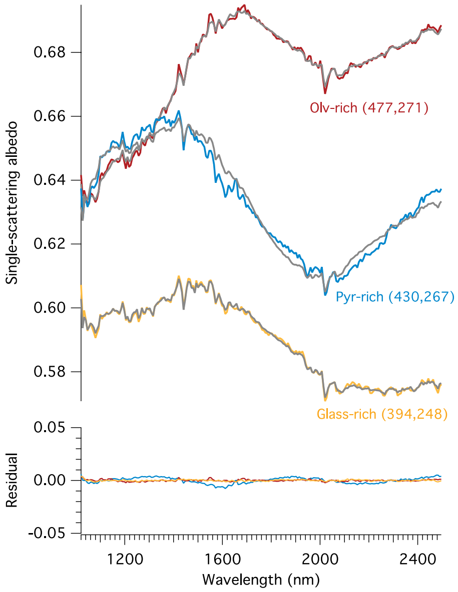

Figure 3. Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) spectra from observation FRT00006415 in Alga Crater of a modeled olivine (Olv)-rich region, pyroxene (Pyr)-rich region, and glass-rich region, showing measured CRISM data (converted to single-scattering albedo) and modeled spectra (gray lines). Residuals (calculated as measured minus modeled) are shown at bottom. All spectra are single pixels, and pixel coordinates (sample number, column number) from the non-map projected CRISM scenes are given in parentheses.

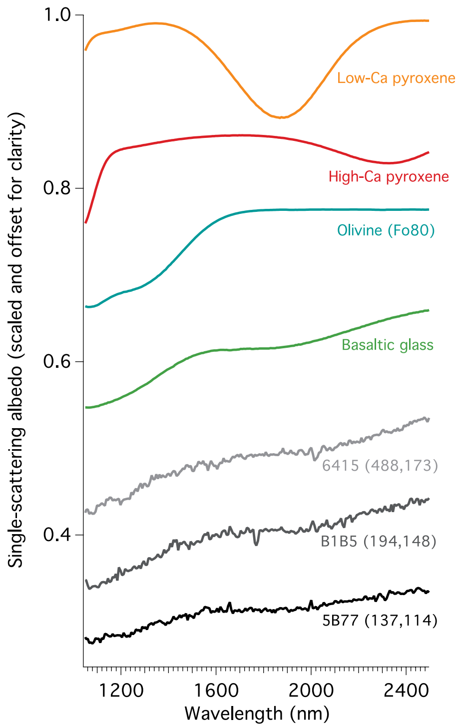

Figure 4. Laboratory spectra of pyroxenes, olivine, and mafic glass (NASA Reflectance Experiment Laboratory [RELAB] IDs are listed in Table DR1 [see footnote 1]) compared to Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) single-scattering albedo spectra from regions with high modeled glass spectral fractions, after subtracting all other end members in their modeled proportions. Examples are shown above for Alga Crater (CRISM ID: FRT00006415), Toro Crater (FRT0000B1B5), and Taytay Crater (HRL00005B77). All spectra are single pixels, and pixel coordinates (sample number, column number) from non-map projected CRISM scenes are given in parentheses.

glass structure to form leached rinds (Minitti et al., 2007; Horgan and Bell, 2012). If leached rinds cause the negative spectral slopes in the impactite spectra (Minitti et al., 2007; Horgan and Bell, 2012), these rinds must be very thin (<10 µm), otherwise electromagnetic radiation at VNIR wavelengths would not penetrate the rinds. This suggests that the deposits in this study were not pervasively altered, but does not rule out interactions with liquid water. Fluvial and lacustrine deposits elsewhere on Mars commonly retain unaltered mafic mineral signatures (e.g., Goudge et al., 2012). Therefore, preserving mafic glass on Mars for millions to billions of years may not be difficult because of profoundly cold and dry conditions during the Amazonian era, even if these glasses were in contact with liquid water earlier in martian history (see discussion in Tornabene et al. [2013]). It is difficult to accurately date the medium-sized craters in this study, but some (e.g., Ritchey Crater) show evidence for fluvial erosion, suggesting formation ages older than 3 Ga (Mangold et al., 2012).

Recognizing preserved quenched impact glass on Mars is significant because this material represents a means to entomb and preserve biosignatures (Howard et al., 2013; Schultz et al., 2014). During the impact process, complex organic molecules and even solid biomass can become entrained in superheated silicate melts (Howard et al., 2013; Schultz et al., 2014). When these melts are rapidly quenched to glass, this process can preserve biosignatures, like insects in amber, for millions of years on Earth. This preservation mechanism is only viable for Mars if quenched glass was produced and preserved throughout martian history, which we believe to be the case based on theoretical arguments (Newsom, 1980; Lorenz, 2000; Schultz and Mustard, 2004; Wrobel and Schultz, 2007; Schultz and Wrobel, 2012) and the observations presented here. However, it is not clear whether impact glasses on Mars still exist from when a magnetic field would have protected surface environments from harmful radiation, because there is no evidence that any craters shown in this study are older than ca. 4.0 Ga. Burial and later exhumation could provide a way to sample these truly ancient glasses on the surface today. Alternatively, younger impact events could have sampled deeper subsurface biospheres shielded from the surface radiation environment, as impact-melting depths are significantly greater than the sterilized zone caused by ultraviolet radiation and galactic cosmic rays (e.g., Dartnell et al., 2007).

Impact glasses may have also created niches for martian microbial life in post-impact environments, including lacustrine and hydrothermal settings (Cockell et al., 2002; Izawa et al., 2010; Osinski et al., 2013; Sapers et al., 2014). Terrestrial microbes preferentially colonize glasses rather than crystalline rocks (Sapers et al., 2014), and the putative microbial tubules produced in glass substrates can be preserved by subsequent mineralization (Izawa et al., 2010; Sapers et al., 2014). In terms of lacustrine settings, most candidate closed-basin paleolakes on Mars are hosted in craters (T. Goudge, 2015, personal commun.), and the database of these possible lakes includes craters with evidence for preserved impact glass (e.g., Balvicar Crater; Fig. DR1). Therefore it is possible that impact glasses were in intimate contact with liquid water in lacustrine settings on Mars. Post-impact hydrothermal systems have also been proposed on Mars (e.g., Marzo et al., 2010; Osinski et al., 2013), including inside of Toro Crater where we identify signs of preserved glass (Fig. 1B). Hydrothermal environments may be more promising than lakes for microbial colonization of glass, but they are also more likely to cause significant chemical alteration, removing spectral signatures of mafic glasses.

Searching for signs of an ancient martian biosphere has progressed from "following the water" to characterizing "habitable" environments, and there is now a push to look for preserved biosignatures directly. While previous work has focused on clay-rich sedimentary deposits as hosts of these biosignatures, our detection of preserved impact glass on Mars suggests a promising alternative target.

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