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Notes

Widespread weathered glass on the surface of Mars

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ABSTRACT

Low albedo sediments cover >10^7 km^2 in the northern lowlands of Mars, but the composition and origin of these widespread deposits have remained ambiguous despite many previous investigations. Here we use near-infrared spectra acquired by the Mars Express OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité) imaging spectrometer to show that these sediments exhibit spectral characteristics that are consistent with both high abundances of iron-bearing glass and silica-enriched leached rinds on glass. This interpretation is supported by observations of low-albedo soil grains with possible rinds at the Phoenix Mars Lander landing site in the northern lowlands. By comparison with the extensive glass-rich dune fields and sand sheets of Iceland, we propose an explosive volcanic origin for these glass-rich sediments. We also propose that the glassy remnant rinds on the sediments are the result of postdepositional alteration, as these rinds are commonly formed in arid terrestrial volcanic environments during water-limited, moderately acidic leaching. These weathered, glass-rich deposits in the northern lowlands are also colocated with the strongest concentrations of a major global compositional surface type previously identified in mid-infrared spectra, suggesting that they may be representative of global processes. Our results provide potential confirmation of models suggesting that explosive volcanism has been widespread on Mars, and also raise the possibilities that glass-rich volcaniclastics are a major source of eolian sand on Mars and that widespread surficial aqueous alteration has occurred under Amazonian climatic conditions.

INTRODUCTION

The northern lowlands of Mars are composed of several overlapping extensive basins that have been partially filled by lava and sediments. Today, low-albedo sediments mantle this region and form the north polar sand sea, which encircles the north polar cap. Unlike many other low-albedo regions on Mars, most of the northern lowlands do not exhibit spectral characteristics consistent with a typical basaltic surface. In the mid-infrared, the model-derived composition of these deposits differs from the olivine-basaltic composition common elsewhere on Mars by the presence of a poorly crystalline high-silica phase, the nature of which is not well constrained (e.g., Bandfield et al., 2000; Michalski et al., 2005; Rogers and Christensen, 2007). Possible high-silica phases include both primary volcanics (e.g., obsidian) and secondary alteration products (e.g., zeolites, opal, amorphous silica coatings). These possibilities have significantly different implications for martian history. If the northern plains were derived from an andesitic magma, this could imply substantial magmatic evolution from typical martian basalt. If the northern plains contain a silica-rich aqueous alteration product, this could instead imply widespread alteration under the assumed hyperarid conditions of the past billion years. Previous studies in the near-infrared (NIR) have not resolved this ambiguity, as the dark plains are nearly spectrally featureless, leading previous authors to speculate on the presence of spectrally obscuring coatings or spectrally featureless glasses (Mustard et al., 2005; Poulet et al., 2007). Here we show that the overall continuum shape and subtle absorptions in NIR spectra of the northern plains are consistent with iron-bearing glass partially obscured by a silica-enriched leached glass rind, potentially implying widespread acidic leaching and a history of explosive volcanism in the northern plains.

METHODS

We have analyzed Mars Express OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité) visible (0.36–1.07 μm) and NIR (0.93–2.5 μm) spectra from the first

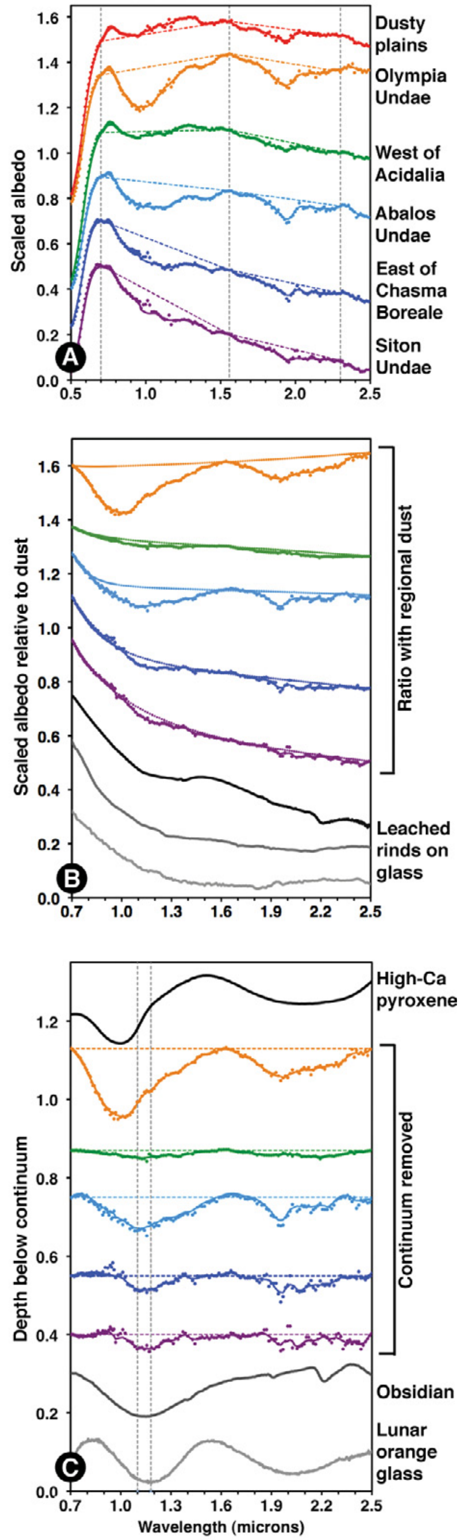

Figure 1. OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité) near-infrared spectra of Mars northern lowlands that are consistent with iron-bearing glass, compared with north polar average regional dust (red) and spectrum consistent with pyroxene (orange). Points indicate unsmoothed spectra. A: Spectra showing concavity variations, scaled to 1.0 at 0.7 μm and offset for clarity. Vertical lines indicate wavelengths used to calculate concavity. B: Spectra from A ratioed with average regional dust spectra, compared to leached glass rinds. Black—glassy basaltic sand after 83 days exposure to oxidizing, acidic solution (pH 1) (Horgan et al., 2011); gray—MIO and MUO black coatings of Minitti et al. (2007). Continua are indicated by bounding curves. C: Spectra from B after continuum removal, compared to laboratory spectra of mafic phases. Vertical lines indicate typical range of 1 μm band centers for glass.

year of observations above 45°N (Bibring et al., 2005). Spectra were converted to estimated Lambert albedo and mapped into regional mosaics prior to analysis (see the GSA Data Repository[1] for details). While most spectra in the northern lowlands have concave-down shapes between 0.7 and 2.5 µm, we have found a class of spectra that exhibit unusually strong concave-up slopes between 0.7 and 1.5 µm, as shown in Figure 1. We can parameterize the concavity of the spectral slope by comparing a ratio in the concave part of the spectrum to a ratio at longer wavelengths:

$$\text{Concavity} = \frac{A(0.71)+A(0.73)+A(0.75)}{A(1.53)+A(1.54)+A(1.56)} - \frac{A(1.53)+A(1.54)+A(1.56)}{A(2.29)+A(2.30)+A(2.31)}, \quad (1)$$

where A is the estimated Lambert albedo at the indicated wavelength (in µm). Positive values of this parameter indicate a concave-up continuum.

Typical mafic minerals may be discriminated based on the wavelength position and shape of the 1 µm iron absorption band (e.g., Cloutis and Gaffey, 1991). In this study we examined the position of the 1 µm band center in OMEGA spectra, after contributions from the atmosphere, dust, instrumental artifacts, and the overall continuum shape were suppressed or removed (see the Data Repository). The band center is derived by locating the reflectance minimum between 0.75 and 1.3 µm, fitting a second-order polynomial to the channels within 0.075 µm of the minimum, and finding the wavelength of the minimum of the fit.

RESULTS

We find that the 1 µm band centers of spectra in some regions of the northern lowlands are consistent with high-calcium pyroxene and possibly olivine, in agreement with previous investigations (Poulet et al., 2007). However, one of the largest dune fields in the north polar sand sea, Siton Undae, and much of Acidalia and Utopia Planitiae exhibit high concavity values and relatively broad, shallow, and symmetric bands centered between 1.10 and 1.16 µm (Figs. 2 and 3). This is beyond the band center range for olivine or high-calcium pyroxene, but is consistent with iron-bearing glass (Fig. 1C; Adams et al., 1974). Furthermore, in laboratory spectra, we find that a mixture of iron-bearing minerals must contain at least 80–90 wt% glass for the band center to fall in this region, consistent with previous investigations (Lucey et al., 1986). That we observe such a long-wavelength band suggests that glass is the primary iron-bearing phase in these deposits, the extremely low albedo (< 0.1) of which is consistent with a glass-rich composition. In general, our glass detections occur in regions of high eolian activity, as indicated by the presence of eolian bedforms and dust devil tracks (e.g., Fig. 3E), suggesting that the ubiquitous dusty mantle covering much of the northern plains may obscure more extensive glass deposits.

Regions of the northern lowlands with glass-like spectral characteristics also tend to exhibit unusually strong concave-up slopes between 0.7 and 1.4 µm, as demonstrated in Figure 2A. The concave slope is not consistent with pristine glass or any known mineral absorptions, so it must be the result of some other effect, such as possible continuum slope variations observed in coarse grains (mm) and rocks (Harloff and Arnold, 2002; Carli and Sgavetti, 2011). However, the strongest concave slopes in the lowlands are associated with eolian bedforms, implying sand-size grains. In addition, positive concavity values are highly correlated with glass detections (e.g., 77% of concave-up spectra in the north polar region have band centers beyond 1.1 µm), suggesting that the source of the concave slope is associated with the glass.

Based on these constraints, we hypothesize that the concave spectral slope we observe is consistent with the spectra of thin (3–10 µm) silica-enriched leached glass rinds (Fig. 1), formed when silicate glass is exposed to acidic fluids (Minitti et al., 2007). During acidic leaching, diffusion into the glass causes migration of

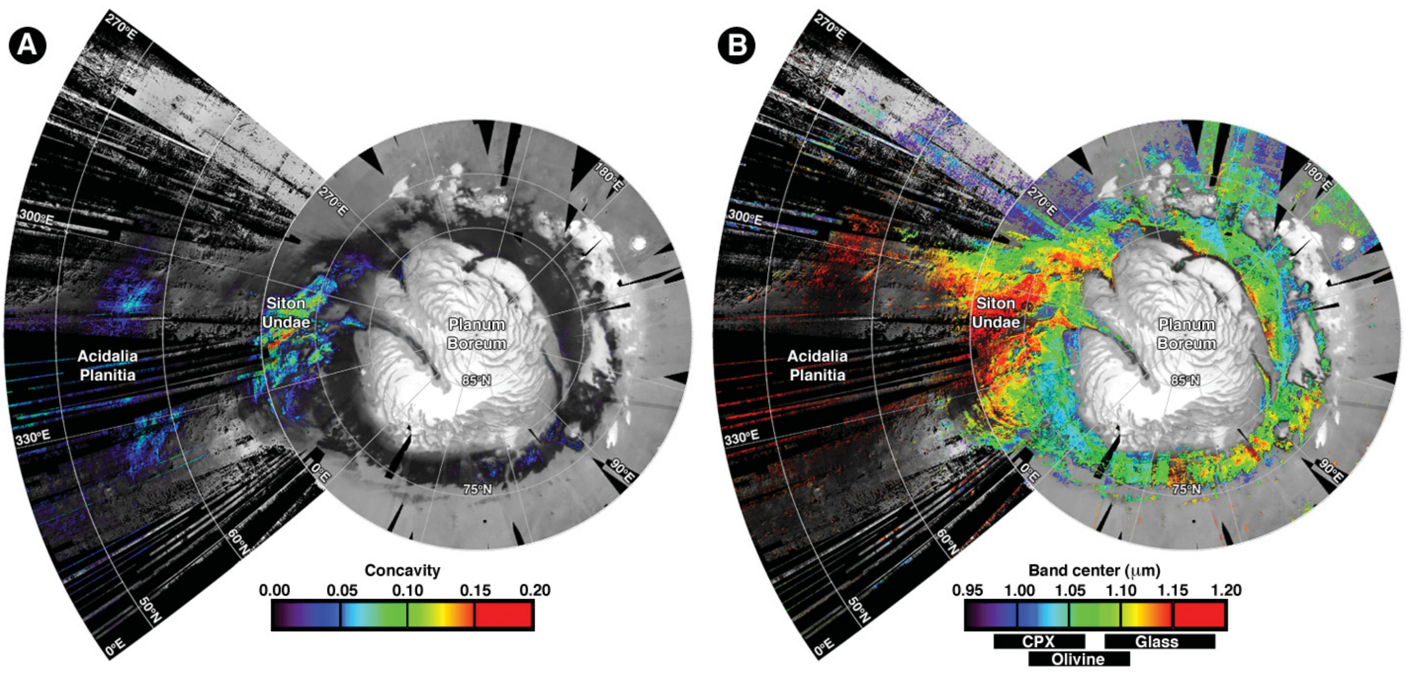

Figure 2. A: Concavity parameter mapped over Mars north polar region and northern Acidalia Planitia, showing only positive values, which are concentrated in Siton Undae and central Acidalia. B: 1 µm band center mapped over same region. Blue and green regions are consistent with clinopyroxene (CPX) or olivine; yellow and red regions are consistent with iron-bearing glass. 1°N ≈ 60 km.

[1]GSA Data Repository item 2012121, spectral processing details, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

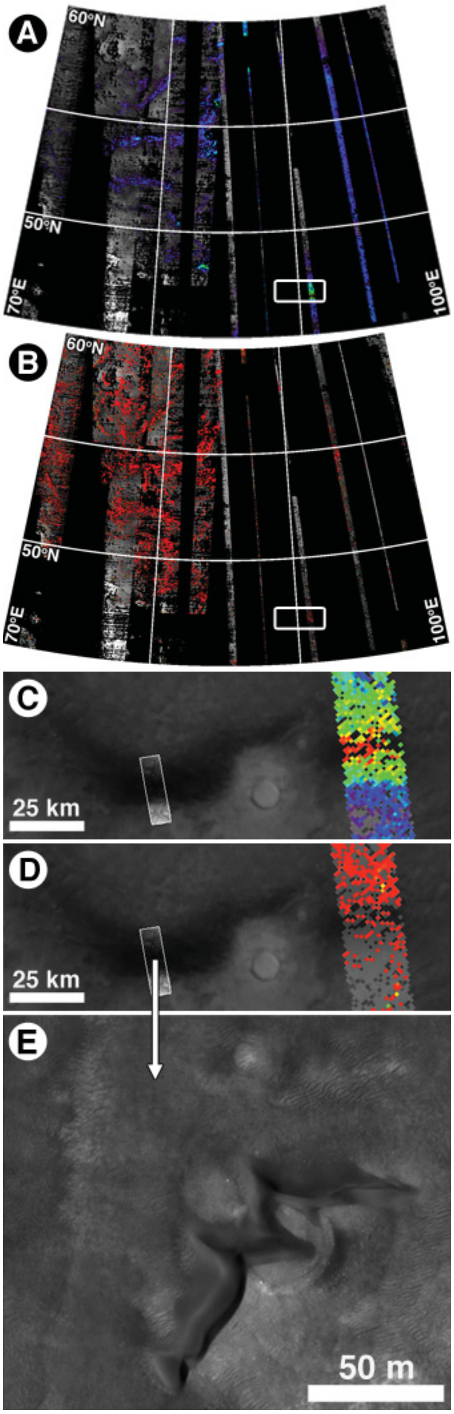

Figure 3. Leached glass detections in Utopia Planitia, Mars. A: Indicated by positive concavity values. B: 1 μm band centers beyond 1.1 μm. (See Fig. 2 for legends; box indicates location of C and D). C, D: Strongest leached glass signatures in Utopia (background: Mars Orbiter Camera). These deposits are characterized by dark sediments mobilized into dunes and ripples, as shown in E. E: High Resolution Imaging Science Experiment (HiRISE) image PSP_009401_2270 (location indicated in C and D).

lower valence cations (e.g., Mg^{2+}, Fe^{2+}, Ca^{2+}) out of the glass surface, leaving behind the higher valence cations that form the structural network (e.g., Si^{4+}, Ti^{3+}, Al^{3+}; Chemtob et al., 2010). Thus, the rind is still structurally similar to the source glass, but is relatively enriched in SiO_2. Leached Fe^{2+} can precipitate as a thin coating on top of the rind (Minitti et al., 2007), and such coatings may be consistent with the linear blue slopes observed beyond 1 μm in central Acidalia (Poulet et al., 2007). A strong concave-up slope without a strong linear blue slope in Siton Undae and other dune fields may be consistent with the removal of this Fe-rich coating and exposure of the underlying silica rind during saltation.

It is critical to note that the leached glass rinds that we propose are distinct from depositional silica coatings, which are formed by dissolution of silicate minerals and precipitation of amorphous silica (Minitti et al., 2007). While rinds retain the loosely bound tetrahedral structure of the host silicate glass, coatings have an opaline structure distinctly different from their substrate (Chemtob et al., 2010). In addition, coatings have not been observed to exhibit concave-up spectral signatures (Kraft et al., 2007).

DISCUSSION

We have detected spectra consistent with iron-bearing glass in pixels totaling $>10^6$ km^2 north of 45°N on Mars, and several million additional square kilometers of glass-rich surfaces may be obscured under a dusty mantle. Because the glass is durable enough to form sand dunes, a significant fraction of the glass must be sand sized with, at most, minor vesicle content. Glass derived from distant impacts could be consistent with these constraints (Bouška and Bell, 1993; Schultz and Mustard, 2004), but it is not clear if impact processes could produce such a large, concentrated deposit. Instead, we propose that a more plausible origin for these deposits is explosive volcanism, which may have produced extensive ash deposits across the planet (Wilson and Head, 2007). A potential analog for these glass-rich, sandy deposits are the extensive sand plains of Iceland that are composed of 55%–90% glass created during explosive subglacial eruptions (Arnalds et al., 2001). Possible causes of explosive volcanism on Mars include interactions with ice and/or water, high silica or volatile content, or eruption under modern atmospheric conditions (Wilson and Head, 2007). While we cannot currently rule out any of these possibilities, the apparent low vesicularity of the glass may be consistent with ice-magma interactions (Heiken and Wohletz, 1991), and these deposits could be related to putative Late Hesperian or Early Amazonian subglacial volcanism in Southern Acidalia (Martínez-Alonso et al., 2011). However, the glass deposits could also be sourced from other putative volcanic features elsewhere in the northern lowlands (Keszthelyi et al., 2010; Farrand et al., 2011) or from one of the large volcanic edifices (Kerber et al., 2010).

We interpret the leached glass rinds on the northern lowlands glass as the result of post-depositional weathering, as these rinds are a common weathering product on glassy materials in arid volcanic environments on Earth. In the Ka'u Desert of Hawaii (United States), leached rinds and silica coatings have formed on chilled lava-flow surfaces (Minitti et al., 2007; Chemtob et al., 2010) and ash grains (Seelos et al., 2010) due to interactions with precipitation acidified by volcanic aerosols. These surfaces exhibit concave-up slopes in aerial spectra similar to those observed at hand-sample scale. Laboratory studies have also confirmed the formation of rinds on sand-sized grains (Fig. 1B; Horgan et al., 2011). The chemistry of glass leaching constrains the processes that may have produced these rinds. As basalt alteration tends to alkalize solutions, the fluid that creates the rind must be either initially very acidic (pH < 2–3), moderately acidic (pH 3–6) and constantly renewed, or moderately acidic with high (>100) water:rock ratios (Minitti et al., 2007). Without invoking abundant surface water during the arid Late Hesperian or Amazonian, a plausible constantly renewed fluid source is melt from surface ice sheets or snow packs, acidified due to oxidizing conditions (Hurowitz et al., 2010). Atmospheric water or seasonal frost melt are also plausible fluid sources; however, Phoenix Mars Lander results suggest that these phases promote neutral-alkaline soil conditions (Hecht et al., 2009).

Our interpretations appear to be consistent with Phoenix optical microscope observations. Soils at the 68°N landing site include nonvesicular black sand grains with rounded morphologies, which would be consistent with hydrovolcanic glass grains. In addition, the black grains tend to exhibit muted surfaces overlying shiny interiors. This has been interpreted as evidence for a weathering rind on the grains, and this interpretation is supported by at least one observation of a broken black grain with a putative thin rind at the limit of Optical Microscope resolution (~4 μm; Goetz et al., 2010).

Our interpretations are also broadly consistent with thermal emission spectrometer (TES) spectral models of the northern lowlands. Our most concentrated leached glass detections correlate well with the highest concentrations on the planet of both the surface type 2 high silica component and basaltic glass (Bandfield, 2002; Ruff and Christensen, 2007). While we hypothesize that the high-silica component in TES data is the leached glass rind that we postulate here, it is possible that the glass also has a high-silica composition, as glasses like obsidian can exhibit strong 1 μm iron bands (Fig. 1C). Furthermore, our results place an upper limit of ~20% on pyroxene abundances, and no constraint on feldspar, which is virtually transparent in the NIR. These results are consistent with the mineralogy of Acidalia from TES models, which predict ~15%–20% pyroxene and ~30% feldspar (Bandfield, 2002; Rogers and Christensen, 2007). While the nonlinear effects of rinds may frustrate accurate mineral abundance estimates from TES (Kraft et al., 2007), the overall predicted TES mineral assemblage is still consistent with our results.

The qualitative correlation between our leached glass detections and TES surface type 2 may have major implications for the composition, sources, and alteration histories of global martian sediments. Surface type 2 appears to be at least as widely distributed as surface type 1, and we propose that this distribution may be consistent with globally distributed glassy sediments, most likely produced by explosive volcanism. Such a scenario would require widespread late-stage explosive volcanism on Mars, and suggests that glass may be a major component of martian sediments.

In summary, the spectra of low-albedo regions of the northern lowlands of Mars are consistent with glass-rich deposits leached by moderately acidic fluids. We propose that these deposits were created during explosive volcanic eruptions and were later leached at low water:rock ratios by fluids derived from ice or snow melt. These extensive deposits represent a new class of igneous materials on Mars and the first detection of widespread surface weathering under Amazonian climatic conditions.

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