Global geologic context for rock types and surface alteration on Mars

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ABSTRACT

Petrologic interpretations of thermal emission spectra from Mars orbiting spacecraft indicate the widespread occurrence of surfaces having basaltic and either andesitic or partly altered basalt compositions. Global concentration of ice-rich mantle deposits and near-surface ice at middle to high latitudes and their spatial correlation with andesitic or partly altered basalt materials favor the alteration hypothesis. We propose the formation of these units through limited chemical weathering from basalt interactions with icy mantles deposited during periods of high obliquity. Alteration of sediments in the northern lowlands depocenter may have been enhanced by temporary standing bodies of water and ice.

Keywords: Mars, crust, basalt, andesite, alteration, thermal emission spectroscopy.

INTRODUCTION

Mars Global Surveyor (MGS) thermal emission spectrometer (TES) data reveal that low-albedo regions on Mars are characterized by assemblages of igneous minerals (plagioclase and pyroxenes) (Bandfield, 2002) with local concentrations of olivine (e.g., Hoefen et al., 2003) and hematite (e.g., Christensen et al., 2000a). The lack of abundant carbonates and limited amounts of other alteration phases imply that the Martian surface has not been pervasively altered by liquid water. The identification of both olivine and hematite, however, is intriguing, because these minerals imply past environments without significant water-rock interactions (olivine) and others with low-temperature aqueous precipitation (hematite) (Glotch et al., 2003). Modest surface alteration is also suggested by Martian high-albedo regions containing fine-grained dust (possibly plagioclase, zeolite, and/or palagonite) (e.g., Bandfield and Smith, 2003; Ruff, 2004) with nanophase iron oxides (Morris et al., 2000) and minor amounts of carbonates (Bandfield et al., 2003). Understanding the extent to which volatiles have altered surface rocks is central to unraveling the geologic history of Mars.

Studies of TES data related to classifying Martian surface lithologies have resulted in an ongoing debate centered on the interpretation of one of two global spectral end members that characterize low-albedo regions (Bandfield et al., 2000). Surface type 1 (ST1) is consistently interpreted as basaltic (e.g., Christensen et al., 2000b); however, surface type 2 (ST2) is variously interpreted as andesitic (Bandfield et al., 2000; Hamilton et al., 2001) or as partly altered basalt (Wyatt and McSween, 2002; Morris et al., 2003; Kraft et al., 2003; Ruff, 2004). Ambiguity in classifying ST2 arises because a spectral component of this unit can be interpreted as either volcanic siliceous glass (an abundant phase in andesite) or secondary phases common to altered basalt (smectite, palagonite, silica coatings, and zeolite).

Here we assess these conflicting interpretations of Martian surface lithologies in light of the new geologic context emerging from the MGS and Mars Odyssey (ODY) missions. We compare the mapped distributions of ST1 and ST2 with topography and estimates of crustal thickness derived from the MGS Mars Orbiter laser altimeter (MOLA) (Zuber et al., 2000), abundances of near-surface water ice measured by the ODY gamma ray–neutron spectrometer (GRS) (e.g., Boynton et al., 2002), distributions of ice-rich mantles (Mustard et al., 2001) and inferred snow deposits (Christensen, 2003) observed by the MGS Mars Orbiter camera (MOC) and ODY thermal emission imaging system (THEMIS), and location of geologic units interpreted to reflect surface-volatile interactions (e.g., Kreslavsky and Head, 2002; Tanaka et al., 2003; Head et al., 2003). On the basis of global geologic context, we propose a model to explain the distributions of ST1 and ST2, and argue that parts of Mars underwent surface alteration over a cold and episodically wet geologic history.

GLOBAL DISTRIBUTION OF TES SURFACE COMPOSITIONS

A global context image illustrating major subdivisions of the Martian crust made from MOC and MOLA data sets is shown in Figure 1A. The southern highlands are of Noachian to Hesperian age, whereas the northern lowlands are younger Hesperian to Amazonian materials covering a Noachian basement (Head et al., 2001; Frey et al., 2002). The white line in Figure 1A approximates a 40 km crustal-thickness dichotomy separating thinner crust to the north from thicker crust to the south (Zuber et al., 2000), and the yellow line marks the boundary of the Vastitas Borealis Formation (Tanaka et al., 2003). The Vastitas Borealis Formation is generally thought to be comprised of sediments derived from erosion of highland rocks, some of which were deposited by water in channels that empty into the basin. Vastitas Borealis Formation materials have recently been interpreted as altered sediments formed by the reworking of near-surface, in situ volatile-driven processes (Tanaka et al., 2003) and as a sublimation residue from frozen bodies of water (Kreslavsky and Head, 2002).

The global distribution of ST1 (green) and ST2 (red) is shown in Figure 1B. Blue pixels on this TES map represent regions covered by fine-grained dust, which prohibits spectral analysis of sand and rock. ST1 is restricted to a near-equatorial band of the southern highlands and Syrtis Major regions and a few local occurrences in the northern plains (Bandfield et al., 2000; Rogers and Christensen, 2003). The largest distribution, and highest concentration, of ST2 is in the northern lowland regions and circumpolar sand seas (Bandfield et al., 2000), which are within the area mapped as Vastitas Borealis Formation. ST2 is also present in moderate to high abundances, and mixed with ST1 materials, throughout southern mid- to high-latitude regions (Bandfield, 2002). The transition from ST1 to ST2 in the Southern Hemisphere appears gradual and has no obvious distinguishing boundaries, unlike the topographic dichotomy to the north (Bandfield, 2002).

There is no global systematic relationship between crustal thicknesses (Rogers and Christensen, 2003) or age and the distribution of ST1 and ST2. ST1 crosses over the 40 km crustal dichotomy, and large expanses of ST2 overlie both the thick crust of the southern highlands and the thin crust of the northern plains. ST2 materials range from Noachian to

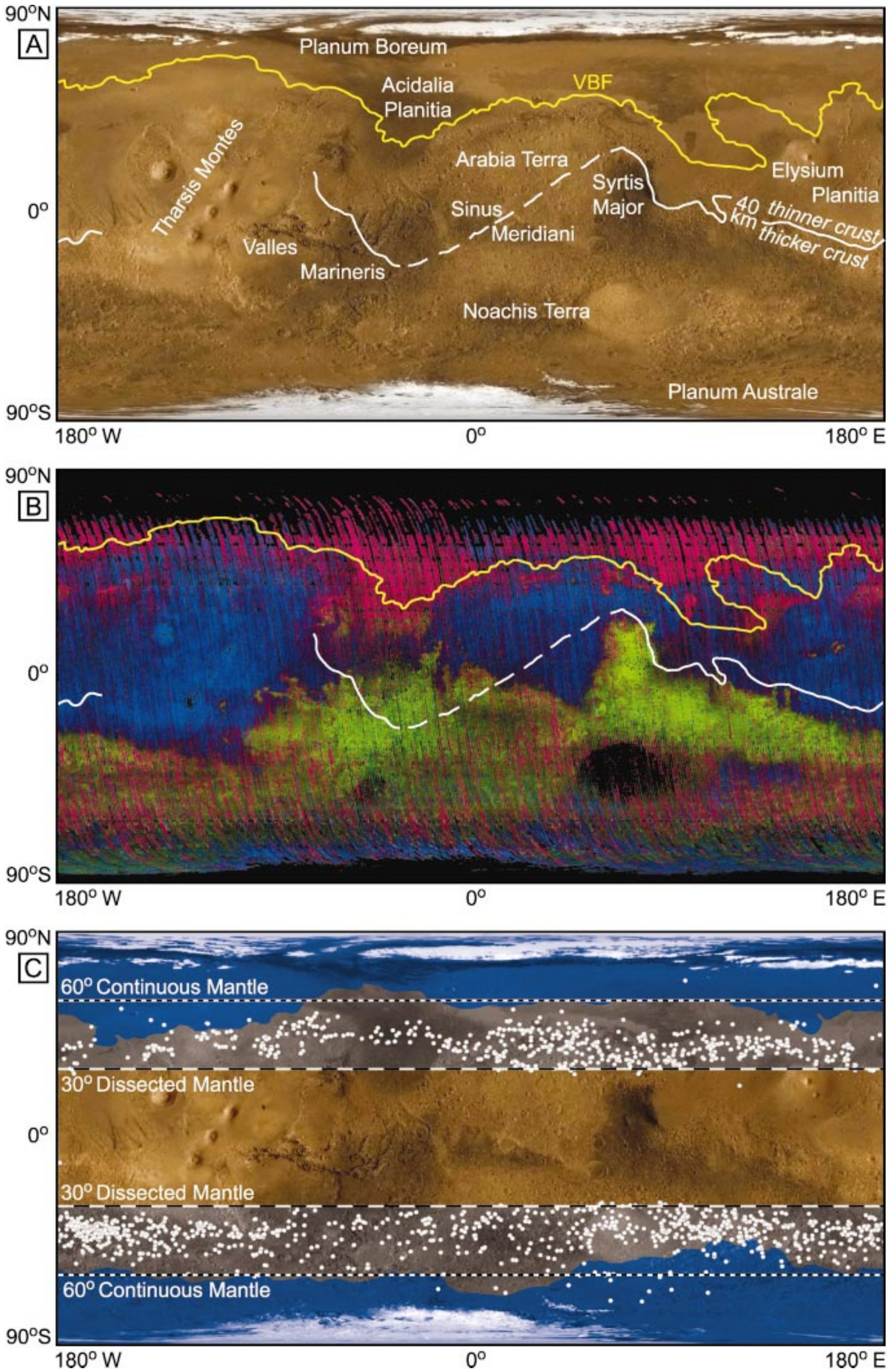

Figure 1. A: Major subdivisions of Martian crust illustrated by using Mars Global Surveyor (MGS), Mars Orbiter camera (MOC) and Mars Orbiter laser altimeter (MOLA) data sets. VBF—Vastitas Borealis Formation. B: Thermal emission spectrometer image of distribution of surface type: ST1 (green) and ST2 (red) materials and dust (blue). C: Distribution of near-surface water ice and ice-rich mantles. MOC-MOLA context image with gamma ray–neutron spectrometer (GRS) near-surface ice (blue) and mantle deposits (shaded gray from 30° to ~60°; poleward of 60°, continuous mantle deposits overlie GRS-measured near-surface ice, shown as blue). MOC observations of discontinuous mantle deposits are shown as white points.

Amazonian and overlap ST1 materials, which are Noachian and Hesperian. Instead, the global distributions of ST1 and ST2 are best correlated with latitude: ST1 dominates near-equatorial regions and ST2 dominates middle to high latitudes. This relationship is not perfect at all scales, as local abundances of ST1 exist in the northern lowlands (Rogers and Christensen, 2003) and regional mixing of ST1 and ST2 occurs in southern Acidalia Planitia (Wyatt et al., 2003) and western Syrtis Major (Ruff, 2004). However, at a global scale, a nearly bimodal distribution of ST1 and ST2 compositions is evident.

NEAR-SURFACE ICE AND ICE-RICH MANTLES

Analysis of GRS epithermal-neutron data indicates near-surface water ice (>50 wt%) in both hemispheres from ~60° to the poles (e.g., Boynton et al., 2002). Visible images from MOC have been used to map a mantling morphology interpreted as meter-thick ice-rich sediments at middle to high latitudes in both hemispheres (Mustard et al., 2001; Head et al., 2003). Poleward of 60° the mantle is continuous; from 30° to 60° it is partly degraded, interpreted as a formerly ice-cemented deposit from which ice sublimated (Mustard et al., 2001). Similar mantles identified in THEMIS visible images in mid- to high-latitude regions are interpreted as possible remnant snow packs (Christensen, 2003). Icy mantles are thought to form by deposition of atmospheric condensates during phases of high obliquity when water is transported from the poles to lower latitudes (e.g., Jakosky and Carr, 1985). Development of near-surface ice is likely connected to surface ice deposition, as GRS-measured abundances are too high to be accounted for by vapor diffusion alone (e.g., Christensen, 2003). Figure 1C illustrates the bimodal distribution of ice with a global MOC-MOLA context image superimposed with the mapped abundance of GRS-measured near-surface ice (blue) (e.g., Boynton et al., 2002) along with ice-rich mantles (shaded gray from 30° to ~60°; poleward of 60° the mantles overlie GRS-measured near-surface ice, shown as blue). MOC observations of discontinuous mantle deposits are shown as white points (Mustard et al., 2001).

RELATIONSHIP OF SURFACE COMPOSITIONS AND VOLATILES

Distributions of ST1 (green), ST2 (red), near-surface water ice and ice-rich mantles are compared in Figure 2 on north and south polar-projected images. Solid white lines encompass GRS-measured subsurface ice. Dashed white lines mark the areas from lat 60° to the poles of continuous ice-rich mantles and the areas from lat 30° to lat 60° of discontinuous mantle deposits. Also shown in the north-polar projected image is a yellow solid line marking the Vastitas Borealis Formation contact. ST1 is most abundant in near-equatorial regions where ice is absent. ST2 is most abundant poleward of ~30° in both hemispheres and is spatially correlated with ice-rich mantle deposits. In the Northern Hemisphere, ST2 distribution is mostly encompassed by the Vastitas Borealis Formation, whereas in the Southern Hemisphere,

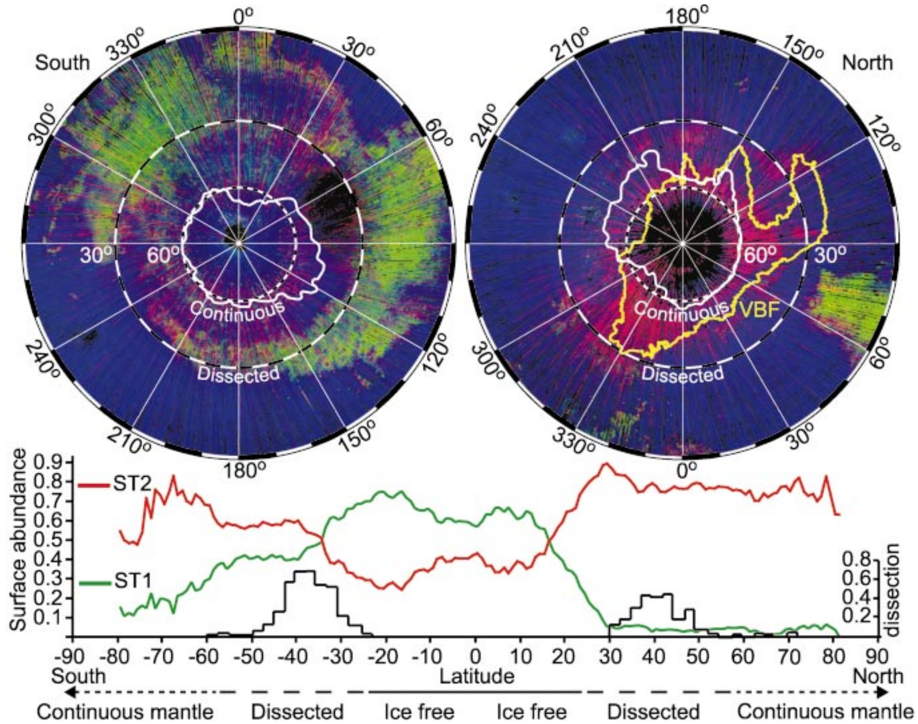

Figure 2. Distributions of surface type ST1 (green), ST2 (red), dust (blue), near-surface water ice, and ice-rich mantle deposits on north- and south-polar–projected images. Solid white lines encompass gamma ray–neutron spectrometer–measured near-surface ice, dashed white lines mark continuous (60° to poles) and discontinuous (30° to 60°) extent of mantle deposits, and yellow solid line shows Vastitas Borealis Formation (VBF) contact. Lower plot is of ST1 and ST2 normalized abundances from 90° south to 90° north, averaged across 0.5° bins of longitude and compared to percentages of Mars Orbiter camera observations (histogram) of dissected ice-rich mantle deposits.

ST2 becomes gradually more abundant toward the pole. Also shown in the lower part of Figure 2 is a plot of ST1 and ST2 normalized abundances from 90° south to 90° north averaged across 0.5° bins of longitude and compared (in a histogram) to percentages of MOC observations (Mustard et al., 2001) of the dissected ice-rich mantle deposit. In both hemispheres, the highest percentage of dissection occurs at ~40° and decreases toward the equator and pole. The transition from ST1 to ST2 in the Southern Hemisphere correlates well with the transition from a lack of ice-rich material (0°–25°S), to a maximum percentage of dissection (25°S–60°S), to uniform mantles of ice-rich deposits (60°S–90°S). In the Northern Hemisphere, a more dramatic crossover from ST1 to ST2 occurs at ~20° and is not as well correlated with the transition from ice-free to ice-rich mantles.

INTERPRETATION OF ST2

Formation mechanisms operating on a global scale are required to explain the extensive distribution of ST2 throughout the southern and northern mid- to high-latitude regions as well as its enhanced concentration in the northern lowlands of Mars. We examine both interpretations of these materials in light of the global geologic context described here.

ST1 Basaltic and ST2 Andesitic Lithologies

On Earth, andesites form primarily in subduction zones as a result of melting and fractional crystallization under hydrous conditions and assimilation of overlying silicic crust (Rudnick, 1995). Consequently, andesitic volcanism is mostly associated with thick continental crust. On Mars, however, the largest distribution of ST2 overlies thin crust in the northern plains. Moreover, the occurrence of ST2 without associated ST1 in the northern plains argues against its derivation by fractionation of basaltic magma. Fractionation should produce basaltic and andesitic rocks similar in age, but ST2 materials in the northern lowlands are significantly younger than southern highlands basalts. Partial melting of an ancient basaltic crust (rather than ultramafic mantle) might conceivably produce andesitic magmas, but such a scenario would require long-lived heat sources that were latitude dependent. The absence of Martian meteorites having andesitic compositions and appropriate ages argues against this scenario. These considerations leave us without a global-scale igneous model to explain the distribution of ST1 and ST2, although andesitic lavas could have formed on regional to local scales.

ST1 Basaltic and ST2 Partly Altered Basalt Lithologies

We propose that the spatial relationship between TES surface compositions and near-surface ice and ice-rich mantle deposits indicates both a latitude and topographic influence on the global surface alteration of Mars. The distribution of ST1 in near-equatorial regions is interpreted to reflect basaltic materials that have not been significantly affected by volatile-driven processes. This is consistent with the identification of local near-equatorial occurrences of olivine-rich rocks (e.g., Hoefen et al., 2003), which would likely be altered by prolonged ice and water interactions. The gradual poleward transition from ST1 to ST2 in the Southern Hemisphere is interpreted to reflect increased amounts of chemical weathering from basalt interactions with icy mantles deposited during periods of high obliquity. The more abrupt transition from ST1 to ST2 in the Northern Hemisphere marks the boundary of the Vastitas Borealis Formation and is correlated both with ice-rich mantle deposits and fluvial transport of materials into the northern lowlands depocenter. Alteration of sediments in the northern lowlands may have been enhanced by temporary standing bodies of water and ice.

NATURE OF SURFACE ALTERATION

The Dry Valleys of Antarctica may be a terrestrial analogue for characterizing chemical weathering on Mars because of the cold hyperarid environment, stable permafrost, and ground ice (e.g., Gibson et al., 1983). Additional analogues include the cold and arid climate of the summit of Mauna Kea, Hawaii (e.g., Morris et al., 1990), and volcano–ground ice interactions in Iceland (e.g., Squyers et al., 1987). Basalts in these environments are dominated by plagioclase and pyroxene, with limited abundances of a variety of alteration phases such as palagonites, zeolites, smectites, silica coatings, and/or carbonates. This group of minerals is similar to partly altered basalts proposed for ST2 materials on Mars (Wyatt and McSween, 2002; Morris et al., 2003; Kraft et al., 2003; Ruff, 2004), and the production of secondary phases does not require abundant liquid water. The formation of ice-rich mantles on Mars during periods of high obliquity likely enhances chemical surface alteration at middle to high latitudes over geologic time. The correlation between the sedimentary Vastitas Borealis Formation basin and concentrations of ST2 may also support temporary standing bodies of water and/or ice in the northern lowlands. However, the dominance of igneous minerals measured by TES still implies limited alteration.

SUMMARY

The controversy over TES surface lithologies is significant for understanding the petrogenesis of the Martian crust and its subsequent alteration. ST1 is concentrated in a near-equatorial band of the southern highlands, whereas ST2 dominates the middle to high latitudes in both hemispheres. The competing spectral interpretations for ST2 can be addressed by considering the geologic context of this global distribution pattern. ST2 does not correlate with thicker crust, as would be expected if it were andesite, and the different ages of ST1 and ST2 appear to preclude relating these units through fractional crystallization. Partial melting of an ancient basaltic crust might have produced andesitic magmas, but this mechanism would require latitude-controlled heat sources, and the lack of Martian meteorites having andesitic compositions and appropriate ages argues against this scenario. Instead, ST2 occurs in the southern highlands, where there is geomorphic evidence of ice-rich mantles and orbital measurements indicating subsurface water ice. In the northern lowlands, the distribution of ST2 conforms to the mapped Vastitas Borealis Formation, inferred to be fluvially transported sediments altered by interaction with water and/or ice. The distribution of ST1 in near-equatorial regions is correlated with materials that have not significantly interacted with volatile-driven processes. Thus, the global geologic contexts for ST1 and ST2 are consistent with basaltic and partly altered basalt lithologies rather than basaltic and andesitic lithologies. We propose that the spatial relationship between TES surface compositions and near-surface ice and ice-rich mantle deposits indicates both a latitude and topographic influence on the global surface alteration of Mars.

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