

BASALT, ALTERED BASALT, AND ANDESITE ON THE MARTIAN SURFACE: OBSERVATIONS, INTERPRETATIONS, AND OUTSTANDING QUESTIONS. M. B. Wyatt¹, H. Y. McSween, Jr.², P. R. Christensen¹, and J. W. Head III³, ¹Department of Geological Sciences, Arizona State University, Tempe, AZ 85287 (michael.wyatt@asu.edu), ²Department of Geological Sciences, University of Tennessee, Knoxville, TN 37919, ³Department of Geological Sciences, Brown University, Providence, RI 02912.

Introduction: To classify a volcanic rock accurately, and distinguish it from an altered volcanic surface or sedimentary rock of similar composition, one must utilize an assortment of chemical, mineralogical, and textural analyses. Questions and uncertainties in classifications can arise without a full suite of such measurements as some mineral phases and chemical trends alone are not discriminating factors for assigning petrologic names. Such difficulties are common when classifying rocks on Mars using in-situ and orbital remote sensing techniques because of a lack of chemical, mineralogical, and textural measurements at comparable spatial and spectral resolutions. We can, however, add a perspective to improve our understanding of the origin and composition of martian surface materials by placing existing compositional measurements into newly emerging geologic contexts.

The purpose of this work is to summarize current observations and interpretations of martian low-albedo surface compositions, focusing on those derived from the Mars Global Surveyor Thermal Emission Spectrometer (MGS-TES) experiment, and place them into geologic contexts relevant to mapped distributions. Outstanding questions pertaining to the origin and composition of martian low-albedo surface materials are discussed and ongoing work to address these issues is presented.

Background: Prior to MGS-TES, measurements of mineral and bulk rock chemistries have led to a variety of interpretations of the surface composition of martian low-albedo regions.

Orbital Remote Sensing. Visible/near-infrared spectroscopic data of some martian low-albedo regions, interpreted to be composed of rock and residual dark soil, are characterized by ~1 and 2- μm absorptions that are commonly attributed to the presence of ferrous iron (Fe^{2+}) in the form of pyroxene and hematite (both nanophase and crystalline) [e.g., 1-4]. Based on these observations, Phobos-2 ISM spectra of Syrtis Major have been interpreted to represent two-pyroxene basalts similar to basaltic shergottite meteorites [5]. A different perspective suggested by [6] attributes the observed signatures in dark regions to lesser amounts of pyroxene plus dark altered materials that are more consistent with the observation of a 3- μm water band in intermediate to low albedo regions. High-resolution

telescopic spectra of Acidalia Planitia [7] exhibit weaker mafic mineral bands compared to Syrtis Major which may be consistent with the presence of basaltic glass and/or surface coatings.

In-situ Measurements. Mars Pathfinder rocks were determined to be chemically similar to andesite based on alpha proton X-ray spectrometer (APXS)-measured element abundances [8], but textural and visible/near-infrared multispectral evidence supporting the hypothesis that these rocks are volcanic is more ambiguous [9]. A sedimentary origin or surface coating could thus not be ruled out without textural or mineralogical data. A re-analysis of APXS chemistry indicates that Pathfinder rocks may in fact have a high water content, which supports a non-igneous classification [10]. Furthermore, soil compositions at the Viking and Mars Pathfinder landing sites were compared by [11] and it was concluded that the global dust formed by weathering of basalt rather than andesite.

MGS-TES: Mineral Abundances and Bulk Oxides: Studies of low-albedo regions on the martian surface using atmospherically corrected thermal emissivity data from the Mars Global Surveyor Thermal Emission Spectrometer (MGS-TES) have identified two distinct global surface spectral signatures [12-15]. The Surface Type 1 (ST1) spectral end-member has been interpreted as an unaltered basalt characterized by high deconvolved modal abundances of plagioclase and clinopyroxene [12-13, 16]. The Surface Type 2 (ST2) spectral end-member has been variously interpreted as an unaltered andesitic composition (basaltic andesite to andesite) [13, 16] or partly altered basalt [17]. The unaltered andesitic composition is characterized by high deconvolved modal abundances of plagioclase and high-silica volcanic glass [13, 16]. The partly altered basalt is characterized by high deconvolved modal abundances of plagioclase and alteration phases (sheet silicates, K-feldspar, and silica coatings) and low modal pyroxene [17]. Detectable abundances of hematite [e.g. 18], orthopyroxene [e.g. 19], and olivine [e.g. 19] have also been identified in regional and local occurrences where ST1 basaltic compositions dominate surface units. The identification of these phases may represent unique surface lithologies (i.e. dunite), or higher abundances of each phase in a basaltic surface unit (i.e. olivine bearing basalt).

Although TES is a mineralogical tool, bulk rock geochemistry can be derived from deconvolved modal mineralogies by combining the compositions (wt. % oxides) of spectral end-members in proportion to their relative modes. Estimated ST1 and ST2 chemical compositions [20] from deconvolutions derived using modified spectral end-member sets of [13,16-17, 21] were shown to be very similar in their overall respective bulk chemistries. Assuming an igneous composition for both ST1 and ST2 lithologies, [20] suggested that ST2 andesites might have formed by fractional crystallization under hydrous conditions of a ST1 basaltic andesite parent magma. The required H₂O for this is intriguing because such high contents are typically found only in terrestrial subduction zone environments and are in contrast with predicted martian mantle volatile contents. Assuming an igneous composition for ST1 and an altered composition for ST2, [20] also suggested that weathering of ST1 could produce sediments with ST2 compositions. Neither surface type was shown to be compositionally similar to basaltic shergottites or the global dust, but dust formation was shown to be possible by the addition of iron-oxides to ST2.

Terrestrial Examples. The cut surfaces of Deccan and Columbia River flood basalts are terrestrial examples of rocks with similar spectral shapes, deconvolved mineral abundances, and derived bulk rock chemistries compared to the ST1 spectral end-member [12-13, 16]. The flood basalt samples contain phenocrysts of plagioclase and pyroxene in a microcrystalline groundmass of the same phases and have bulk silica and alkali values which classify them as subalkaline basalt-basaltic andesites (49.5-51.7 wt% SiO₂ and 3.2-4.1 wt% Na₂O+K₂O) [22]. The cut surface of a continental arc-andesite from the Medicine Lake Highlands and a partly altered Columbia River flood basalt surface (whose cut surface is the same as the CRB sample above) are terrestrial examples of rocks with similar spectral shapes compared to the ST2 spectral end-member [13, 16, 17]. The Medicine Lake Highland sample contains small amounts of plagioclase and pyroxene phenocrysts with a glassy to microcrystalline-intergranular groundmass composed of the same phases and has bulk silica and alkali values which classify it as a subalkaline andesite (57.2 wt% SiO₂ and 5.15 wt% Na₂O+K₂O) [22]. The partly altered Columbia River flood basalt surface contains small amounts of plagioclase and pyroxene and secondary products interpreted as amorphous silica and sheet silicates (Fe-smectite and Ca-montmorillonite) [22].

Mapped Distributions of Surface Compositions. The distribution of the ST1 unit (basalt) is restricted to southern highlands and Syrtis Major regions that are of

Noachian or Hesperian age and a few local deposits in the northern plains [13, 23]. The ST2 unit (andesitic and/or altered basalt) displays the highest concentrations in the younger Amazonian-age northern lowlands regions of Acidalia Planitia and the circumpolar sand seas [13]. ST2 compositions are also present in moderate abundances, or an intermediate composition, throughout the low-albedo highlands south of ~ 40°S with higher concentrations in several isolated regions south of Solis Planum, southeast of Hellas Basin, and along the edge of the southern polar cap [13, 21]. The distribution of the highest concentrations and largest extents of the two surface spectral units is thus split roughly along the planetary dichotomy which separates ancient, heavily cratered crust in the southern hemisphere from younger lowland plains in the north. However, intermediate compositions and/or mixing of units and isolated regions are also present [13, 21].

Outstanding Questions: The initial ambiguity in interpreting the ST2 lithology from deconvolved mineral abundances and laboratory rock spectra arose because volcanic siliceous glass (a major component of andesite) was shown to be spectrally similar to some alteration phases (sheet silicates and suggested silica coatings) over the spectral ranges used in deriving the atmospherically corrected ST1 and ST2 spectral end-members [17]. Absorption features between 500-550 cm⁻¹ in laboratory spectra distinguish sheet silicates from high-silica volcanic glass; however, this region was excluded while deriving the ST1 and ST2 spectral end-members because the CO₂ atmosphere of Mars becomes largely opaque near this spectral region. The original interpretation of the high-silica glass spectral end-member phase as a primary volcanic glass was also shown to be too limited, as deconvolved modal abundances of the natural surface of a Columbia River flood basalt suggested it could also represent an amorphous high-silica alteration product [17]. Analyses by [24] have further shown that the addition of high-silica alteration coatings on basalts results in a surface that is spectrally similar to andesite. Recent work by [25] and [26] have shown additional alteration phases such as zeolites and palagonites to be spectrally similar to high-silica glass, thus adding to the possible range of mineral phases present in ST2 materials. Future work is needed to understand better the degree of substitution and spectral effects of varying crystallinity in amorphous phases over a range of chemical compositions as accurate deconvolution of mixture spectra is largely dependent on the input of spectral end-members that represent an appropriate range of compositions in the mixture.

Geologic Context: A perspective can be added to improve our understanding of the origin and composi-

tion of martian surface materials by placing existing compositional measurements and distributions of surface materials into newly emerging geologic contexts. An important but often overlooked perspective is that a single interpretation of spectra may not be warranted everywhere on Mars (Ockam wasn't always right). Here we focus on the distribution of TES derived ST2 materials in three different martian geologic environments: 1) northern lowlands, 2) north circumpolar sand seas, and 3) southern highlands.

Northern lowlands. The mapped distribution of ST2 in the northern lowlands is shown to be concentrated in Acidalia Planitia, part of the low-albedo surfaces of the Vastitas Borealis Formation (VBF) [13, 17]. The VBF makes up one of the largest surface units on Mars and was initially mapped on the basis of its morphologic and albedo characteristics and its occurrence below the martian highland/lowland boundary [27]. Volcanic, tectonic, glacial, periglacial, and sedimentary related processes have been attributed to various landforms observed in the unit [28-37 references therein].

The VBF plains have most recently been interpreted as sedimentary deposits derived from outside the basin [38] or altered sediments formed through local reworking of earlier deposits by permafrost processes [39]. The sediments are interpreted to be underlain by ancient ridged volcanic plains. Both of the VBF "new-view" theories propose these materials have undergone significant reworking by either transport and/or indigenous weathering and may support alteration of basaltic sands within this depocenter. The VBF morphology is characterized by a mixture of smooth plains, polygonal troughs and fractures, and pitted domes whose origins have been suggested to involve interactions between surface, and near-surface, volatile-rich material (water and/or ice) [38,39]. TES spectra of the VBF boundary in southern Acidalia Planitia, where it is not obscured by dust, indicate that the proportion of ST1 (unaltered basalt) material increases outside the basin [40].

Recent work by [41 and references therein] summarizes evidence for the probability of sedimentary silica existing on Mars and emphasizes the highly mobile nature of silica during near surface alteration of basaltic rocks under a wide variety of temperature, pressure, and fluid conditions. Palagonitization is a commonly proposed alteration process for the martian surface and the production of palagonites and secondary clays, both of which have been shown to be spectrally similar to high-silica volcanic glass, result in a high degree of silica mobilization [41 and references therein]. The geologic context of the VBF as a sedimentary basin with either transported or indigenous

materials having interacted with surface or near-surface volatile rich materials [38-39] supports an altered basalt classification for the TES ST2 unit in the northern lowlands.

North circumpolar sand seas. The largest continuous area of dunes on Mars are the transverse dune fields in the north circumpolar sand seas. Small simple barchan dunes and large mega-barchans also occur on the margins of the sand seas and in areas of thin sand cover. Observations of possible reversals of dune-forming wind directions suggest that these dunes are active today and there is evidence the dunes have some sources within the polar layered deposits.

The ST2 unit (andesitic and/or altered basalt) displays the highest concentrations in the northern lowlands regions of Acidalia Planitia and the circumpolar sand seas [13]. The north circumpolar sand sea environment is however very different from the northern lowland plains. It is very unlikely that weak alteration rinds or coatings (i.e. sheet silicates, palagonites, and zeolite) could persist on the primarily active north polar sands that are being constantly abraded. Silica coatings can however be resistant to mechanical weathering and may remain as coatings or cementing agents.

If polar dune fields are derived from polar layer deposits, they could represent basaltic compositions with resistant silica coatings. Conversely, the polar dune fields could be locally derived from an andesitic source or transported from a regional andesitic source. The presence of weak alteration rinds and coatings is very unlikely, leaving silica (coating vs. primary volcanic glass) as the likely phase contributing to the ST2 spectral shape.

Southern highlands. ST2 materials are present in moderate amounts, or as an intermediate composition, throughout the southern highlands with higher concentrated abundances occurring in several isolated regions south of Solis Planum, southeast of Hellas Basin, and along the edge of the southern polar cap [13, 21]. ST1 materials are also located in the southern highlands and Syrtis Major regions that are of Noachian or Hesperian age [13].

It has been shown that ST2 andesites might have formed by fractionation of ST1 basaltic andesite magma under hydrous conditions in the shallow martian crust based on TES derived bulk chemistry [20]. The required H₂O for this is intriguing because such high contents are typically found only in terrestrial subduction zone environments and are in contrast with predicted martian mantle volatile contents. Although the addition of water to the martian mantle through subduction has not generally been advocated, [42] suggested that andesitic crust could have formed on

Mars through hydrous melting. In this model, mantle water is primordial, leading to an early crust of andesite with later dry, basaltic volcanism. Bimodal magmatism, leading to the production of siliceous melts from basaltic parent magmas, was argued by [43] to occur through the formation of lenses within solidification fronts. It is not obvious however that such a mechanism could operate on a global scale and produce volumetrically significant amounts of andesite. ST2 is an altered ST1 in the southern hemisphere, the observed distribution of materials could represent incomplete weathering. However, the southern highlands are old and heavily cratered with little evidence for resurfacing or interactions between surface or near-surface volatile rich materials. It is therefore very unlikely that the processes which resurfaced the northern lowlands are the same processes which affected the surface compositions of the southern highlands.

Ongoing Work: An outstanding question regarding deconvolved mineral abundances of ST1 and ST2 is the ability to distinguish alteration phases (sheet silicates, silica coatings, zeolites, and palagonites) from high-silica volcanic glass. The original TES atmospheric and surface spectral shapes were derived using conservative spectral ranges (233-508 cm^{-1} and 825-1301 cm^{-1}) in part to avoid CO_2 hot band and isotope features [13]. Absorption features between 500-550 cm^{-1} in laboratory spectra distinguish some sheet silicates from high-silica volcanic glass. Silica coatings and some zeolites and palagonites do not exhibit the same distinctive spectral shapes as sheet silicates, and may be extremely difficult to distinguish from high-silica volcanic glass [24-26].

Current work is focused on re-deriving local TES atmospheric and surface spectral shapes at wavelengths that cover the diagnostic 500-550 cm^{-1} range to determine if sheet silicates or other alteration phases (zeolites and palagonites) are identified or distinguished from high-silica volcanic glass. Atmospheric gas shapes (H_2O and CO_2) have been accurately modeled by [44 and references therein] and are removed from spectra thus allowing a greater spectral range for deriving surface spectral shapes. New atmospherically corrected surface spectral shapes of the northern lowlands, north circumpolar sand seas, and southern highlands are being individually derived to examine spectral differences and similarities between the different geologic environments.

References: [1] Adams J. B. and T. B. McCord (1969) *JGR*, 74, 4851-4856. [2] Singer R. B. et al., (1979) *JGR*, 84, 8415-8426. [3] Morris R. V. et al., (1989) *JGR*, 94, 2760-2778. [4] Mustard J. F. et al., (1993) *JGR*, 98, 3387-3400. [5] Mustard J. F. and J.

M. Sunshine (1995) *Science*, 267, 1623-1626. [6] Calvin W. M. (1998) *GRL*, 25, 1597-1600. [7] Merényi, E. R. et al., (1996) *Icarus*, 124, 280-295. [8] Rieder R. et al., (1997) *Science*, 278, 1771-1774. [9] McSween H. Y. et al., (1999) *JGR*, 104, 8679-8715. [10] Foley C.N. et al., (2001) *LPSC XXXII*, Abstr #1979. [11] McSween H. Y. and Keil K. (2000) *GCA* 12, 2155-2166. [12] Christensen P. R. et al. (2000) *JGR*, 105, 9609-9622. [13] Bandfield J. L. et al. (2000) *Science*, 287, 1626-1630. [14] Bandfield J. L. et al. (2000) *JGR*, 105, 9573-9587. [15] Smith M. D. et al. (2000) *JGR*, 105, 9589-9609. [16] Hamilton et al. (2001) *JGR*, 106, 14733-14746. [17] Wyatt M. B. and McSween H. . (2002) *Nature* 417, 263-266. [18] Christensen P. R. et al., (2000) *JGR*, 105, 9632-9642. [19] Hamilton V. E. et al., (2002) *LPSC XXXIII*, Abs #1937. [20] McSween H. Y. et al., (2003) *LPSC XXXIV*, Abs # 1189. [21] Bandfield J. L. (2002) *JGR* 107 (E6), 10.1029/2001JE001510. [22] Wyatt M.B. et al. (2001) *JGR* 106, 14,711-14,732. [23] Rogers D. et al. (2001) *LPSC XXXII*, Abstr #2010. [24] Kraft M. D. et al. (2003) *LPSC XXXIV*, Abstr #1420. [25] Ruff S. W. and Christensen P. R. (2003) *LPSC XXXIV*, Abstr #2068. [26] Morris R. V. et al., (2003) *LPSC XXXIV*, Abstr #1874. [27] Scott D. H. et al., (1986-87) USGS Maps I-1802A, B, C. [28] Tanaka K. L. et al., (2003) *JGR*, 2002je001908, in press. [29] Scott D. H. et al., (1986-87) USGS Maps I-1802A, B, C. [30] Parker T. S. et al., (1989) *Icarus*, 82, 111-145. [31] Head J. W. et al., (1999) *Science* [32] Tanaka K. L. et al., (2001) *Geology*, 29, 427-430. [33] Kargel J. S. et al., (1995) *JGR*, 100, 5351-5368. [34] Kreslavsky M. A. and Head J. W. (2002) *JGR*, 107, 10.1029/2001JE001831. [35] Tanaka K. L. (1997) *JGR*, 102, 4131-4149. [36] Clifford S. M. and Parker T. J. (2001) *Icarus*, 154, 40-79. [37] McGill G. E. and Hills L. S. (1992) *JGR*, 97, 2633-2647. [38] Head J. W. et al. (2002) *JGR* 107(E1), 10.1029/2000JE001445. [39] Tanaka K.L. et al. (2003) *JGR*, in press. [40] Wyatt M. B. et al. (2003) *JGR*, in press. [41] McLennan S. C. (2003) *Geology*, v. 31, no. 4, 315-318. [42] Lowman P. D. (1989) *Precambrian Res.*, 44, 171-195. [43] Marsh B. D. (2002) *GCA*, 66, 2211-2229. [44] Bandfield J. L. and Smith M.D. (2003) *Icarus*, 161, (47-65).