

**THE CHEMICALLY ALTERED BASALTIC NORTHERN PLAINS OF MARS: TES, OMEGA, AND GRS INTEGRATED DATA SETS AND CONCLUSIONS.** M. B. Wyatt, Department of Geological Sciences, Brown University, Providence, RI 02912 (Michael\_Wyatt@Brown.Edu).

**Introduction:** To classify a volcanic rock, and distinguish it from an altered volcanic surface or sedimentary rock of similar composition, one must utilize an assortment of mineralogical, chemical, 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 have been common in the past when classifying rocks on Mars because of a lack of compositional measurements at comparable spatial and spectral resolutions. Today, there is an unprecedented collection of high-quality mineralogical, chemical, and textural data from in-situ and orbital remote sensing techniques that allow us to better constrain the origin and evolution of martian surface materials.

The purpose of this work is to summarize our current understanding of the compositions of the northern lowlands of Mars from MGS Thermal Emission Spectrometer (TES), ODY Thermal Emission Imaging System (THEMIS), ODY Gamma Ray Spectrometer (GRS), and MEX Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité (OMEGA) observations. The combined mineral and chemical abundances, mapped distributions, and geologic context from all of these instruments lead to the following conclusions: 1) the northern plains of Mars are basaltic in composition; 2) the basalt is chemically altered, with secondary amorphous to poorly crystalline silica-rich phase(s) occurring within thin weathering rinds or as coatings; 3) the alteration is immature, spatially extensive, limited by low water to rock ratios, and likely resulted from northern plains sediments interacting with near-surface volatiles deposited as ice (snow) during phases of high obliquity.

**TES Mineralogy Background:** The abundances and compositions of TES mineral-phases in the low-albedo northern plains of Mars have been a focus of considerable study and debate in recent years. Large expanses of Acidalia Planitia surface materials were originally characterized by the TES Surface Type 2 (ST2) spectral endmember [1]. The ST2 spectrum is distinguished by a rounded, slightly V-shaped 800 to 1200 wavenumber region of absorption and uniform absorption at low wavenumbers. A central question with this endmember is whether it represents the spectral signature of a high-silica primary volcanic lithology (andesite) [1] or the effects of chemical alteration on basaltic surface materials [e.g. 2]. Constraining the

composition of the northern lowlands is significant for understanding the petrogenesis of the Martian crust and its subsequent alteration. Identification of widespread andesite may imply a recent episode of plate tectonics on Mars while altered basalt would indicate extensive surface-volatile interactions.

**TES Mineralogy – Progress from The 6<sup>th</sup> International Conference on Mars to Today:** Over the past 4 years, significant contributions have been made by numerous authors that address the fundamental questions relating to lithologic interpretations of the TES ST2 spectral endmember. Selected studies will be divided into laboratory work and TES data analysis.

**Laboratory work.** Detailed studies have examined a wide range of alteration products in terrestrial basaltic rocks and their effects on thermal emission spectra. The primary question that attracted numerous authors involved the modeling of phyllosilicate minerals and amorphous high-silica phases for ST2 materials. Both of the original linear deconvolutions of ST2 by [1] (andesitic) and [2] (altered basalt) required smectite clay minerals to be modeled at or above the TES detectability limit of 10 – 15 vol. %. Furthermore, [2] demonstrated that smectites could be forced to abundances up to 30 vol. % by removing all spectrally similar phases (high-silica glasses), with comparable RMS errors to [1], while modeling over the same wavenumber range (400-508  $\text{cm}^{-1}$  and 825-1280  $\text{cm}^{-1}$ ). The favored model for ST2 in both studies [1, 2], however, was a combination of phyllosilicates and a synthetic high-silica- $\text{K}_2\text{O}-\text{Al}_2\text{O}_3$  rich glass. The differences in lithologic interpretations (andesite vs altered basalt) originally arose from the different interpretations of the high-silica glass endmember as a primary volcanic glass [1] or as an amorphous alteration product similar to ones found on Columbia River Basalt natural surfaces [2].

Major steps towards addressing the question of the origin of high-silica phase(s) in ST2 materials were taken in papers by Michalski et al [3-5], Kraft et al [6], and Morris et al. [7]. Detailed laboratory examinations of silica polymorphs [3,6] and well-characterized smectite clay minerals and clay bearing rocks [4-5] provide evidence that smectite clays alone, and any clay minerals with similar structural and chemical properties, cannot adequately explain the high-silica component in ST2 materials. Michalski et al [3-5] demonstrate that the position of the emissivity minimum in ST2 suggests a Si/O ratio of 0.4-0.5 for the

high-silica component, while all clay minerals have Si/O ratios  $< 0.4$ . Furthermore, laboratory examination of the  $450\text{--}540\text{ cm}^{-1}$  spectral region for clay minerals, and comparison with previous TES results from [8], demonstrate that ST2 regions on Mars do not show evidence for abundant, Fe- or Al- bearing dioctahedral clay minerals. This wavenumber range is outside the original spectral range used by [1] and [2] for linear deconvolution and thus provided new insight to the origin of the high-silica component. Michalski et al [3-5] conclude that the high-silica spectral component to ST2 can only be explained by the incorporation of a silica-rich and highly polymerized material with limited long-range structural order. Minerals or mineraloids that could satisfy these criteria include Al- or Fe-rich opaline silica, silica-rich allophane-like mineraloids, and the most silica-rich zeolites [3-6, 8]. They note it is also possible that the material represents an intimate-physical mixture of pure opal and a poorly crystalline aluminosilicate phase, including clay-precursors, and palagonites [7].

Koepfen and Hamilton [9] specifically examined the question of discriminating glass and phyllosilicate minerals in thermal infrared data and found that mixtures of high-silica- $\text{K}_2\text{O-Al}_2\text{O}_3$  glass and phyllosilicates are susceptible to overestimating phyllosilicate abundances, with minimal increases in RMS error, if the glass spectrum is not present in the end-member set. This result is directly comparable to the test performed by [2]. Missing phyllosilicates, however, are more likely to be modeled as combinations of other phyllosilicates rather than additional glasses [9]. From their study, if glasses are included in the endmember sets, a total uncertainty of  $\pm 15\%$  is found for glass and phyllosilicate modeled abundances. Koepfen and Hamilton [9] apply these laboratory results to ST2 and find that the high-silica- $\text{K}_2\text{O-Al}_2\text{O}_3$  glass abundance is above the instrument detection limit and is a likely component on the martian surface. These results are consistent with the favored model for ST2 in [1-2].

**Summary.** The laboratory studies summarized above constrain the types of high-silica phase(s) that contribute to the ST2 spectral endmember. It has been demonstrated that phyllosilicate minerals alone do not account for the unique spectral signature of ST2. These results limit the degree of possible alteration for ST2 materials. However, the uncertainty between a high-silica primary volcanic lithology (andesite) [1] and the effects of chemical alteration on basaltic surface materials [2-8] still exists using laboratory thermal emission data alone.

**TES Data Analysis.** Several studies have examined the geologic context of the abundances and distributions of TES derived minerals to constrain li-

thologic interpretations [e.g. 10]. Other studies have re-derived the global TES endmembers and examined in detail compositional trends on regional scales [11]. Studies summarized below are from Wyatt et al. [10] and Rogers and Christensen [11].

The competing spectral interpretations for ST2 were addressed by Wyatt et al. [10] by examining the geologic context of the ST1 and ST2 global distribution pattern. It was shown by [10] that there is no global systematic relationship between crustal thickness [12] or age and the distribution of ST1 and ST2, as would be expected in a basalt-andesite model. Andesitic volcanism on Earth is mostly associated with thick, continental crust; however, on Mars 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 being derived 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, especially under wet conditions, but the absence of Martian meteorites having andesitic compositions and appropriate ages argues against this possibility.

Instead, [10] demonstrated that ST1 materials dominate equatorial and mid-latitude regions and ST2 materials dominate the high-latitude northern lowlands and southern highlands. Wyatt et al. [10] relate this spatial distribution to near-surface ice and ice-rich mantle deposits and proposed both a latitude and topographic influence on the global surface alteration of Mars. A gradual transition from ST1 to ST2 in the Southern Hemisphere correlates well with the transition from a lack of ice-rich material ( $0^\circ\text{--}25^\circ\text{S}$ ), to a maximum percentage of dissection ( $25^\circ\text{S--}60^\circ\text{S}$ ), to uniform mantles of ice-rich deposits ( $60^\circ\text{S--}90^\circ\text{S}$ ). This trend is interpreted to reflect increased amounts of chemical weathering from basalt interactions with icy mantles. In the Northern Hemisphere, an abrupt transition from ST1 to ST2 occurs at  $\sim 20^\circ$  and is correlated both with ice-rich mantle deposits and the Vastitas Borealis Formation (VBF) boundary. VBF materials have been interpreted as sediments formed by the reworking of near-surface, in situ volatile-driven processes [13] and as a sublimation residue from frozen bodies of water [14]. Thus, alteration of sediments in the northern lowlands may have been enhanced by temporary standing bodies of water and ice.

Rogers and Christensen [11] have identified eleven unique regional TES spectral endmembers while noting that groups of these spectral shapes can be aver-

aged to produce spectra that are similar to ST1 and ST2 [1]. In their study, four compositional units are defined based on relative abundances of plagioclase, pyroxene, and high-silica phase(s) [11]. Three basaltic compositional units distributed between  $\pm 45^\circ$  latitude (equatorial to mid-latitudes) are correlated with distinct provinces defined by large-scale morphology, elevation, and to some extent age [11]. These relationships suggest that the compositional differences between these spectral units are connected to original bedrock mineralogies. Specifically, Syrtis Major exhibits differences in mineralogy that suggests different degrees of fractional crystallization, assimilation, or source region composition [11]. These exciting results demonstrated that a variety of igneous processes have occurred on Mars and produced distinct basaltic surface materials.

Rogers and Christensen [11] also find that high-latitude regions ( $>45^\circ$ ) are dominated by high-silica phase(s) and that surface alteration is more likely to be the primary control on differences in observed spectral signatures. It is also noted that some local units equatorward of  $45^\circ$  contain moderate abundances of high-silica phases. They also examine in detail the compositions of high-latitude and low-latitude regions to infer a composition of the unaltered high-latitude substrate [11]. They specifically examine if the high-latitude substrate is similar to or different than the average equatorial to mid-latitude compositions. Rogers and Christensen [11] find that the pyroxene mineralogy of the high-silica regions is dominated by low-Ca pyroxene, while the equatorial highlands are dominated by high-Ca pyroxene. Also, high-latitude surfaces exhibit more than 10 % lower pyroxene abundances and  $\sim 5\%$  greater plagioclase abundances relative to the average equatorial to mid-latitude basalts. Given the differences in the type of pyroxenes found between high- and low- latitudes, and the higher plagioclase abundances at high-latitudes, [11] propose that the substrate mineralogy at high-latitudes may have consisted of higher abundances of less-stable minerals such as glass and/or olivine. These minerals and phases may have thus been more easily chemically weathered. It is important to note that this substrate mineralogy described for high-latitude surfaces would be basaltic in nature.

**Implications for Water.** The dominance of igneous minerals measured by TES for ST1 and ST2, as well as the 11 regional endmembers from [15], implies limited global chemical alteration on Mars, but greater alteration at high-latitudes and in the low-lying northern plains. The Dry Valleys of Antarctica may be the best terrestrial analogue for weathering on Mars because of the cold, hyper-arid environment, stable

permafrost, and ground ice. Basalts in these environments are dominated by plagioclase and pyroxene, with limited abundances of alteration phases similar to those proposed for ST2 materials (palagonites, zeolites, and silica coatings). All of these secondary products can be produced on Mars by chemical weathering of basalt without an abundance of liquid water.

**TES Summary.** The global geologic context and distributions of mineral abundances and compositions derived from TES are most consistent with equatorial to mid-latitude basalts and high-latitudes altered basalt. Laboratory studies of thermal emission spectra of altered basalts have constrained the secondary phases. The secondary phases likely consist of some combination of Al- or Fe-rich opaline silica, silica-rich allophane-like mineraloids, palagonites, and/or the most silica-rich zeolites [2-8].

#### **OMEGA and GRS: “Completing the Picture”**

The following sections examine OMEGA and GRS data of the northern plains of Mars to further constrain the primary and (now likely) secondary mineral-phase abundances and compositions modeled in TES data.

**TES and OMEGA.** TES ST2 areas are characterized by an OMEGA spectral signature that is relatively featureless, but with a strong blue slope (decreasing reflectance as a function of wavelength) from 0.9 to 2.6 microns [15]. The OMEGA spectrum lacks evidence of distinct mafic mineral bands (found in basalt and andesite) as well as molecular vibration absorptions due to  $\text{H}_2\text{O}$  and/or  $\text{OH}^-$ , which might indicate the presence of well-crystalline alteration products and phyllosilicates [15]. Mustard et al. [15] note that the observed OMEGA spectral signature of the northern lowlands is consistent with alteration rinds or coatings that would mask underlying mafic mineral signatures. OMEGA observations are thus consistent with TES observations and interpretations of limited chemical weathering of basaltic materials in the northern plains of Mars.

**TES and GRS.** The TES and GRS datasets provide unique and complementary insights into martian surface compositions. TES measures the composition of the upper hundred microns of the surface while GRS measures the composition of the upper few tens of centimeters. Recent GRS studies report Si, K, Fe, Th, and K/Th for “regions” with TES ST1 areal fractions exceeding 17% (RT1) and TES ST2 areal fractions exceeding 36% (RT2) [16,17].

RT2 chemistries have higher abundances of Fe, K, and Th compared to RT1 [16,17]. Abundances of Si and K/Th ratio are similar to the bulk planet and do not show significant spatial variations [16,17]. It should be noted that absolute Si measurements from GRS are tied to Pathfinder values and that the normalization is a

constant factor across the Si dataset [17]. GRS estimates of relative variations in Si content are rigorous; however estimates of absolute Si content are not. As a result, GRS data cannot be used to evaluate processes that require accurate knowledge of absolute Si content [17].

The TES instrument has mainly been utilized as a mineralogical tool, but thermal emission spectroscopy also provides a means for deriving chemical oxide abundances. MGS-TES chemical compositions are calculated from deconvolved modal mineralogies (vol. %) by combining the compositions of the spectral endmembers (wt. % oxides) in proportion to their relative modeled abundances [18]. Wyatt et al. [19] quantified the uncertainties in derived chemical compositions and demonstrated their use in correctly classifying volcanic rocks. The one-sigma standard deviations of the absolute differences between measured and modeled major oxide abundances range from 0.4 to 2.6 wt. % [18,19].

The most significant chemical differences between TES ST1 and ST2 are higher abundances of FeO for ST1 (ST1 15.2 % vs. ST2 12.4 %) and higher abundances of SiO<sub>2</sub> for ST2 (ST2 57.9 % vs. ST1 53.9 %). GRS RT2 chemistries however have higher abundances of FeO (RT2 20.1 % vs. RT1 17.6 %), K, and Th compared to RT1. Abundances of SiO<sub>2</sub> (RT1 44.7 % and RT2 45.8 %) and K/Th ratio are similar to the bulk planet and do not show significant spatial variations.

**Discussion.** The major chemical trends from TES and GRS appear to be in disagreement. TES ST1 is enriched in FeO while GRS RT1 is depleted in FeO. TES ST2 is enriched in SiO<sub>2</sub> while GRS RT2 shows no relative enrichment in SiO<sub>2</sub>. One can account for these apparent discrepancies, and constrain igneous and alteration processes, by considering the dramatic sampling depth differences between TES and GRS.

The relatively constant K/Th ratio across RT1 and RT2 is not consistent with subaqueous or deep (centimeters to meters) subaerial aqueous weathering of basaltic compositions as K would fractionate from Th in both scenarios [16, 17]. Fractional crystallization and subduction zone magmatism could enrich K and Th, however GRS does not detect any relative enrichment of Si which would be expected in both models [16, 17]. The lack of any significant relative enrichment in SiO<sub>2</sub> abundances between GRS RT1 and RT2 indicates that evolved volcanics (andesites) are not present in high-abundances within the upper few tens of centimeters of the surface at regional to global scales. The favored model by the GRS team is thus initial bulk differentiation processes on Mars producing compositionally distinct magma source regions in

the mantle. RT1 and RT2 basaltic provinces with distinct trace element compositions could then be produced [16, 17]. However, the significant differences in SiO<sub>2</sub> abundances between TES ST1 and ST2 must be taken into consideration. Thin coatings or rinds of secondary amorphous high-silica phases (tens of microns) significantly affect the overall shape and position of absorptions in thermal emission spectra of basalt. Such coatings on Mars may form from near-surface ice and/or surface-atmosphere interactions with little to no water penetrating or cycling into the surface. Limited degrees of alteration in only the upper few tens of microns of the surface may significantly affect TES derived chemistries and be undetectable to GRS due to its deep sampling depth.

**TES, OMEGA, and GRS Summary:** We find that TES, OMEGA, and GRS support: 1) the northern plains of Mars are basaltic in composition; 2) the basalt is chemically altered, with secondary amorphous to poorly crystalline silica-rich phase(s) occurring within thin weathering rinds or as coatings; 3) the alteration is immature, spatially extensive, limited by low water to rock ratios, and likely resulted from northern plains sediments interacting with near-surface volatiles deposited as ice (snow) during phases of high obliquity.

**References.** [1] Bandfield et al. (2000) *Science*, 287, 1626-1630. [2] Wyatt and McSween (2002) *Nature*, 417, 263-266. [3] Michalski et al. (2003) *GRL*, 30, No 19. [4] Michalski et al. (2005) *Icarus*, 174, 161-177. [5] Michalski et al. (2006) *JGR*, 111, E03004. [6] Kraft et al. (2003) *GRL*, 30(24), 2888. [7] Morris et al. (2003) 6 Int. Conf. Mars, Abstract # 3111. [8] Ruff et al. (2003) 6 Int. Conf. Mars, Abstract # 3258. [9] Koeppen and Hamilton (2005), *JGR*, 110, E08006. [10] Wyatt et al. (2004) *Geology*, 32, 644-648. [11] Rogers and Christensen (2007), *JGR*, 112, E01003. [12] Rogers and Christensen (2003), *JGR*, 108, 5030. [13] Tanaka et al. (2003) *JGR*, 108, 8043. [14] Kreslavsky and Head (2002) *JGR*, 107, 5121. [15] Mustard et al. (2005) *Science*, 307, 1594-1597. [16] Taylor et al. (2007) *JGR*, 112 (E3) 2005JE002645. [17] Karunatillake et al. (2007) *JGR*, 112 (E3) 2006JE002675. [18] Hamilton and Christensen (2000) *JGR*, 105, 9717-9733. [19] Wyatt et al. (2001) *JGR*, 106, 14711-14732.