Earth and Planetary Science Letters 404 (2014) 261–272

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The dominance of cold and dry alteration processes on recent Mars, as revealed through pan-spectral orbital analyses

M.R. Salvatore [a,*], J.F. Mustard [b], J.W. Head III [b], A.D. Rogers [c], R.F. Cooper [b]

[a] School of Earth and Space Exploration, Arizona State University, 201 E. Orange Mall, Tempe, AZ 85287-6305, USA
[b] Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA
[c] Department of Geosciences, Stony Brook University, Stony Brook, NY, USA

ARTICLE INFO

Article history:
Received 18 December 2013
Received in revised form 25 July 2014
Accepted 2 August 2014
Available online 23 August 2014
Editor: C. Sotin

Keywords:
infrared spectroscopy
Mars
alteration
weathering
volcanics
remote sensing

ABSTRACT

Classic low-albedo regions of the martian surface are investigated using combined reflectance and emission ("pan-spectral") data to constrain the types of alteration mineral phases that are present at spectrally significant abundances (>10–15%). The lack of hydrated mineral species observed using near-infrared data suggests that anhydrous chemical alteration dominates at the regional scale. Spectral characteristics in the VNIR and TIR are consistent with those associated with weathering processes identified in the hyper-arid, hypo-thermal, and geologically stable McMurdo Dry Valleys of Antarctica, where oxidative weathering processes dominate and significant aqueous alteration does not occur. In addition, the spectral trends associated with oxidative weathering processes are similar to regional trends in VNIR spectral characteristics observed on Mars and potentially complicate the spectral interpretation of basaltic terrains. Collectively, these relationships suggest that the martian surface has been dominated by cold, dry, and stable conditions since the formation of these low-albedo regions. While significant at regional scales early in martian history, aqueous alteration appears to be predominantly absent from large-scale basaltic regions on Mars.

1. Introduction

The dominantly basaltic nature of the martian surface was initially identified through telescopic investigations (e.g. Adams and McCord, 1969; McCord and Adams, 1969) and was later confirmed by orbital analyses (e.g. Erard et al., 1990; Mustard et al., 1993; Christensen et al., 2000a). Subsequently, a variety of altered compositions have been identified using orbital spectroscopy (e.g. Poulet et al., 2005; Bibring et al., 2006), analysis of martian meteorites (e.g. Bridges et al., 2001), and landed datasets (e.g. Squyres et al., 2008), suggesting a host of alteration environments ranging from low to high temperatures, water:rock ratios, and pH (Carter et al., 2013; Ehlmann et al., 2011). These alteration mineralogies are primarily localized in the oldest geologic terrains (Bibring et al., 2006), while younger and more globally homogeneous units, including martian dust, soils, and post-Noachian (~3.7 Ga to present) volcanic plains, exhibit little evidence for widespread aqueous alteration.

Nonetheless, considerable spectral variability between martian low-albedo regions has been observed from orbit (Mustard et al., 1993, 1997, 2005; Mustard and Sunshine, 1995; Bandfield et al., 2000; Christensen et al., 2000a; Bibring et al., 2005; Rogers and Christensen, 2007; Rogers et al., 2007). Early thermal infrared (TIR) investigations using the Thermal Emission Spectrometer (TES) instrument identified two unique spectral shapes, referred to as Surface Type 1 (ST1) and Surface Type 2 (ST2) (Fig. 1a; Bandfield et al., 2000). These two spectral signatures were subsequently expanded into 11 unique spectral groups, located throughout martian low albedo terrain (Rogers et al., 2007; Rogers and Christensen, 2007). While ST1-like signatures have been interpreted as minimally altered basalt, the nature of spectral signatures resembling ST2 has been widely debated. Initial hypotheses of an andesitic composition (e.g., Bandfield et al., 2000) have been largely abandoned in favor of one or several alteration phases at spectrally significant abundances (>10–15%, Bandfield et al., 2000). Wyatt and McSween (2002) initially proposed smectites as a principal ST2 component due to their narrow absorption feature near 1100 cm^{-1}, although later work contested the presence of smectites based on the lack of a diagnostic smectite absorption feature present at 530 cm^{-1} (Ruff and Christensen, 2007). Wyatt et al. (2004) were the first to suggest that the apparent dominance of ST2 at high latitudes is related to the interaction of geologic materials with near-surface ground ice. Other possible altered materials (commonly referred to

---

[*] Corresponding author. Tel. +1 480 727 2461.
E-mail address: msalvatore@asu.edu (M.R. Salvatore).

http://dx.doi.org/10.1016/j.epsl.2014.08.006
0012-821X/

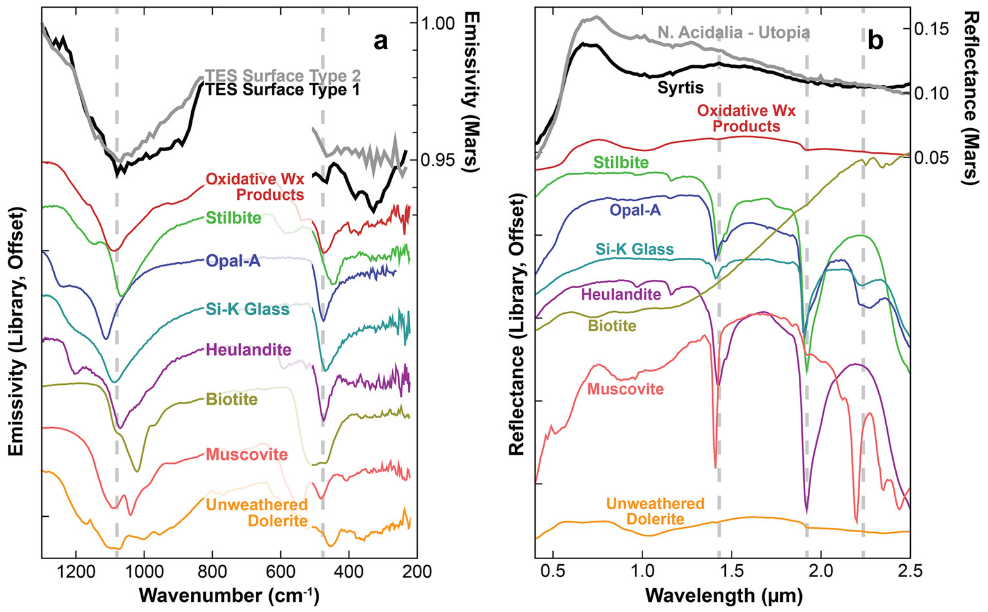

Fig. 1. (a) Thermal infrared spectra of Surface Type I (ST1, black) and Surface Type II (ST2, grey) from the Thermal Emission Spectrometer (TES) instrument. Also provided are thermal emission spectra of materials commonly used to model the narrow shape of ST2, as well as an unaltered Antarctic dolerite spectrum for comparison. (b) Visible and near-infrared spectra of archetypal ST1 (Syrtis, black) and ST2 (N. Acidalia–Utopia, grey) regions of Mars, with the VNIR spectra of the same phases shown in Fig. 1a. Spectra are not scaled in either plot, and vertical lines are provided to highlight the location of many common absorption features.

as "high-silica phases") that have been proposed as potential contributors to the TIR spectra of ST2 include micron-thick coatings of amorphous silica (Kraft et al., 2003; Minitti et al., 2007), palagonite (Morris et al., 2003, 2008), microfractures filled with amorphous aluminosilicate materials (Michalski et al., 2006), altered basaltic glass (Minitti et al., 2007), zeolites (Minitti and Hamilton, 2010), Al- or Fe-rich opaline silica (Michalski et al., 2005), Si-rich mineraloids (Michalski et al., 2005), and allophane (Rampe et al., 2012) (Fig. 1a). Experimental analyses also suggested that anhydrous oxidation may produce similarly narrow absorption features (Minitti et al., 2002), although these experiments were run at high temperatures and no environmental analogs were identified. The analysis of such anhydrous oxidative weathering products resulting from subaerial chemical alteration in the Stable Upland Zone (SUZ) of the McMurdo Dry Valleys (MDV), Antarctica (Marchant and Head, 2007), confirmed that the resultant TIR spectral signatures are comparable to those observed on Mars (Salvatore et al., 2013a, 2013b). Despite these similar TIR spectral shapes, many of these proposed alteration phases exhibit diagnostic spectral signatures at visible and near-infrared (VNIR) wavelengths (Fig. 1b, Table 1) that can be used to further constrain which of these mineral phases are present on the martian surface. However, regional-scale VNIR spectral investigations have never been undertaken in a manner similar to that of Rogers and Christensen (2007) in the TIR, which is the goal of this proposed work.

In this study, we more closely investigate the validity of oxidative weathering products (OWPs) as a potentially significant alteration phase in martian low-albedo regions. We begin with a summary of the unique "pan-spectral" (VNIR and TIR) signatures associated with OWPs from within the Antarctic SUZ (Part I). Using the geographic boundaries for spectrally distinct low-albedo regions in the TIR, as defined by Rogers et al. (2007), we then produce regionally averaged VNIR spectra from the same surfaces. VNIR spectra are derived using data from the Observatoire pour la Mineralogie, l'Eau, les Glaces et l'Activite (OMEGA; Bibring et al., 2004) instrument (Part II) (Fig. 2). Analyses of these regionally derived VNIR spectra will help to constrain the spectrally significant (>∼10% abundance at the surface; Ehlmann et al., 2012) end members present throughout the martian low albedo terrain. Lastly, the regional TIR data assembled by Rogers et al. (2007) are reinterpreted using modified spectral libraries to determine whether these new mineralogical constraints can sufficiently model the surface composition of these low albedo regions (Part III). The results of these analyses indicate that not only do OWPs uniquely explain martian TIR data, but their VNIR spectra are also able to explain several previously enigmatic properties observed globally.

Table 1
List of major visible and near-infrared vibrational absorptions associated with hydrated alteration phases that are commonly proposed as thermal infrared end members.

Wavelength	Assignment	Common Minerals
1.12 μm	H_2O Combination	Zeolites
1.4 μm	OH Overtone, H_2O Combination	Most Hydrated Species
1.79 μm	H_2O Combination	Zeolites
1.9 μm	H_2O Combination	Most Hydrated Species
2.2 μm	Al–OH Bend, OH Combination	Smectites, Hydrated Silica, Amorphous Phases
2.21 μm	Si–OH Bend (Isolated), OH Combination	Hydrated Silica, Amorphous Phases
2.24 μm	Al, Fe–OH Bend, OH Combination	Smectites
2.26 μm	Si–OH Bend (H-Bound), OH Combination	Hydrated Silica, Amorphous Phases
2.29 μm	Fe–OH Bend, OH Combination	Smectites, Palagonite
2.31 μm	Mg–OH Bend, OH Combination	Smectites, Palagonite
2.5 μm	H_2O Combination	Zeolites

2. Part I: Spectral trends of oxidative weathering products

Oxidative weathering processes and products in the SUZ of Antarctica were first characterized by Salvatore et al. (2013a) for the Ferrar Dolerite, which is a shallow intrusive igneous lithology of basaltic and basaltic–andesitic composition. These analyses confirmed that the chemical, mineralogical, and spectral signatures of dolerite surfaces were the result of anhydrous oxidation due to exposure to the hyper-arid and hypo-thermal SUZ. The results discussed in Salvatore et al. (2013a) are briefly summarized below.