Icarus 276 (2016) 39–51

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Elevated bulk-silica exposures and evidence for multiple aqueous alteration episodes in Nili Fossae, Mars

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ARTICLE INFO

Article history:
Received 8 December 2015
Revised 8 April 2016
Accepted 11 April 2016
Available online 20 April 2016

Keywords:
Mars, surface
Spectroscopy
Mineralogy
Geological processes
Infrared observations

ABSTRACT

The Nili Fossae region of Mars contains some of the most mineralogically diverse bedrock on the planet. Previous studies have established three main stratigraphic units in the region: a phyllosilicate-bearing basement rock, a variably altered olivine-rich basalt, and a capping rock. Here, we present evidence for the localized alteration of the northeast Nili Fossae capping unit, previously considered to be unaltered. Both near-infrared and thermal-infrared spectral datasets were analyzed, including the application of a method for determining the relative abundance of bulk-silica (SiO_2) over surfaces using thermal emission imaging system (THEMIS) images. Elevated bulk-silica exposures are present on surfaces previously defined as unaltered capping rock. Given the lack of spectral evidence for phyllosilicate, hydrated silica, or quartz phases coincident with the newly detected exposures—the elevated bulk-silica may have formed under a number of aqueous scenarios, including as a product of the carbonation of the underlying olivine-rich basalt under moderate water: rock scenarios and temperatures. Regardless of formation mechanism, the detection of elevated bulk-silica exposures in the Nili Fossae capping unit extends the history of aqueous activity in the region to include all three of the main stratigraphic units.

1. Introduction

Spectrometers on orbital spacecraft around Mars inform our understanding of the mineral composition of the upper few microns to tens of microns of the martian surface. This mineralogy provides a record of the geochemical conditions present during the time of formation and allows past environmental conditions to be ascertained, especially when local mineralogies are investigated with respect to regional compositions and geologic context. Orbital spectroscopy has been used extensively to identify regional surface mineralogy on Mars and given that specific wavelength regions are sensitive to different phases, a combined analysis can lead to a more comprehensive view of the surface.

This study focuses predominately on spectral data acquired by the 2001 Mars Odyssey Thermal Emission Imaging System (THEMIS; Christensen et al., 2004) and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; Murchie et al., 2007) on the Mars Reconnaissance Orbiter (MRO). The combined wavelength coverage from CRISM and THEMIS allows for the characterization of both bulk surface compositions and the identification of secondary alteration products.

This study has two goals:

(1) To introduce a detailed and systematic approach to analyzing near-infrared CRISM and thermal-infrared THEMIS spectral datasets in a complementary fashion, including the applicability of using a new index map, the "weighted absorption center", as a tool for the reconnaissance of THEMIS images with elevated bulk-silica compositions. We use Nili Fossae as the test locale for this approach given its high mineralogical diversity.
(2) To document the presence of elevated bulk-silica exposures in the Nili Fossae region. These newly observed exposures are associated with local olivine-rich basalts and phyllosilicate-bearing basalts but are not spatially co-located with either unit. The units likely represent a period of aqueous activity in Nili Fossae, separate from that which formed the previously identified phyllosilicates.

1.1. Geologic setting

The Nili Fossae are a set of concentric graben surrounding the north–west rim of the Isidis impact basin (Schultz and Frey, 1990) and likely formed due to mass unloading and flexure associated

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http://dx.doi.org/10.1016/j.icarus.2016.04.015
0019-1035/

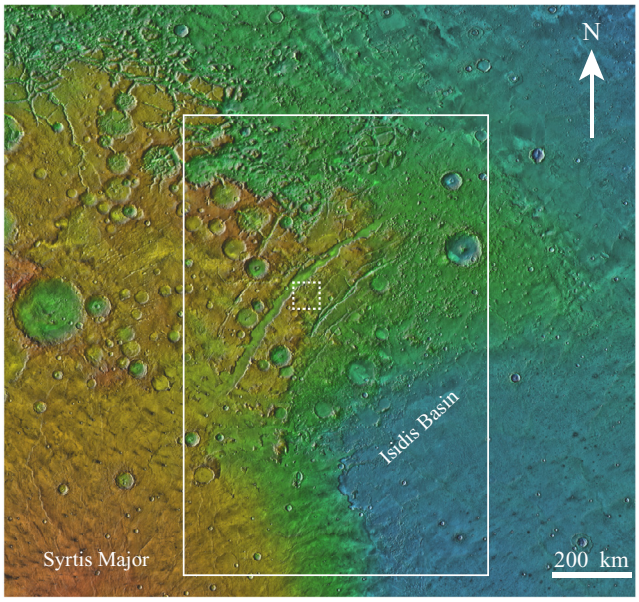

Fig. 1. Nilo-Syrtis Major colorized elevation map with THEMIS Global Day IR mosaic used for shading. Solid white box indicates initial THEMIS image search area. Dashed white box indicates area covered by Fig. 10. Image is centered around 77.02°E and 21.86°N.

with the Isidis impact event that occurred approximately 4 Ga (Wichman and Schultz, 1989) (Fig. 1). With the exception of the early Hesperian-aged flood basalts from Syrtis Major that inundate the floor of the Nili Fossae trough (Hiesinger and Head, 2004) the fossae provide a rare glimpse into Mars' geologic and geochemical past with extensive exposures of Noachian crustal materials. The fractures themselves, local impact craters, as well as the relatively low dust cover (Ruff and Christensen, 2002), reveal compositionally heterogeneous exposures that can be spatially resolved from orbit. The diverse surface compositions and alteration products found in Nili Fossae imply unique igneous activity during the region's history in addition to multiple phases of aqueous alteration (e.g. Hoefen et al., 2003, Hamilton and Christensen, 2005; Poulet et al., 2005; Bibring et al., 2006; Mangold et al., 2007; Mustard et al., 2007, 2009; Ehlmann et al., 2008, 2009, 2010; Tornabene et al., 2008; Brown et al., 2010; Viviano et al., 2013; Edwards and Ehlmann, 2015).

The basement rock in the region is described as a massive to brecciated basalt with localized signatures of Fe/Mg-smectite, likely due to subsurface aqueous alteration prior to the Isidis impact event (e.g., Poulet et al., 2005; Bibring et al., 2006; Mangold et al., 2007; Mustard et al., 2007; Ehlmann et al., 2009). Alternatively, the Fe/Mg-smectites may have formed syn-/post-Isidis impact from ground water circulation (Viviano et al., 2013). An olivine-rich basalt unit is primarily exposed in the eastern portion of the Nili Fossae troughs, stratigraphically above the Noachian basement unit (Hoefen et al., 2003; Hamilton and Christensen, 2005; Mustard et al., 2007; Tornabene et al., 2008). Quantitative deconvolution analyses of emission spectra from the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) have shown that this basalt contains between 20 and 30 wt. % olivine with olivine compositions ranging from Fo_{68-75} (Hamilton and Christensen, 2005; Koeppen and Hamilton, 2008; Edwards and Ehlmann, 2015). The olivine-rich unit appears to drape pre-existing topography and may have formed as a post-Isidis impact melt sheet (Mustard et al., 2009), or post-Isidis volcanic lava flows (Hamilton and Christensen, 2005; Tornabene et al., 2008). Isolated locations of the olivine-rich basalt have subsequently been variably altered to Fe/Mg-carbonates (Ehlmann et al., 2008, 2009; Edwards and Ehlmann, 2015), Mg-phyllosilicates (*e.g.*, Mg-serpentines) (Ehlmann et al., 2009, 2010), and talc and/or saponite (Brown et al., 2010; Viviano et al., 2013). The presence of these mineral phases has been attributed to localized hydrothermal alteration of both the underlying Fe/Mg-smectites and the olivine-bearing basalt during the emplacement of Hesperian aged lava flows (e.g., Viviano et al, 2013).

Both the northeastern and northwestern portions of Nili Fossae are capped by an olivine-poor basalt (e.g., Tornabene et al., 2008; Mustard et al., 2009). The source of this basalt is still debated, though Mustard et al. (2009) hypothesized that it may represent the upper (less dense) portion of the impact melt sheet that formed the olivine-rich basalt unit. More recently, Edwards and Ehlmann (2015) proposed that the capping unit may be an eroded volcanic ash based on Hapke modeling of single scattering albedo from CRISM data and low thermal-inertia values derived from THEMIS observations, in addition to observed composition and morphology. This is similar to work presented by Bandfield et al. (2013a) who argued that much of Mars' older surfaces are composed of relatively friable volcanic ash of a basaltic composition. The region also shows evidence for reworking by late Noachian/early Hesperian fluvial activity, based on the presence of channel networks (e.g., Ehlmann et al., 2009). The fluvial activity likely led to the transport and re-emplacement of Fe/Mg-smectites into fan deposits (e.g., Ehlmann et al., 2009).

2. Data and methods

In order to determine the surface composition of exposures of interest in Nili Fossae, we incorporated both near-infrared (NIR; defined here as ~1.0–3.0 μm) and thermal-infrared (TIR; ~5.0–50.0 μm) spectral datasets that provide highly complementary information based on their particular sensitivities. When present as coarse particulates, TIR spectral measurements are sensitive to the major phases present and the bulk-rock compositions (e.g., Thomson and Salisbury, 1993; Ramsey and Christensen, 1998; Smith et al., 2013). NIR spectral measurements are sensitive to hydrated and Fe-bearing phases (e.g., Hunt, 1977). This property allows for the detection of specific phases, even when present only as minor constituents, although it can be difficult to retrieve quantitative mineral abundance information from the NIR spectra (e.g., Hunt, 1977). In-depth examination of both NIR and TIR wavelength regions can reveal details that might be otherwise missed by the investigation of either dataset alone. Here, we present an updated TIR data analysis technique and a new approach to comparing the two wavelength regions in a complementary fashion.

2.1. Thermal Emission Imaging System (THEMIS)

THEMIS multispectral thermal-infrared data can be used to understand the bulk mineralogy of martian surfaces (e.g., Huang et al., 2013; Edwards and Ehlmann, 2015). We applied several analysis techniques to the THEMIS data. Decorrelation stretch image products were first used as a preliminary survey tool to obtain a broad understanding of the variability in rock composition within the region (e.g., Bandfield et al., 2004a). Similarly, colorized index images mapping the weighted absorption center (WAC), or "center of gravity" (e.g., Smith et al., 2013), of THEMIS emissivity spectra were produced and used to infer the variability in bulk-silica abundance (Smith et al., 2013). Based on the regions of interest identified from the broad survey products, a more detailed analysis of emissivity spectra from individual locations was conducted using the atmospherically corrected images.

2.1.1. Introduction to data and atmospheric corrections

THEMIS is a multi-spectral visible, near-infrared, and thermal-infrared imager on the 2001 Mars Odyssey spacecraft. The imager