Planetary and Space Science 138 (2017) 55–74

Contents lists available at ScienceDirect

Planetary and Space Science

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

Hydrothermally-altered dacite terrains in the Methana peninsula Greece: Relevance to Mars

Edward A. Cloutis[a,*], Victoria Jonatanson[a], Joshua L. Bandfield[b], Elena S. Amador[c], Frances Rivera-Hernández[d], P. Mann[a], Stanley A. Mertzman[e]

[a] Department of Geography, University of Winnipeg, 515 Portage Avenue, Winnipeg, Manitoba, Canada R3B 2E9
[b] Space Science Institute, Boulder, CO 80301, USA
[c] Department of Earth and Space Sciences, University of Washington, 4000 15th Avenue NE, Seattle, WA 98195-1310, USA
[d] Department of Earth and Planetary Sciences, University of California, Davis, 1 Shields Avenue, Davis, CA 95616, USA
[e] Department of Earth and Environment, Franklin and Marshall College, Lancaster, PA 17604-2615, USA

ARTICLE INFO

Keywords:
Mars
Spectroscopy
Igneous
Mineralogy

ABSTRACT

Dacitic rocks, often indicative of crustal recycling on Earth, have been identified in some regions on Mars, as have possible hydrothermally/aqueously-altered dacites. To enable more robust identification of unaltered and altered dacites on Mars and other planetary bodies, we undertook a spectroscopic-structural-compositional study of altered and unaltered dacites from a dacitic volcanic region in Methana, Greece. Dacites erupted in this region range from fresh to pervasively hydrothermally altered, resulting in friable, Si-enriched products, as well as fumarolic deposition of Si and S-rich precipitates. Spectrally, fresh dacites are unremarkable in the 0.35–2.5 µm region with low, generally flat, reflectance and few, if any, absorption bands. Dacite infrared spectra exhibit Si-O absorption features in the 8–10 µm region (which are characteristic of Si-bearing rocks, in general). With increasing alteration, reflectance over the 0.35–2.5 µm range increases, absorption bands in the 1.4 and 1.9 µm region, associated with H_2O/OH, and in the 2.2–2.3 µm region, associated with SiOH, become deeper, Fe^{3+}-associated absorption bands in the 0.43 and 0.9 µm region appear, and the Christiansen feature near 8 µm moves to shorter wavelengths. Silica-rich coatings appear to be spectrally indistinguishable from Si-rich alteration. Alteration-formed sulfates may be detectable by the presence of diagnostic absorption features in the 0.35–2.5 µm region. Spectral similarities between different poorly crystalline high-Si phases make it difficult to uniquely determine the processes that formed high-Si surfaces that have been identified on Mars. However, the samples described here show a variety of spectral features that correspond to variable amounts of alteration. We find a similar range of spectral features, likely due to similar phases, on Mars, perhaps indicating a similar range of alteration environments. Comparison of laboratory spectra to Mars observational data also suggests that the major Si-rich regions likely consist of assemblages that more mineralogically complex than those included in this study.

1. Introduction

Dacite is defined by the International Union of Geological Sciences (IUGS) as an intermediate igneous rock containing between 63% and 77% SiO_2 and up to 7% total alkalis (Na_2O+K_2O) (Le Bas and Streckeisen, 1991). Petrologically, they are defined as being plagioclase feldspar-rich and quartz- and alkali feldspar-poor (Le Bas and Streckeisen, 1991). Dacitic-type compositions can form as primary igneous products, or as a result of alteration of preexisting rocks through a variety of processes. Therefore, the presence of dacitic rocks can be used to infer or determine the presence of more evolved magmatic processes and/or the operation of hydrothermal alteration that can result in an increase in bulk silica of more mafic precursors.

The spectroscopic properties of dacites have not been comprehensively studied. Hunt et al. (1973) measured reflectance spectra (0.35–2.5 µm) of three dacites. They found that the low wavelength region was dominated by Fe^{3+}-associated absorption bands, while the longer wavelength region spectra were flat to slightly red-sloped and showed absorption bands near 1.4, 1.9, and 2.5 µm, all attributable to water of hydration. They noted that the bands were surprisingly weak given the

* Corresponding author.
E-mail addresses: e.cloutis@uwinnipeg.ca (E.A. Cloutis), tjonatanson@gmail.com (V. Jonatanson), paul.mann347@gmail.com (J.L. Bandfield), jbandfield@spacescience.org (E.S. Amador), esamador@uw.edu (F. Rivera-Hernández), friverah@ucdavis.edu (P. Mann), stan.mertzman@fandm.edu (S.A. Mertzman).

http://dx.doi.org/10.1016/j.pss.2017.01.013
Received 3 August 2016; Received in revised form 24 January 2017; Accepted 26 January 2017
Available online 09 February 2017
0032-0633/

degree of alteration, although compositional data were not provided for the samples.

On Mars, the Moon, and Mercury there is evidence for primary Si-rich volcanic terrains (e.g., Bandfield et al., 2004; Christensen et al., 2005; Glotch et al., 2010, 2011; Greenhagen et al., 2010; Skok et al., 2010; Jolliff et al., 2011; Sautter et al., 2015; Thompson et al., 2015; Vander Kaaden et al., 2015). There is also evidence for widespread hydrothermal alteration on Mars (e.g., Bandfield, 2008; Skok et al., 2010; Horgan and Bell, 2012; Smith and Bandfield, 2012; Bandfield et al., 2013; Smith et al., 2013; Amador and Bandfield, 2016). Distinguishing primary Si-rich terrains from those produced by secondary processes on Mars, the Moon, and on Mercury is important for understanding and constraining the geological history of these bodies. To better understand how and whether dacites, altered dacites, and compositionally similar rocks can be recognized spectroscopically, we undertook a mineralogical-spectroscopic study of a suite of dacite samples from the Methana peninsula region in Greece.

The paper is organized as follows: in Section 2 we discuss observational evidence for dacites on various planetary surfaces, this is followed by a description of the study area (Section 3), methodology (Section 4), spectroscopic properties of the samples (Section 5), discussion of the results (Section 6), implications for Mars (Section 7) and conclusions (Section 8).

2. Observational evidence for dacites on planetary surfaces

2.1. Mars

The evidence for true dacitic rocks on Mars is sparse, but includes observations from both orbit and on the surface, as described below. However, dacitic rocks may actually be more widespread on Mars than is currently known, because their spectral properties are not well understood. Distinguishing primary Si-rich (dacitic) terrains from those produced by secondary processes, such as hydrothermal/aqueous alteration, may be possible by combining analyses of spectroscopic, geomorphological, and geochemical data.

2.1.1. Regional scale occurrences of Si-rich terrains

Ongoing studies of the surface composition of Mars are revealing an ever-increasing mineralogical diversity on the local to global scale (e.g., Bandfield et al., 2000; Bandfield, 2002; Bandfield et al., 2004; Christensen et al., 2005; Poulet et al., 2005; Murchie et al., 2009; Horgan and Bell, 2012; Viviano-Beck et al., 2014; Smith et al., 2013). Two main spectral surface types were identified on Mars based largely on analysis of Mars Global Surveyor Thermal Emission Spectrometer (MGS-TES) data; the first (termed Surface Type 1) is found largely in the equatorial to mid-latitude regions and is of basaltic composition, dominated by plagioclase feldspar and clinopyroxenes. The second (Surface Type 2) is found predominantly in the low-albedo northern lowlands region, with lesser concentrations in other low-albedo regions (Bandfield et al., 2000).

The nature of Surface Type 2 has not been fully constrained (e.g., Bandfield et al., 2000; Ruff and Christensen, 2007; Karunatillake et al., 2007). It was initially interpreted to be a basaltic andesite to an andesitic mixture of minerals including feldspars and glass and with a higher silicate/silica content than Surface Type 1 (Bandfield et al., 2000; Koeppen and Hamilton, 2005). Type 2 spectra most closely resemble the spectra of plagioclase and volcanic glass and were interpreted as being dominated by plagioclase (~45 vol%), potassium-rich glass (~40 vol%), and pyroxene (~10 vol%) (Bandfield et al., 2000). Although Surface type 2 has been shown to be composed primarily of plagioclase and amorphous silicates with minor amounts of pyroxene (Ruff and Christensen, 2007; Rogers et al., 2007), the origin of the amorphous material remains ambiguous; although it may be precipitates from chemical weathering (e.g., Kraft et al., 2003). Consequently Surface Type 2 may be primary igneous products with varying silica content and/or hydrothermally/aqueously altered materials. K, which is enriched in dacite, is elevated in Surface Type 2 regions, but Si does not show a similar enrichment that would be consistent with dacite (Karunatillake et al., 2007).

2.1.2. Localized occurrences of Si-rich terrains

In addition to these two main spectral types, a number of other terrains also appear to be silica-rich, but differ spectrally from Surface Type 2. A number of them have been interpreted as being consistent with various silica-rich assemblages, including dacite. However, the origin of many of them (primary or secondary) is uncertain. These detections have been made both from orbit and on the surface of Mars.

Feldspar-enriched surfaces were identified in eight sites in the southern highlands (Carter et al., 2013; Wray et al., 2013). These were interpreted initially as either anorthosites (Carter et al., 2013) or Si-rich felsic lithologies (Wray et al., 2013). More recently, complementary thermal infrared measurements over the largest exposures show no evidence for Si enrichments, suggesting that some of the exposures are either anorthosites or plagioclase-rich basaltic eruptive products (Rogers and Nekvasil, 2015).

2.1.3. Alteration-associated occurrences of Si-rich terrains

Evidence for impact-exposed granitoid (Si-rich) rocks on Mars has been advanced by the analyses of remotely sensed imagery and spectroscopic data of two craters near Syrtis Major. Spectroscopic data from Thermal Emission Imaging System (THEMIS) on board the Mars Odyssey orbiter and MGS-TES and orbital images show exposed materials in the craters' central uplifts with emissivity spectra that closely match the spectral properties of lithologies dominated by quartz and plagioclase (Bandfield et al., 2004). These rocks were interpreted as having formed through the melting of metamorphosed basaltic rocks, and likely represent exposure of a granitoid pluton (Bandfield et al., 2004). The central uplift exposures of granitic material make up a small portion of the 30 km diameter craters, with roughly 1×3 km exposures (Bandfield et al., 2004). More recently, (Smith and Bandfield, 2012; Smith et al., 2013), using MGS-TES and CRISM data, suggested that, while the initial interpretation of these materials being composed of quartz and plagioclase feldspar is correct, the quartz may not be primary igneous quartz but rather an authigenic quartz resulting from significant alteration of amorphous silica (Smith and Bandfield, 2012; Smith et al., 2013). However, producing a quartz-enriched product from alteration of a surrounding basaltic plains precursor is problematic. There is also evidence of aqueous alteration within these craters, including the presence of phyllosilicates and hydrated silica (Ehlmann et al., 2009; Smith and Bandfield, 2012).

Hydrothermal/aqueous alteration of volcanic materials on Mars, based on the silica-rich nature of specific areas and deposits, has also been suggested for a number of other regions (Bandfield, 2008; Skok et al., 2010; Horgan and Bell, 2012; Smith and Bandfield, 2012). Possible silica enrichment formed via alteration was identified by Horgan and Bell (2012) in the northern plains. These materials have glass-like spectral characteristics but are unlike pristine glass, suggesting the possibility of other processes occurring and leading to the formation of glassy materials, specifically silica-enriched glass rinds formed by exposure to acidic fluids.

Amador and Bandfield (2016) identified an Si-rich unit (58–78 wt% bulk silica: consistent with dacite) in Nili Fossae that is otherwise spectrally unremarkable in the visible-near infrared. This material was interpreted as resulting from localized aqueous alteration of the capping unit.

Using MGS-TES data, Bandfield (2008) identified high silica surfaces (characteristic of sheet silicates, amorphous silica, zeolites, and volcanic glass) in western Hellas Basin that they attributed to aqueous alteration on the basis of geomorphology and composition. Bandfield et al. (2013) used orbital data acquired by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) to show these high-Si surfaces