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REPORT

Olivine and Pyroxene Diversity in the Crust of Mars

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Data from the Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité (OMEGA) on the Mars Express spacecraft identify the distinct mafic, rock-forming minerals olivine, low-calcium pyroxene (LCP), and high-calcium pyroxene (HCP) on the surface of Mars. Olivine- and HCP-rich regions are found in deposits that span the age range of geologic units. However, LCP-rich regions are found only in the ancient Noachian-aged units, which suggests that melts for these deposits were derived from a mantle depleted in aluminum and calcium. Extended dark regions in the northern plains exhibit no evidence of strong mafic absorptions or absorptions due to hydrated materials.

The igneous composition of the martian crust has been examined through remotely sensed data, meteorites, and in situ observations by landers and rovers (*J*). Meteorites exhibit the greatest petrologic diversity but are, with the exception of one sample, <1.3 billion years in age and thus young. Remotely sensed and landed measurements imply that, where exposed, the igneous crust is dominantly basaltic, composed mostly of feldspar and pyroxene (2, 3). Two major divisions in crustal composition are recognized on the basis of their thermal infrared (IR) spectral signatures (2). Type I material, predominantly in the equatorial highlands, is basaltic. Type II, found predominantly in the northern lowland plains, has been interpreted to be andesite or basaltic andesite (4) as altered basalt with a large component of hydrolytic weathering materials (5, 6), oxidized basalt (7), or silica-coated basalt (8). There have been a few outcrops of ancient crust identified in thermal emission data that exhibit concentrations of olivine (9) and low-calcium pyroxene (LCP) above the limits of detection (10).

Here, we present the first results for the crustal composition of Mars derived from the OMEGA reflectance observations. Visible/near-infrared (NIR) reflectance measurements are most sensitive to the presence of iron-bearing mafic minerals. These analyses complement existing observations, help to

resolve issues, and provide insight into the crustal composition and evolution.

The OMEGA experiment and operations are described elsewhere (11, 12). This analysis focuses on visible/NIR reflectance measurements of OMEGA (0.35 to 2.6 μm), where observations of surface reflectance also include atmospheric contributions from dust, water ice aerosols, CO₂, and H₂O vapor. We perform an atmospheric correction assuming that the surface and atmospheric contributions are multiplicative and that the atmospheric contribution follows a power law variation with altitude (13). An atmospheric spectrum is derived from a high-resolution observation crossing the summit of Olympus Mons. Assuming a constant surface contribution, the ratio of a spectrum from the base of Olympus Mons to one over the summit provides the atmospheric spectrum at a power function of their difference in altitude. The atmospheric contribution to each spectrum is then removed by dividing the observation by the derived atmospheric spectrum, scaled by the strength of the CO₂ atmospheric absorption measured in the observation.

Olivine and pyroxene are two important classes of rock-forming minerals that have absorption bands in the visible/NIR that result from electronic crystal field transitions of Fe in octahedral coordination (14). These absorptions are diagnostic of the minerals and their chemical composition (15, 16). Olivine [(Mg,Fe)₂SiO₄] has a broad, complex absorption centered near 1 μm that varies in width, position, and shape with increasing Fe content (16). Pyroxenes [(Ca,Fe,Mg)₂Si₂O₆] are recognized by the presence of two distinct absorptions centered near 1 and 2 μm , where

the band centers shift toward longer wavelengths with increasing calcium content. LCPs (e.g., orthopyroxene) have short-wavelength band centers (0.9 and 1.8 μm), whereas high-calcium pyroxenes (HCPs) (e.g., clinopyroxene) typically have long-wavelength band centers (1.05 and 2.3 μm) (15). Laboratory measurements of these minerals and their mixtures (15–18) provide the basis for interpreting the OMEGA reflectance spectra.

The detection of specific minerals from reflectance spectra involves several steps. First the atmospherically corrected data must demonstrate the presence of unique spectral features that exceed the noise or any systematic variations of the measurements. Typically, the spectral features are weak because of mixing with bright dust on Mars. In addition, there may be residual atmospheric or instrumental effects that affect the shape and strength of diagnostic absorptions and, thus, mineral interpretation. To enhance the spectral features of the important material, we find the ratio of the observed spectrum to that of a nearby dusty region with a similar atmospheric path length acquired during the same observation sequence. Spectra of bright dust exhibit no mafic mineral features, and this dust is a product of alteration processes (i.e., not fine-grained or powdered crustal material). Thus, spectral properties that are common between the measurements, including residual atmospheric effects, cancel out, leaving in the ratio the spectral properties of the material of interest. In the mineral identifications presented here, we show the original OMEGA spectra of the target terrain and nearby dusty terrain, with atmospheric correction, the ratio of target terrain to dusty terrain, and candidate spectra of minerals measured in the laboratory.

The detection of olivine is made on the basis of a broad complex of overlapping absorptions centered near 1 μm . The spectrum of the olivine-bearing surface shown in Fig. 1 exhibits a broad and strong absorption between 0.8 and 1.5 μm but is relatively featureless for wavelengths >1.5 μm . This is

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emphasized in the ratio spectrum, where the strength of the broad mafic band relative to the dusty terrain is nearly 20%. With increasing olivine iron content, the absorptions strengthen and broaden (16). However, laboratory measurements have shown that the spectral shapes depend on both the Fe content and grain size. An increase in grain size broadens the band, shifting the position of the rise in reflectance near 1.5 μm toward longer wavelengths. Thus, a spectrum of forsteritic (low-Fe) olivine with large particles ($\gg 100 \mu\text{m}$) is similar to that of a fayalitic (high-Fe) olivine with fine particle size.

Figure 1 illustrates the spatial distribution of olivine-rich surfaces for an OMEGA observation. The presence of olivine is derived by a spectral index that measures the strength and breadth of the 1- μm band (19). The olivine-rich zone is on the floor of a 65-km-diameter impact crater but constrained to the east-northeast border of the crater floor. High-resolution Mars Orbiter Camera (MOC) images show that the deposit is rough, and Thermal Emission Imaging System (THEMIS) night-time observations indicate that the olivine-rich surface is the warmest in the observation, which indicates a coarse-grained, blocky, or cemented surface. This small, highly localized deposit is typical of most of the observed olivine occurrences.

Similar olivine-rich crater floor deposits are observed elsewhere on Mars, as well as isolated occurrences of olivine-rich rocks in crater rims and massifs distributed throughout

the ancient cratered terrain (Fig. 2). The surface morphology of occurrences in these regions is rugged, which indicates that the crustal rocks have been exposed by erosion, excavated from depth by impact, or subjected to other geological processes. Typically, the exposures are small and are not uniformly distributed, with more numerous occurrences in the regions richer in basalts (i.e., Syrtis Major, southeastern Valles Marineris, and Terra Cimmeria). The largest exposure identified so far is in Nili Fossae (Fig. 2), where Hoefen *et al.* (9) reported olivine detected with thermal IR data. Several isolated olivine-rich deposits have been observed in floors and ejecta of craters in the Northern Hemisphere between 50°N and 65°N (12).

Areas with a strong signature of LCP are identified in the OMEGA data on the basis of the position of two main absorption bands near $\sim 0.9 \mu\text{m}$ and $\sim 1.9 \mu\text{m}$. As shown in Fig. 3, the OMEGA spectrum of an LCP-rich region, relative to the nearby dusty region, shows enhanced, broad 1- and 2- μm bands. The ratio spectrum emphasizes these bands and shows that their strengths are approximately 10 to 15%, relative to dusty regions. The band minima are located near 0.93 and 1.92 μm and, with reference to laboratory spectra, the surface material is dominated by LCP.

OMEGA data indicate that outcrops with high concentrations of LCP are typically located in Noachian-aged cratered terrain [see global maps in (12)]. Many are located

in crater rims, central peaks, and isolated outcrops in the cratered terrain (Fig. 3) as well as in the walls and along the floor of Valles Marineris. These outcrops rarely exceed a few square kilometers. Most of the regions occur in the southern hemisphere: The important morphogeologic aspect is the occurrence in Noachian-aged cratered terrain.

High concentrations of LCP are also identified near Syrtis Major and in Terra Meridiani. Here, the spatial extent of the deposits can reach several hundred square kilometers. The deposit near Syrtis Major is associated with the Noachian terrain located northeast of the volcanic shield (20). In Terra Meridiani, LCP is identified inside the Noachian Dissected Cratered Terrain (21).

HCP-rich areas are identified in the OMEGA data set on the basis of absorption-band minima close to 1.05 and 2.3 μm (Fig. 4). However, the observed absorptions are too wide to correspond to pure HCP (18), and thus most likely are a mixture of LCP and HCP (3, 22). We have modeled these regions using an approach based on the Modified Gaussian Model (MGM) (3, 18, 23). The spectra cannot be fit by a single-pyroxene model but are well fit by a mixture of two pyroxenes with MGM band centers appropriate for LCP and HCP. These analyses

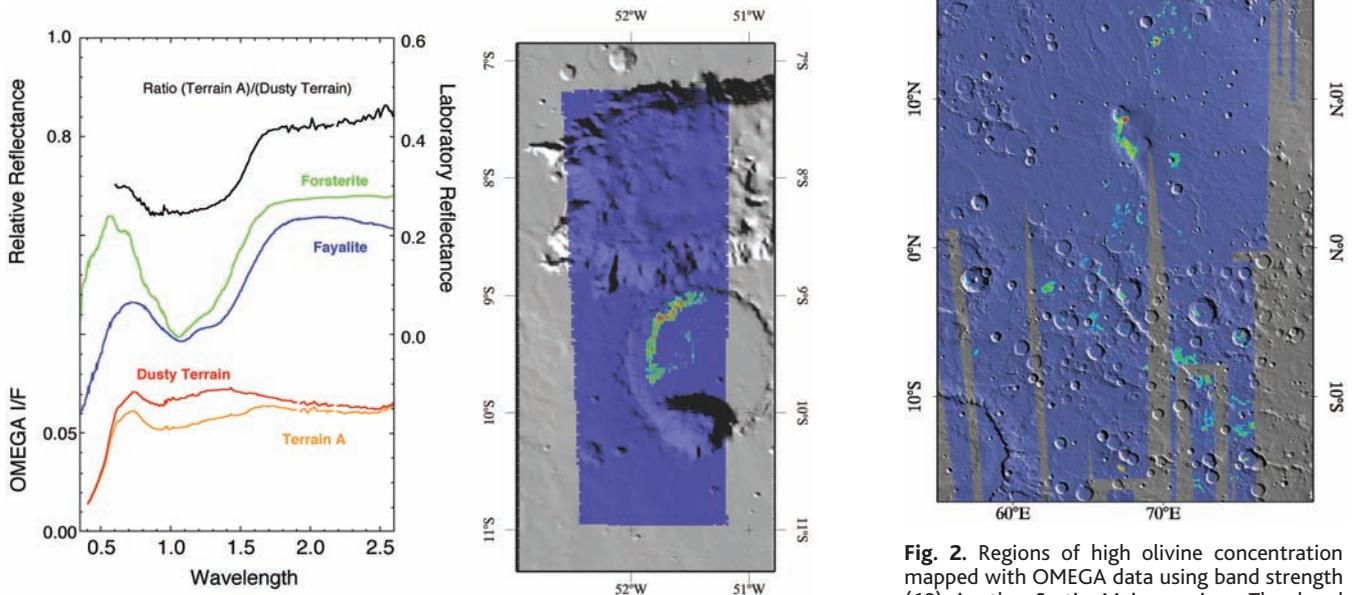


Fig. 1. Identification of Olivine. Spectral plot on left showing two OMEGA I/F atmospherically corrected spectra with target spectrum (Terrain A) and nearby spectrally neutral region (Dusty Terrain), laboratory spectra of Fe-rich (Fayalite) and Mg-rich (Forsterite) olivine, and ratio of (Terrain A)/(Dusty Terrain). On the right is a map of olivine band strength (19) from the OMEGA data showing the spatial distribution draped over Mars Orbiter Laser Altimeter (MOLA) 128 pixels per degree (ppd) shaded relief. Red indicates olivine absorption-band strengths in excess of 10%, and blue indicates no olivine detected with this parameter.

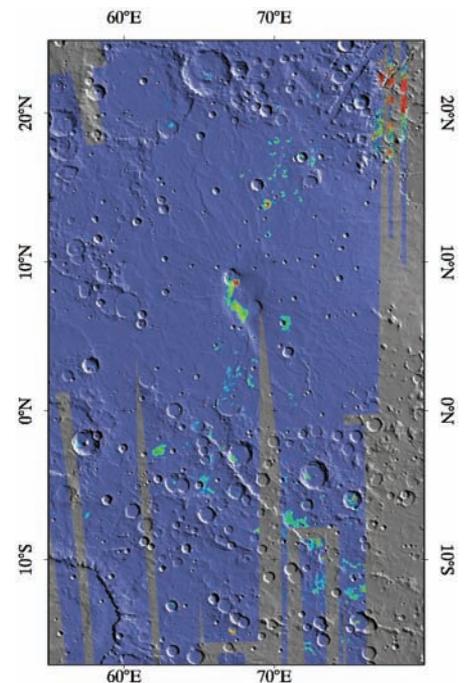


Fig. 2. Regions of high olivine concentration mapped with OMEGA data using band strength (19) in the Syrtis Major region. The band strength is draped over MOLA 128-ppd shaded relief. Red indicates olivine absorption band strengths in excess of 6% grading through green to blue, which indicates no olivine detected with this parameter. The Nili Fossae region in the northeast of this map is the largest area of olivine observed with OMEGA.

show distinct changes in the relative strength of the LCP and HCP absorptions. Laboratory-derived relationships between relative band strengths and LCP:HCP abundance (18) can be used to estimate the relative proportions of pyroxene if the pyroxenes on Mars have the same chemistries as the pyroxenes used in the laboratory studies. Although we cannot demonstrate this congruence, the MGM band centers and widths are comparable to those used in laboratory studies, and this similarity is sufficient to estimate broad differences in relative abundance. Applying the relationships of (18), the surfaces with the strongest HCP bands correspond to a mixture of 20:80 LCP:HCP, but more typically the ratio is 40:60. This relative abundance is typical of basaltic meteorites from Mars (referred to as the Shergotty, Nakala, and Chassigny, or SNC, meteorites) (24), and thus we interpret these surfaces dominated by HCP to be basaltic in composition, in agreement with the results of the Thermal Emission Spectrometer (TES) for Type I terrain (1, 2).

Many areas with total 2- μm HCP band depths greater than 10%, as determined with the MGM, extend over several hundred square kilometers [Fig. 4 and global maps shown in (12)]. Many areas enriched in HCP are associated with wind streaks, which suggests that the surface material is or was mobile (e.g., sand dunes or dark dust). Over sand dunes, a systematic enrichment in HCP relative to the surrounding areas is observed. HCP 2- μm band strengths of between 10 and 15% (determined with the MGM) are found over large regions of Mars associated with dark terrains and outcrops in the southern highlands. One notable area is the Hesperian-aged Syrtis Major volcanic shield. The spectral properties indicating an enrichment in HCP for this region are consistent with previous investigations with visible/NIR (3) and thermal IR (2). In some of the Valles Marineris canyons, layers of pyroxene-rich material with this basaltic signature are identified in one of the upper layers of the southwestern wall of Juventae Chasma and in the wall of Coprates Chasma.

The distribution of mafic minerals in the data acquired during the first 6 months of operations provides insight into the crustal composition of Mars. Olivine-rich outcrops and deposits are found in a wide range of geologic environments. They are observed in outcrops of ancient crust across a broad swath of Mars, occupying isolated massifs, crater rims, large exposures of ancient crust, and the isolated outcrops in the walls of Valles Marineris. These deposits may be due to ultramafic lava flows erupted during the formation of the early crust or may be the result of fractional crystallization and segregation in magma chambers. Olivine is abundant in the central part of the Hesperian-aged Syrtis

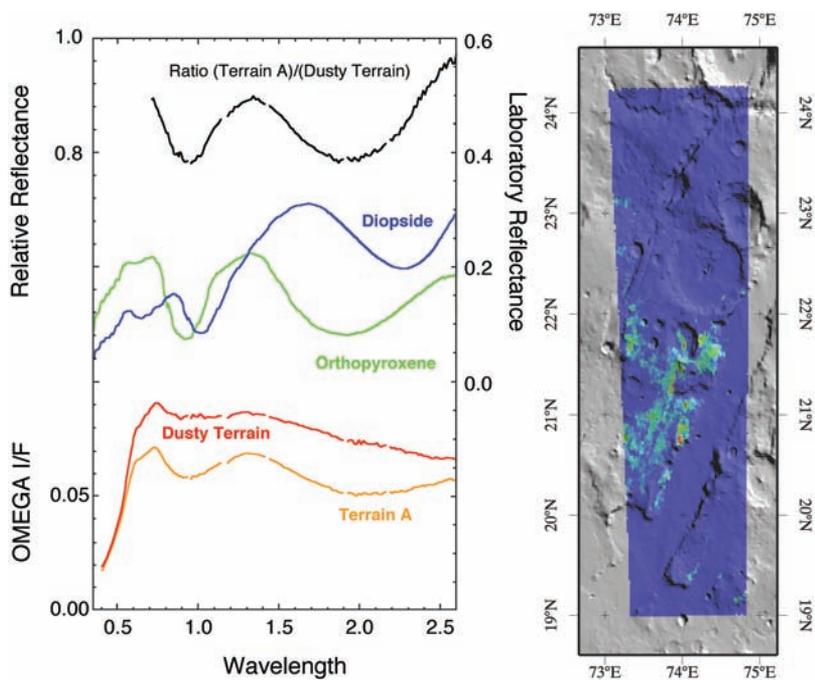


Fig. 3. Identification of LCP. Spectral plot on left showing two OMEGA I/F atmospherically corrected spectra with (a) target spectrum (Terrain A), and (b) nearby spectrally neutral region (Dusty Terrain), laboratory spectra of HCP (Diopside) and LCP (Enstatite), and ratio of (a)/(b). Next to the spectral plot is a map from the OMEGA data showing the spatial distribution draped over MOLA 128-ppd shaded relief. Red indicates LCP absorption-band strengths >10%; blue indicates absorption strengths \leq 4%.

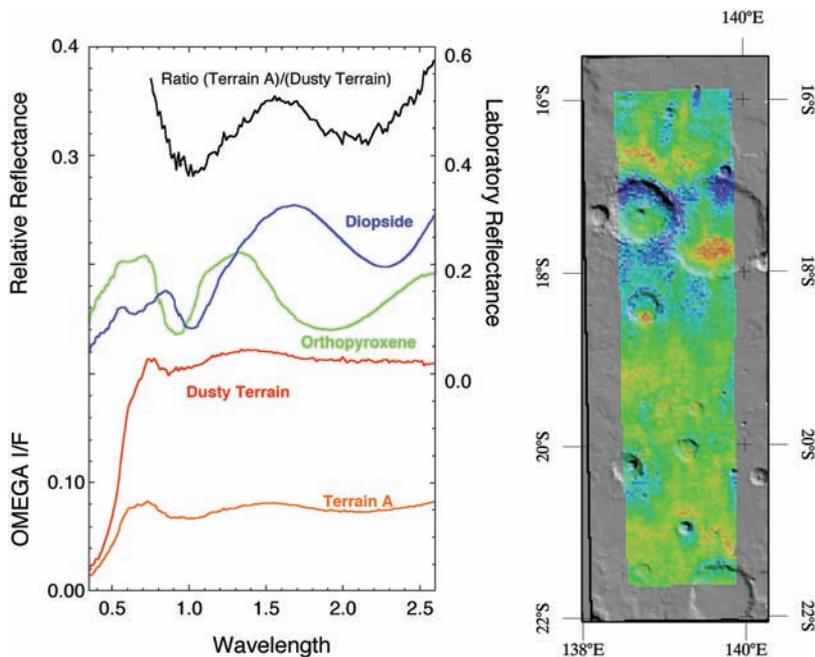


Fig. 4. Identification of HCP. Spectral plot on left showing two OMEGA I/F atmospherically corrected spectra with (a) target spectrum (Terrain A), and (b) nearby spectrally neutral region (Dusty Terrain), laboratory spectra of HCP (Diopside) and LCP (orthopyroxene), and ratio of (a)/(b). Next to the spectral plot is a map from the OMEGA data showing the spatial distribution draped over MOLA 128-ppd shaded relief. Red indicates HCP absorption-band strengths >10%; blue indicates strengths \leq 4%.

Major volcanic complex (Fig. 2). These occurrences are directly associated with volcanic activity and represent mafic, ultramafic,

to perhaps picritic lavas, similar to those observed in the Gusev landing site (25). The widespread occurrence of olivine-rich floors of

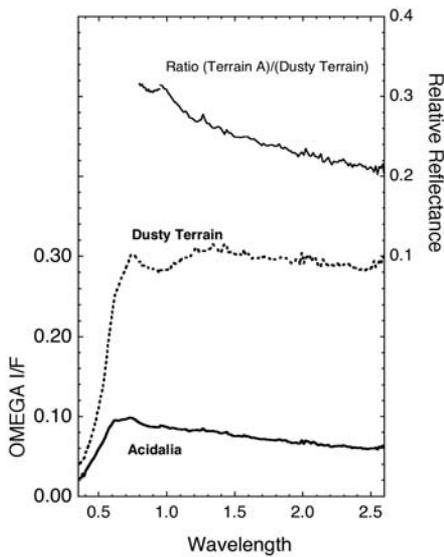


Fig. 5. OMEGA spectra from the Acidalia region of the northern lowlands of Mars. Two OMEGA I/F atmospherically corrected spectra are shown [Acidalia is from a region identified as Type II (2) and a nearby spectrally neutral Dusty Terrain], as well as the ratio of Acidalia/Dusty Terrain. Compared with the spectra shown in Figs. 1, 3, and 4, the Acidalia region exhibits no diagnostic spectral features.

impact craters is interesting. If they are volcanic, there are no obvious local sources for the large number of these deposits. They may instead result from impact melts.

High concentrations of LCP are found only in the ancient cratered terrain [global maps in (12)]. Like olivine occurrences, they are observed in central peaks, crater rims, isolated massifs, and the walls of Valles Marineris, although there is no apparent spatial correlation with olivine. LCP does occur in association with HCP in the more recent volcanic deposits in Syrtis Major and elsewhere. However, the important characteristic of the outcrops enriched in LCP is the exclusive occurrence in ancient cratered terrain. The only orthopyroxenite among the SNC meteorites is also the oldest SNC (~4.5 billion years old) and was likely formed by fractional crystallization of a basaltic parent melt (26). The olivine and LCP outcrops in the ancient cratered terrains are likely remnants of the ear-

ly crustal formation representing cumulates created in large magma chambers or the result of melts extracted from a depleted martian mantle (27).

Low-albedo regions of the southern highlands are enriched in HCP relative to LCP and sometimes contain olivine [see global maps in (12)]. These are interpreted to be mafic volcanic rocks, likely basaltic to picritic (when olivine-rich). A two-pyroxene composition with and without olivine is typical of the basaltic SNC meteorites (24). This mineralogy is best expressed in Syrtis Major, which is the type locality of the basaltic compositions identified with TES (2). However, this spectral type is found widely in the uplands of the southern hemisphere wherever dark materials are exposed, including outcrops in crater rims in the ancient cratered terrain.

We can place these petrologic observations into a stratigraphic context representing the crust of Mars. Olivine is found from outcrops in ancient terrains to high concentrations in Hesperian-aged volcanics and crater floors. Thus, magma compositions capable of crystallizing olivine have occurred throughout much of Mars' history. High concentrations of LCP are found only in the ancient cratered terrains, and thus this rock type appears to have been formed only in the Noachian. HCP is found throughout the stratigraphic column, typically in combination with LCP and olivine, in more recent Hesperian-aged volcanic flows. These volcanic compositions indicate that the source regions were strongly depleted in aluminum and calcium.

OMEGA has sampled broad areas of the northern lowlands, the type locality for Type II materials (2), and also where Mars Pathfinder landed. The spectral properties of these regions (Fig. 5) are best characterized as low albedo with a strong blue slope (decreasing reflectance as a function of wavelength) from 0.9 to 2.6 μm . A weak 2- μm absorption band is observed in some areas north of Arabia, but there is no well defined or apparent 1- μm band. We have searched carefully for evidence of molecular vibration absorptions due to H_2O and/or OH^- , which might indicate the presence of alteration products and phyllosilicates. None of the materials in the areas identified as high

concentrations of Type II (2) exhibit any absorptions due to molecular vibrations. The lack of any evidence of phyllosilicates or hydrated minerals argues against major alteration of basalt by water. The lack of distinct mafic mineral bands indicates that minerals expected in andesite are not expressed in these data. However, alteration rinds or coatings as observed at the Gusev landing site (25) would mask such signatures.

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