with underlying gypsum and minor deposits of carbonates at the base. Kieserite and other K or Mg salts are minor components appearing at the top of the sequence. We can outline the large accumulation of kieserite of the Zechstein basin of the Permian epoch and the deposition of magnesium sulfates in the currently drying Aral Sea.


Spectral Reflectance and Morphologic Correlations in Eastern Terra Meridiani, Mars


The Mars Express Observatoire pour la Minéralogie, l’Eau, les Glaces, et l’Activité (OMEGA) hyperspectral image data covering eastern Terra Meridiani indicate the ubiquitous presence of molecular water in etched terrain materials that disconformably overlie heavily cratered terrains and underlie the hematite-bearing plains explored by the Opportunity rover. Identification of crystalline water in kieserite (MgSO₄·H₂O) is linked to materials exposed in a valley and plateau to the north of hematite-bearing plains. The mineralogical similarities between the etched terrain deposits examined with OMEGA data and the layered rocks examined by Opportunity imply that the ancient aqueous environments inferred from analyses of the rover data extend over regional scales.

The geologic setting of Terra Meridiani is among the most complex on Mars and includes exposures of Noachian-aged cratered terrains that have been dissected by channel systems that were carved by water flowing from the southeast to the northwest (7) (Fig. 1). After channeling ceased, several hundred meters of layered materials were disconformably deposed onto the dissected cratered terrains. To the north of Terra Meridiani, the deposits were then buried by the southern edge of a dust mantle that peaks in thickness over Terra Arabia (5). Subsequent wind erosion then exposed the layered deposits in Terra Meridiani and differentially shaped these materials into a set of domes, ridges, plateaus, and other landforms collectively termed etched terrains (5). The hematite-bearing Meridiani Planum surfaces and materials mapped from Mars Global Surveyor (MGS) Thermal Emission Spectra (TES) (8) and explored by the Mars Exploration Rover, Opportunity (9), are at the top of the stratigraphic section of preserved layered materials. Analyses of rover-based data show that the hematite spherules and associated fragments have been concentrated on the surface as a lag deposit as wind erosion has eroded the weak spherule-bearing, sulfate-rich rocks that underlie the plains (10).

OMEGA Orbit 485 data cover portions of the eastern hematite-bearing plains, sections of etched terrains exposed to the east and north of the plains, and extensive areas of dissected and mantled cratered terrains (Fig. 1). Furthermore, the northern exposures of etched terrains include deposits in a valley and plateau oriented to the northwest-southeast and located just to the north of the transition from the hematite-bearing plains to the etched terrains (Figs. 1 and 2). After retrieval of surface Lambert normal albedos (11), standard reduction analyses using principal components techniques (12) were used to extract spectral endmembers. Extractions focused on the wavelength interval from 1.0 to 2.6 μm because interactive inspection of spectra suggested that this region showed the greatest variety of spectral shapes. Five spectral endmembers (Fig. 3) explain 86% of the variance for plains, etched terrains, and surrounding dark cratered terrains: (i) a “bright etched terrain” spectrum typical of the signatures for etched terrain, (ii) a “dark etched plateau” spectrum representative of darker signatures associated with the northwest-southeast–trending valley and plateau (Figs. 1 and 2), (iii) a “bright plains” spectrum, (iv) a “dark plains” spectrum, and (v) a “dark crater floor” spectrum (located in the cratered terrain).

Between 0.4 and 1.0 μm, each of the five endmembers is characterized by an absorption edge between 0.4 and ~0.6 μm, a slope change near 0.6 μm, a relative reflectance maximum at ~0.75 μm, and a band minimum at longer wavelengths. The position of the minimum ranges from ~0.82 μm (feature A, Fig. 3) for the bright etched terrain spectrum to ~1.0 μm (feature B in Fig. 3) for the dark crater floor endmember. The spectral slope between ~0.6 and ~1.5 μm is steep and positive for the bright etched terrain spectrum and slightly negative for the dark crater floor spectrum. All of these spectral features have been detected in previous observations of Mars made at lower spatial resolution as compared to OMEGA data (~2 km for Orbit 485 data versus ~20 km) (13, 14). The spectral features for the bright etched terrain spectrum are consistent with the presence of Fe³⁺–bearing minerals, interpreted to be a mixture of nanophase ferric iron and hematite (15),
although the minimum for well-crystalline and chemically pure hematite is more typically 0.85 to 0.87 μm (16). On the other hand, the dark crater floor spectrum is interpreted to result from the presence of relatively unaltered materials with a thin Fe3+-bearing mineral alteration or dust-rich surface layer. This spectrum clearly shows evidence for the Fe2+-electronic transition absorption bands (features B and C at ~1 and 2 μm, respectively, in Fig. 3) that are associated with pyroxene in basaltic materials (17).

The bright plains spectral endmember, on the basis of examination of MGS Mars Orbital Camera and Odyssey Thermal Emission Imaging System (THEMIS) image data, shows that the material represented by this endmember is located where hematite-bearing, mottled plains dominate the surface. In some locations, layering is exposed along relatively steep slopes. Additionally, the bright plains spectrum has a similar shape but lower overall reflectance as compared with the bright etched terrain endmember (Fig. 3). We interpret the spectral similarity between bright plains and etched terrain endmembers, and the appearance of the bright plains, as indicative of wind erosion and exposure of some etched terrain material in these areas, with a partial cover of hematite-bearing spherules and basaltic sands similar to what was found at the Opportunity site several hundred kilometers to the southwest (18). The partial cover subdues the water-related spectral features typical of well-exposed etched terrains. The dark plains endmember is spectrally flat from ~1.3 to 2.6 μm and is representative of the spectral signatures for slightly rolling, smooth plains with homogeneous brightness. Bowl-shaped craters are present and well preserved. No exposed layering is evident. These dark plains are interpreted to be covered with an areally uniform dark lag deposit of hematite spherules and basalt sands formed as the plains were slowly eroded by wind. Based on mapping the areal abundance of hematite from TES data (5), the bright and dark plains imaged by OMEGA during Orbit 485 have higher basalt sand–to–hematite spherule abundances as compared with the plains examined by Opportunity.

The deep band at ~3 μm in all spectra (feature D in Fig. 3) results from the well-known stretching fundamental vibrations of the H2O molecule (ν3 and ν4) (19). This feature has been previously detected, including over Terra Meridiani (20). It is estimated that ~4% water is needed to produce the magnitude of the observed absorptions for Mars (21), although the enhanced depths for the bright etched terrain as compared with those of other regions suggest a larger number. The feature at 1.92 μm (feature E in Fig. 3) is well expressed in the spectra for bright etched terrain and is diagnostic of the presence of the H2O molecule and results from combination of two fundamental vibrations (ν3 + ν4) (19). In the absence of spectral evidence for hydrated and hydroxolated phases in the spectrum, we associate feature E with water adsorbed onto surface materials. The strength of the ~3- and 1.92-μm features for etched terrain spectra implies that materials exposed in these deposits are enriched in their water contents relative to the other units for which spectral endmembers were extracted. A spectral feature near 1.4 μm should also be present for these water-bearing materials but is not apparent (Fig. 3), presumably because it is too weak to be observed in the retrieved reflectance data.

The last three spectral features, corresponding to F (~2.5 μm) in the bright etched terrain spectrum and to G (~2.1 μm) and H (~2.4 μm) in the dark etched plateau spectrum, require additional analyses before assignments can be made. Each spectrum was normalized to the endmember spectrum for the dark plains for the 1.6- to 2.6-μm region. The dark plains spectrum is flat in this wavelength interval and thus provides a reason-
The most important conclusion of this paper is that the etched terrain layered materials exhibit evidence for molecular water adsorbed onto the surface materials and, for the dark etched plateau, incorporated as structural water in the hydrated sulfate mineral kieserite. These results complement the analyses conducted by the Opportunity rover on the bright layered rocks in Eagle and Endurance craters, where evidence for hydrated sulfate minerals was also found, including kieserite. It is our conclusion that Opportunity examined the upper section of the etched terrain deposits in these craters and that our results imply that aqueous processes were involved in forming and/or altering the etched terrain materials over distances of hundreds of kilometers and throughout the several-hundred-meter thickness of the etched terrain deposits.

References and Notes

11. OMEGA data for Orbit 485 over Terra Meridiani were reduced to Lambert normal albedos for each of the 352 wavelengths through the use of a multiple scattering code that models atmospheric aerosol (and Rayleigh) scattering and molecular absorption (26) with atmospheric parameters derived from Opportunity and TES data acquired close in time to data for Orbit 485. For wavelengths longer than 2.5 μm, additional terms in the model included thermal emission of the surface and atmosphere. Examination of surface reflectance retrievals demonstrates that atmospheric features are properly modeled and/or the radiometric calibrations for the instrument are well understood for all but the longest wavelengths in the OMEGA data (4.00 to 5.00 μm). Consequently, OMEGA data from this wavelength interval are not discussed in this Report.
24. For an example, see THEMIS image V03445003, which shows areas within the eastern etched terrain exhibit a polygonal ground pattern. In places, the polygons have been eroded to expose interconnected ridges consisting of materials emplaced within the valleys separating the polygons.
Mars Express: OMEGA

Olivine and Pyroxene Diversity in the Crust of Mars


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 (1). 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 materials, 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 outliers 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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