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ma Ray Spectrometer (GRS) has discovered extensive regions of enhanced near-surface hydrogen abundance that are estimated to contain up to 5 to 10% water by mass (12). OMEGA's positive detection of hydrated minerals in selected exposed outcrops increases the likelihood that some, if not most, of the mid-latitude hydrogen detected by the GRS is also in the form of hydrated minerals (1). The ensemble of water-bearing mineral species identified thus far on Mars, and the geological settings in which they are found, appear to require surface climatic conditions that were distinctly warmer and wetter than they are today. Determining whether these more clement environments were local or global, transient or long-lived, will require a more complete knowledge of the range of mineral species present, and their geological context.

OMEGA's discovery of multiple ancient water-rich Earth-like surface environments on Mars should redouble efforts to explore the martian surface widely for signs of past life. Later this year, NASA's Mars Reconnaissance Orbiter will be launched with a powerful suite of new remote-sensing instruments that include

CRISM, the Compact Reconnaissance Imaging Spectrometer for Mars, which has more than 10 times the spatial resolution of OMEGA. If all goes as planned, CRISM will join OMEGA to further define the extent and nature of martian water-formed mineral deposits. The future for orbital remote sensing of Mars continues to look rosy. However, as we look ahead to NASA and ESA's plans for the next decade, there are signs that a large and obvious "rover gap" is developing, given that the two or three rovers currently planned will not be sufficient to explore the diversity of scientifically exciting surface sites identified from orbit. If the successful ongoing Mars missions are teaching us anything, it is that the surface of Mars is even more diverse than had previously been thought, especially at sub-kilometer spatial scales. While the fine-scale diversity of the martian surface increases the chances of finding evidence for previously habitable or inhabited environments, it also increases the number of places that need to be searched. As best we can now determine, Mars has exposed on its surface today a record of its early environment that is better preserved

than, and at least as interesting as, that of Earth. If true, then achieving equivalent levels of insight into the early histories of both planets will ultimately require equivalent levels of exploration and investigation.

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## RESEARCH ARTICLE

# Mars Surface Diversity as Revealed by the OMEGA/Mars Express Observations

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The Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité (OMEGA) investigation, on board the European Space Agency Mars Express mission, is mapping the surface composition of Mars at a 0.3- to 5-kilometer resolution by means of visible–near-infrared hyperspectral reflectance imagery. The data acquired during the first 9 months of the mission already reveal a diverse and complex surface mineralogy, offering key insights into the evolution of Mars. OMEGA has identified and mapped mafic iron-bearing silicates of both the northern and southern crust, localized concentrations of hydrated phyllosilicates and sulfates but no carbonates, and ices and frosts with a water-ice composition of the north polar perennial cap, as for the south cap, covered by a thin carbon dioxide–ice veneer.

Many questions about the evolution of Mars, including the nature of surface-atmosphere interactions, the water and CO<sub>2</sub> cycles on short

to long time scales, crustal formation and evolution, and the role of water in creating and sustaining habitable environments, require

understanding its mineralogy and composition. Analyses of data from OMEGA (1), the hyperspectral visible and infrared imaging spectrometer on board the Mars Express European Space Agency (ESA) mission (2), reveal a diverse and complex surface mineralogy pertinent to these outstanding Mars problems. Here, we describe key surface materials in the form of mafic iron-bearing silicates, ices and frosts, and hydrated minerals and sediments, which have been identified by OMEGA.

During the first 9 months of operations, OMEGA has acquired the spectra of more than 20 million pixels along ~100 tracks. With an

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instantaneous field of view (IFOV) of 1.2 mrad (4.1 arc min), the pixel size depends on the altitude of observation and varies from 300 m, when imaged close to the orbit periapsis, up to 4.8 km from an altitude of 4000 km, whereas the cross-track FOV varies from 16 to 128 IFOV (1.1° to 8.8°). For each resolved pixel, OMEGA acquires the spectrum in 352 contiguous channels covering 0.35 to 5.1 μm. The spectral sampling is 7 nm, 14 nm, and 20 nm from 0.35 to 1.0 μm, 1.0 to 2.5 μm, and 2.5 to 5.1 μm, respectively. The spectral range and resolution have been chosen to allow the identification of major surface and atmospheric species by their diagnostic spectral absorption features, essentially in the solar reflected spectrum and, beyond 4 μm, in the planetary thermal emission.

The Mars Express orbit is almost polar (with an inclination of 86.6°) and highly elliptical, with a period of 6.72 hours (7.58 hours during the first 100 days). Because of the large value of the J2 term of the Mars gravitational field, the periapsis precesses in latitude by ~20° per month. The

period has been selected so as to obtain a drift in latitude that enables the spacecraft in principle to cover the entire planet and to observe all regions at high resolution during the 1-martian-year nominal mission, with longitudinal (cross-track) nadir offsets. Figure 1 illustrates the evolution of the periapsis latitude as a function of time together with the illumination conditions. It indicates that, in the OMEGA data set acquired so far, the southern polar cap, observed at the very beginning of the mission, and northern latitude areas have been observed at medium resolution, with only the southern midlatitude zones covered at high resolution. The coverage of northern latitude areas will be performed from October 2004 until March 2005.

#### Mafic and ultramafic minerals.

OMEGA can identify pyroxene and olivine; it discriminates between the high-calcium pyroxenes (HCPs, e.g., clinopyroxenes) and low-calcium pyroxenes (LCPs, e.g., orthopyroxenes) (3). HCPs dominate in low-albedo volcanic regions of Hesperian age (4), dark

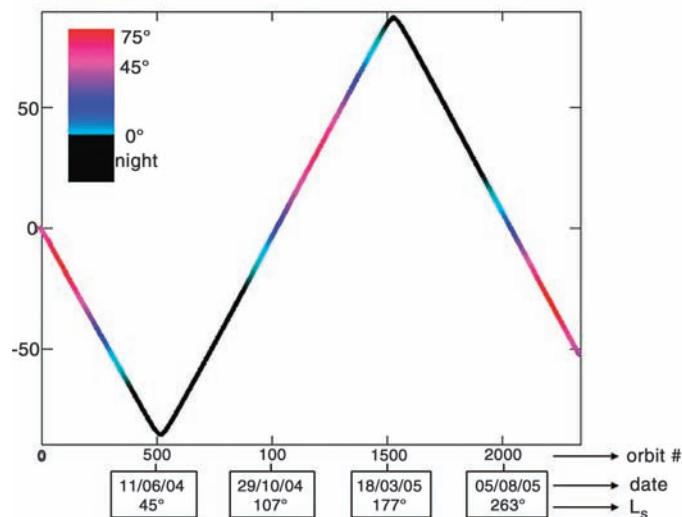
sand, and crater ejecta. The HCP-rich zones match (Fig. 2) the Thermal Emission Spectrometer (TES) data unit identified at medium resolution (>3 km) as basalt rich (5). With its higher resolution capability, OMEGA identifies HCPs in dark sand and crater ejecta. TES has not detected LCP-dominated surfaces (6), except for a few outcrops (7). OMEGA has indeed identified a large number of LCP-rich areas where the high concentrations of LCP occur as moderate to bright outcrops in older, Noachian terrains. This is consistent with previous visible-infrared (vis-IR) analyses (8).

The northern plains of Mars, as well as high-latitude regions in the south, exhibit a distinct emissivity in TES data that has been interpreted as andesitic basalt requiring high-silica glass (5) or altered basalt requiring sheet silicates (9). In the OMEGA data of these regions, absorption features due to primary iron-bearing, well-ordered, crystalline igneous constituents are weak to absent. This could indicate that the surface material of these areas is dominated by mafic (or impact) glasses (10, 11) and/or was altered by a major weathering process. However, the resulting minerals, although highly oxidized, do not show enrichment in hydrated phases (see below).

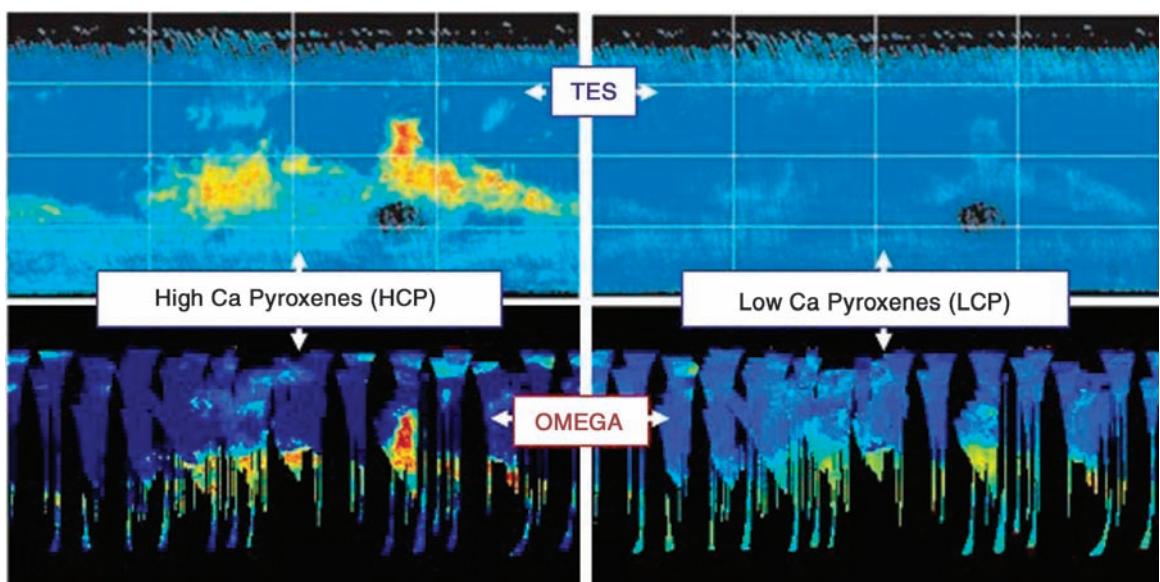
Olivine was found in a few specific areas (3, 7, 12), mainly in crater floors, in crater rims in the southern highlands and in association with volcanic rocks in and around Syrtis Major. A typical olivine-rich outcrop in the southern hemisphere has a composition, derived through modeling (13), in which olivine represents ~30% by volume. The area exhibiting the highest olivine content is in Nili Fossae, as previously identified by Mars Global Surveyor (MGS)/TES (6).

Mafic-rich zones, with the presence of large concentration of olivine, were also found within the craters >20 km in diameter and in some of

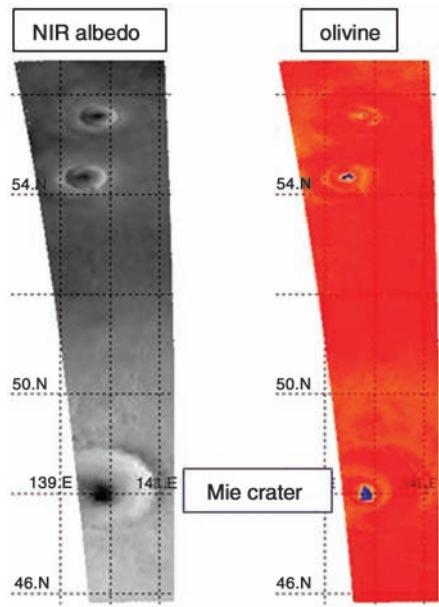
**Fig. 1.** Evolution of the latitude of the orbit periapsis as a function of time, expressed in date, orbit number, and solar longitude,  $L_s$ , along the nominal Mars Express mission. The colors illustrate the illumination conditions at pericenter in solar elevation.



**Fig. 2.** Distribution of the HCPs (left) and LCPs (right) from the TES/MGS (top) and OMEGA/Mars Express (bottom) spectral imagers. OMEGA confirms the TES mapping of HCPs, obtained at moderate (>3 km) resolution, identifies and maps LCPs, and locates at higher resolution (<1 km) a variety of areas with strong mafic features.



their lobate ejecta in the northern plains of Vastitas Borealis (Fig. 3). It cannot be entirely ruled out that these zones, which appear as localized aeolian deposits in the available Mars Orbiter Camera (MOC) images, have been selectively trapped inside the craters after having been transported from remote areas.



**Fig. 3.** Identification of olivine-rich craters within Vastitas Borealis: OMEGA coverage of an area including the Mie crater. The NIR albedo (at 1.3  $\mu\text{m}$ ) shows (left) the presence of three craters, 20 km to 50 km in diameter. The olivine map (right) exhibits an olivine-rich spot (in blue) within the larger crater, fainter in the smaller ones.

However, given the distances from the southern crust, a much denser atmosphere would be required. If accumulated in the early history of Mars, one would not expect these deposits to be present in most impact craters of the northern plains and not further altered, as was the surrounding material. Therefore, we consider that they constitute in-place material, excavated from beneath the northern plains cover, exposing underlying crustal and/or lava materials recently enough not to have been further altered entirely. Their composition thus reflects that of the northern crust, with an olivine abundance of up to ~30% volume.

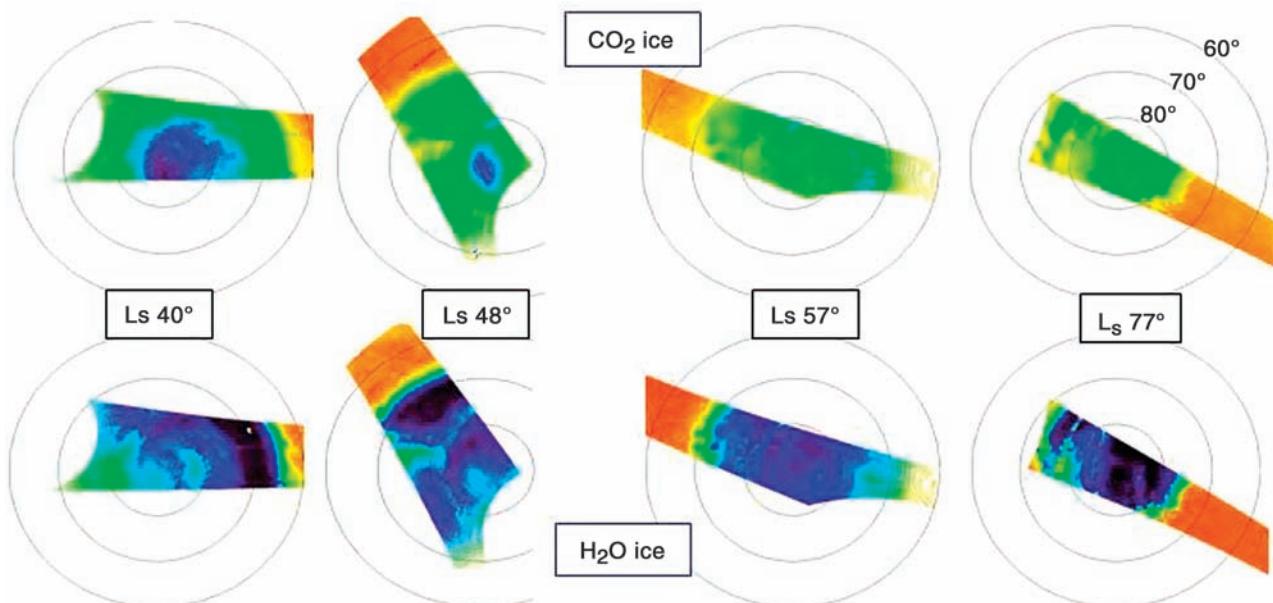
**Surface ices and frosts.** During the first weeks after orbit insertion, corresponding to the late summer of the martian southern hemisphere, OMEGA identified the components of the perennial south polar cap (14): a thin bright CO<sub>2</sub> veneer, no more than some 10 m in thickness as derived from the MOC/MGS high-resolution images (15), covers a massive and extended glacier made of H<sub>2</sub>O ice mixed with dust, which could not be distinguished from the surrounding materials in the previous Viking and MOC visible images. During the northern spring up to the summer solstice (20 September 2004), OMEGA monitored the defrosting of the northern areas. During this period (Fig. 4), the CO<sub>2</sub> frost sublimated, whereas the H<sub>2</sub>O ice retreated, with the receding edge of the seasonal cap constituted of H<sub>2</sub>O frost (with no residual CO<sub>2</sub>). The CO<sub>2</sub> defrost ended before  $L_s \sim 90^\circ$ , exposing a large water-rich residual cap (Fig. 5, right), corresponding to the bright areas mapped by the Viking Orbiter (Fig. 5, left).

By comparison with laboratory measurements of grain size and temperature effects on the near-infrared (NIR) spectra and modifying the depth and slopes of the 1.23-, 1.5-, 1.65-, and 2.0- $\mu\text{m}$  absorption bands, we can assess from the OMEGA spectra the variation in surface water ice properties in terms of mean size and temperature (16). The water ice covering the southern cap is colder ( $T < 180$  K) than that constituting the northern cap ( $T > 200$  K), consistent with the TES/MGS findings (17). The seasonal water frost of the north cap is much finer (<100  $\mu\text{m}$ ) than the underlying permanent water ice (~1 mm) (16).

#### Hydrated minerals and ferric oxides.

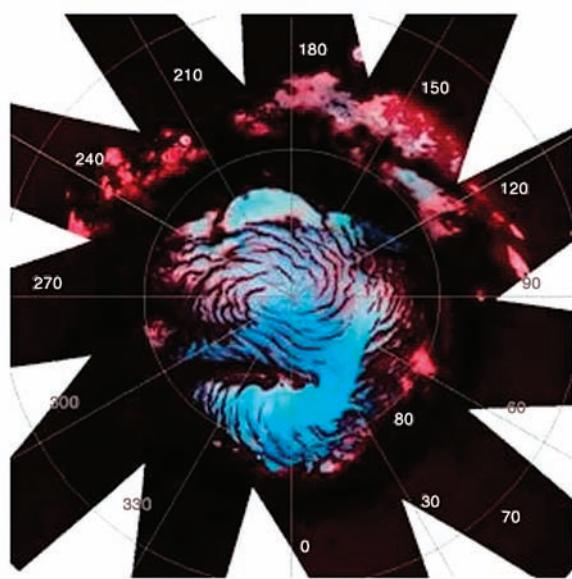
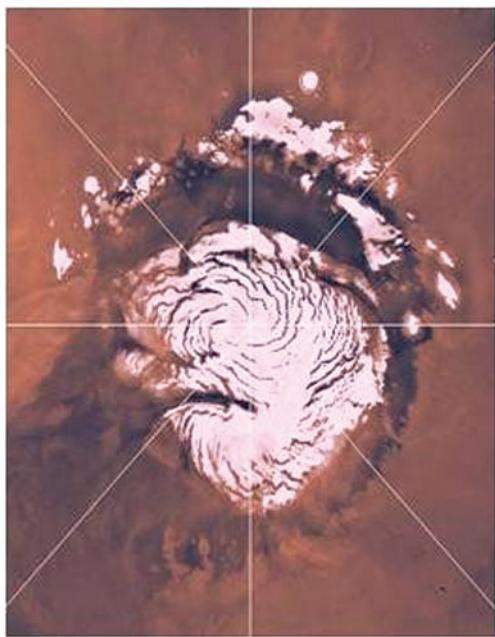
OMEGA detects hydrated minerals by the overtones and combinations of the  $v_1$  (symmetric O-H stretch),  $v_2$  (H-O-H bend), and  $v_3$  (asymmetric O-H stretch) absorption features at ~1.4  $\mu\text{m}$  (shallow), ~1.9  $\mu\text{m}$  (deeper), and ~3  $\mu\text{m}$  (large and saturated). Every OMEGA spectrum exhibits a strong 3- $\mu\text{m}$  absorption, and there is no apparent systematic correlation with other compositional or morphological parameters. This is caused by the presence of a few percent of water strongly bound in minerals in the soils and surface materials (18, 19). The band strengths are strongly correlated to albedo. When they are corrected for albedo (20), a trend appears, with the brightest soil (NIR albedo > 0.30) exhibiting the strongest 3.0- $\mu\text{m}$  band (Fig. 6, A and B).

The 1.9- $\mu\text{m}$  feature is found in a variety of hydrated minerals, hydroxides, phyllosilicates, and salts and serves as an indicator of these important minerals. Their precise composition is determined by diagnostic companion absorption features, such as the sharp metal-OH



**Fig. 4.** CO<sub>2</sub> and H<sub>2</sub>O frost evolution on the northern polar cap over the spring. These false color maps illustrate the evolution with time of the frost coverage during the northern spring, from red (0%) to dark blue (100%): The

CO<sub>2</sub> frost regresses to leave a H<sub>2</sub>O perennial polar cap, mapped in Fig. 5. A contribution of H<sub>2</sub>O ice within the CO<sub>2</sub> ice absorption band used to build the upper images appears as the orange to green areas in the CO<sub>2</sub> maps.



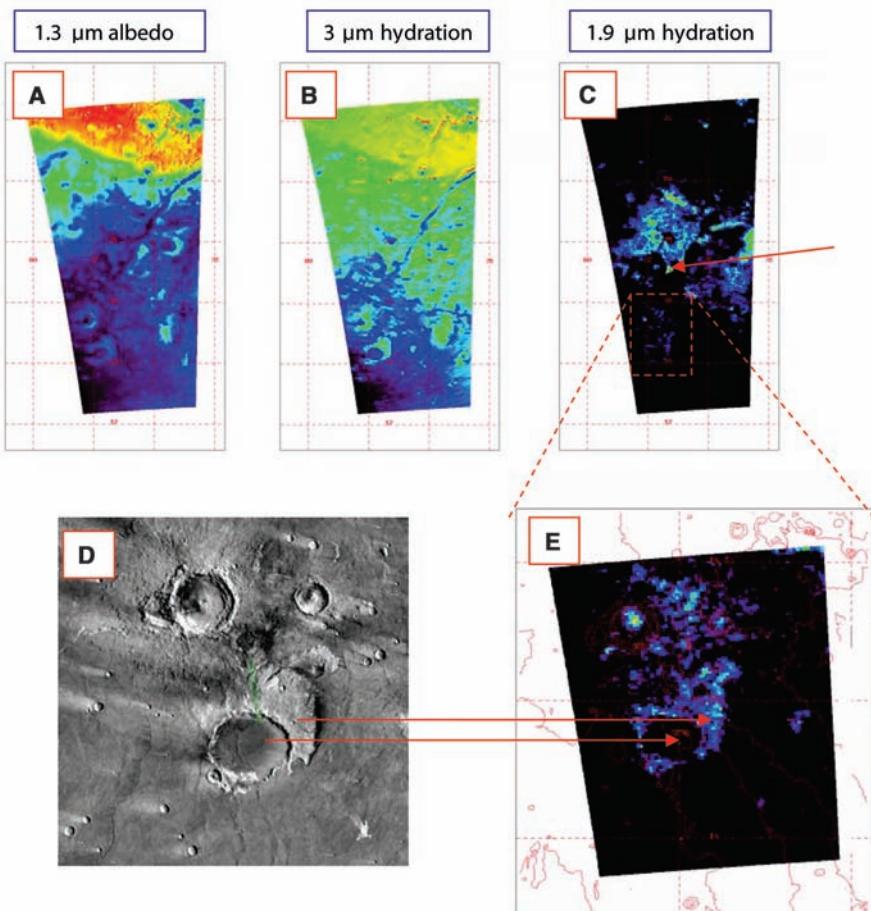
**Fig. 5.** Perennial northern polar cap. Viking visible image (left) (acquired from  $L_s$  from  $110^\circ$  to  $155^\circ$ ) and OMEGA  $\text{H}_2\text{O}$  map (right) (acquired from  $L_s$  from  $93^\circ$  to  $98^\circ$ ). The bright areas are dominated by water ice, when the  $\text{CO}_2$  has entirely sublimated away. The blue to red false colors correspond to different water ice spectra: the blue ice is finer and colder, whereas the red one is coarser and warmer.

bands in the 2.15- to 2.4- $\mu\text{m}$  region. As an example, OMEGA has unambiguously identified the mineral nontronite by its distinct 2.28- $\mu\text{m}$  absorption. Nontronite, known to originate from the alteration of mafic to ultramafic igneous rocks, is the most abundant phyllosilicate detected by OMEGA (Fig. 7).

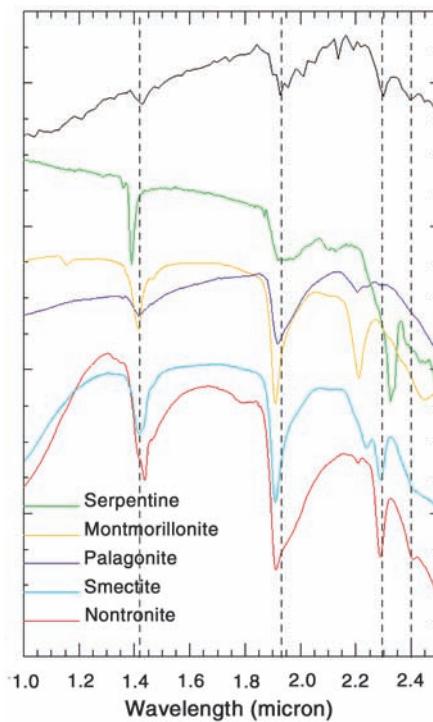
In contrast to the 3- $\mu\text{m}$  feature present in all surface materials, the 1.9- $\mu\text{m}$  feature tracing hydrated minerals is identified in a few specific areas only and in particular within unburied cratered units, such as those expanding out of Nili Fossae in the northern part of Syrtis Major (Fig. 6C). Enrichment in hydrated minerals is identified around an old impact crater (Fig. 6, D and E); this contrasts with the lack of detection of hydrated minerals in the volcanic outflows from Nili Patera, which buried most of the ancient terrains. These OMEGA observations point toward a hydrolytic alteration process more prevalent in the early (Noachian) history of Mars.

No enrichment in hydrated minerals is observed in lobate craters (as expected from impacts into permafrost-rich sublayers) nor within MOC/MGS-identified gully-rich slopes. Similarly, there is no definite identification of phyllosilicates within the soil covering extended areas, such as the large northern plains: This indicates that the alteration process that transformed the volcanic minerals into highly oxidized ones, such as nanophase hematite, does not seem to have led to water-rich compounds.

**Sedimentary minerals.** We have looked for carbonates and so far have not found areas with amounts above the OMEGA detection limit of a few percent in mass. A variety of units have been mapped: areas exhibiting hydrated minerals, layered deposits, fluvial floors, and ejecta of deep craters within Vastitas Borealis. The surface resolution of most observations is still only in the 1- to 3-km range. With  $\text{CO}_2$  ice in the



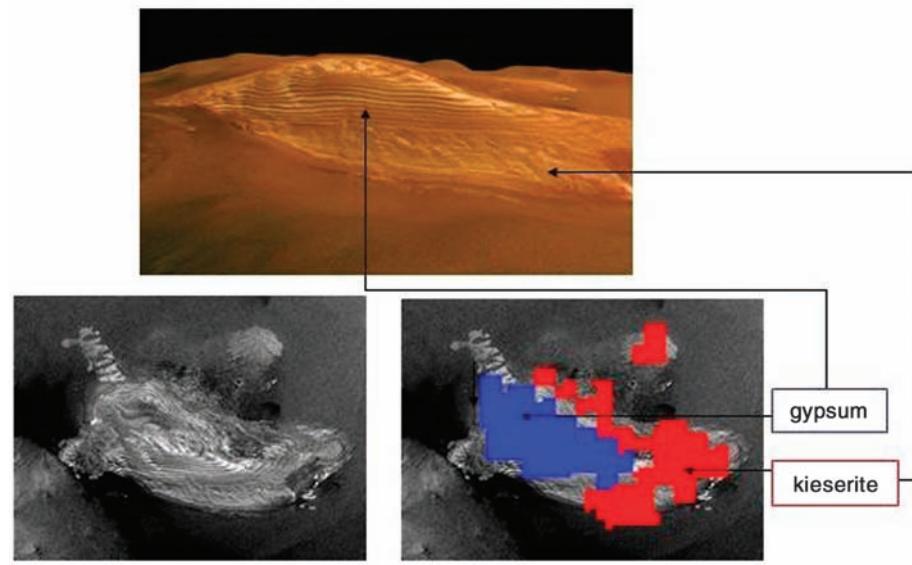
**Fig. 6.** Hydrated minerals; example of the Syrtis Major area. OMEGA identifies hydration (bound and adsorbed water) by the 3- $\mu\text{m}$  saturated feature, in (B) and corrected for the lambertian albedo (A), and the hydrated minerals by their 1.9- $\mu\text{m}$  band (C). The 3- $\mu\text{m}$  band depth increases with albedo, whereas hydrated minerals are predominantly located in older cratered areas, as shown here in Nili Fossae. In Syrtis Major (D and E), the ancient crater ejecta exhibit hydrated minerals (red arrows), whereas the more recent lava flows are essentially free of them. The red arrow in (C) indicates the location of nontronite (Fig. 7). Color scales from blue to red indicate the range 0.05 to 0.4 in (A), 0.3 to 0.6 in (B), 0.02 to 0.06 in (C), and 0.02 to 0.05 in (E).



**Fig. 7.** Nontronite detection. The OMEGA spectrum of the area identified in Fig. 6C (red arrow) is shown in black (top spectrum), ratioed to a reference spectrum of the same session. Laboratory measurements provided by Brown University of a variety of phyllosilicates are shown below, with their diagnostic features in this spectral range. Nontronite is discriminated by its 1.42-, 1.93-, 2.29-, and 2.4- $\mu\text{m}$  absorption bands.

perennial southern polar cap constituting a thin veneer amounting for a small fraction of the present atmospheric  $\text{CO}_2$ , the absence of carbonates, if confirmed, would indicate that no major surface sink of  $\text{CO}_2$  is present. The initial  $\text{CO}_2$ , if indeed it represented a much higher content, would then have been lost from Mars rather than stored in surface reservoirs after having been dissolved in long-standing bodies of water. This scenario would be consistent with a view (27) derived from the  $\text{N}_2/\text{CO}_2$  ratio, which is essentially identical in Mars and in Venus, and similar to the terrestrial ratio if one considers the carbonate-rich surface rocks as the sink of the initial terrestrial  $\text{CO}_2$ . If the three terrestrial bodies are assumed to have accreted a similar volatile inventory, one would not expect that at Mars two entirely different processes with  $\text{CO}_2$  transformed into carbonates, whereas  $\text{N}_2$ , hardly precipitating as a mineral, lost by atmospheric escape, would lead to a huge depletion ( $> 99\%$ ) of these two constituents with almost exactly the same efficiency. The present low martian atmospheric pressure would thus originate from atmospheric loss rather than a surface sink.

OMEGA has identified hydrated sulfates through their distinct vibrational overtones involving water and hydroxyl in the 1- to 2.5- $\mu\text{m}$  region. Sulfates would thus constitute



**Fig. 8.** Sulfate-rich layer deposit. Within Valles Marineris, Juventae Chasma is a 2.5-km-high and  $\sim 40$ -km-long layered deposit, imaged in this spectacular three-dimensional view (30) by the HRSC/Mars Express camera. Superimposed on the corresponding black and white MOC/MGS image is the mapping of the sulfates obtained by OMEGA, with gypsum (blue) dominating in the layered strata and kieserite (red) expanding around.

the best record of a  $\text{H}_2\text{O}$ -driven past activity. Up to now, these salts have been identified by OMEGA in a variety of specific locations: within Valles Marineris and in Aram Chaos, essentially in association with light-toned layered deposits (22), and as large regional units in Terra Meridiani (23) and close to the perennial northern polar cap (24). Not all light-toned layered deposits, however, show evidence for sulfates, such as the White Rock area within Pollack crater: OMEGA confirms, with sub-km-resolution mapping, the lack of evidence for an aqueous origin (25).

Magnesium sulfates (kieserite,  $\text{MgSO}_4 \cdot \text{H}_2\text{O}$ ) and calcium sulfates (gypsum,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) have been identified. In at least one location, Juventae Chasma, kieserite appears as covering and surrounding a massive stratified deposit likely made of layers of gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) (Fig. 8). In Terra Meridiani, a surface layer of sulfates is also found on etched terrains (26) northeast of the Opportunity landing site (OLS). It is likely that the sulfate-rich outcrops found by Opportunity in OLS belong to the same unit and were brought to the surface by erosion. Hydrogen enrichment was found by Gamma Ray Spectrometer/Odyssey in low latitude areas and attributed to hydrated minerals rather than subsurface ice (27). The hydrated minerals detected by OMEGA could be present within a much more extended subsurface layer, appearing at the surface in only a few places. This could also be the case of the wide sulfate-rich area associated with longitudinal dunes within the north polar cap (24): It could indicate that hydrogen-rich areas mapped by GRS at high latitude do include water ice-rich terrains and hydrated minerals spread over much wider areas, with a fraction only exposed to the surface by erosion.

As detected by OMEGA, sulfate deposits are commonly associated with hydrated silicates and/or ferric oxides at a regional and local scale; however, they are not strictly correlated at a pixel level. This would indicate that although sulfates and oxidized minerals bear a large commonality in origin, they have experienced a likely physical sorting process later.

The existence of sulfates requires water at the time of their formation. However, it does not necessarily imply that evaporation in long-standing bodies of water did occur. Other processes might have taken place, such as salt precipitation in supersaturated seeping water either evaporating or sublimating away out of water-rich ice, if the atmosphere was sufficiently tenuous, cold, and dry for water not to be stable in liquid state at the surface of the planet. Water could have been brought to the surface either as liquid or frost and made acidic by volcanic outgassing, with  $\text{H}_2\text{S}$  reacting with atmospheric  $\text{O}$  to form  $\text{H}_2\text{SO}_4$ . Sulfates would thus originate from the acidic rain or frost alteration of basalts, with olivine altered into magnesium-rich to iron-rich sulfates and HCP into calcium-rich sulfates (28).

**Conclusions.** The analyses of the NIR hyperspectral reflectance data OMEGA has acquired so far indicate that the surface of Mars exhibits a large diversity in composition, in particular at small spatial scales ( $\sim 1$  km). At seasonal time scales, compositional variation is dominated by the  $\text{CO}_2$  cycle, the soil transportation, and the sequences of condensation and sublimation of the polar frosts, primarily made of both  $\text{CO}_2$  and  $\text{H}_2\text{O}$ . At geological time scales, the surface diversity originates from a coupled evolution of the magmatic, volcanic, and alteration history of Mars, with no major role played



**Fig. 9.** La bocca della verità: Vassili I. Moroz (33).

by CO<sub>2</sub> within the volatile inventory: OMEGA found no definite evidence that CO<sub>2</sub> sustained a long-term greenhouse effect enabling liquid H<sub>2</sub>O to remain stable at the surface of Mars in the post-Noachian terrains. The OMEGA observations to date are consistent with an early escape of most of the Mars atmosphere, leaving the atmosphere as the major present CO<sub>2</sub> reservoir; water has been found trapped in two sinks: as ice mixed with dust within the two large perennial polar caps and as surface hydrated minerals, which seem to have been synthesized during the early evolution of Mars.

If indeed the water remained essentially stable in solid and gaseous states during the past

3 billion years, with only transient episodes of liquid water brought to the surface, then the episodic evolution of the obliquity (29) might have played a major role in the observed surface composition: in condensing water ice in a variety of areas determined by the atmospheric circulation in different insolation conditions, resulting in morphological and compositional (alteration) effects, that can be observed in the present surface properties of a number of areas.

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- The OMEGA instrument has been developed with the support of Centre National d'Etudes Spatiales (CNES), Agencia Espacial Italiana (ASI), and Russian Space Agency. The scientific activity is funded by national space and research agencies and universities in France, Italy, Russia, Germany, and the United States of America. We are very grateful to the entire ESA teams who, together with industry, enabled this mission. We thank G. Neukum and the High Resolution Stereo Camera (HRSC) team who provided us with images of areas mapped by OMEGA. Vassili I. Moroz (Fig. 9) was a member of the OMEGA team until he passed away 23 June 2004. He was a pioneering planetologist who provided an outstanding contribution to OMEGA. This paper is dedicated to him.

16 December 2004; accepted 8 February 2005

Published online 17 February 2005;

10.1126/science.1108806

Include this information when citing this paper.

#### REPORT

## Summer Evolution of the North Polar Cap of Mars as Observed by OMEGA/Mars Express

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The Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité (OMEGA) visible-infrared imaging spectrometer extensively observed regions of Mars with latitudes above 70°N in late 2004 (heliocentric longitude from L<sub>s</sub> 93° to L<sub>s</sub> 127°). The extent of water ice at the surface and the size of ice grains were monitored as a function of time. Bright, small-grained frost, which initially covered a large fraction of the polar cap, waned in favor of large-grained ice. In outlying regions, dominated by large-grained ice, the albedo increased over the period. Evaluating the dust content was model dependent. However, contamination of ice by dust was low.

The permanent caps of Mars were first comprehensively observed by Viking in 1976. Thermal infrared (IR) observations by Viking and then Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) dem-

onstrated that the surface of the permanent north polar cap is dominated by water ice (1, 2). Analyses of imaging data from Mariner 9, Viking (3), and MGS (4–6) have demonstrated that the albedo of the north circum-

polar regions varies within a single summer season and from summer to summer. Water ice is very bright in the visible spectrum when clean, but even a small amount of dust contamination can reduce the albedo to values close to that of the dust itself if the dust grains are embedded in ice grains (7). Determining

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