OMEGA: Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité

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OMEGA is a VIS/NIR hyperspectral imager. It acquires images of the surface and atmosphere of Mars with a footprint ranging from 300 m to 5 km depending on the altitude of the spacecraft. On each pixel, it provides the spectrum in 352 spectral channels covering the range 0.35–5.1 μ m. In this domain, most surface (minerals, frost, ice) and atmospheric (gas, aerosols, clouds) constituents have diagnostic features that enable their identification. Consequently, OMEGA can monitor their time and space dependence. As a major outcome, OMEGA can derive the evolution of Mars over all timescales, from geological and climatic to seasonal variations.

This chapter presents the main results obtained after four years of operation. The results are discussed in the framework of Mars history that they are likely to modify profoundly, in particular with regard to the role of water. A very early era of potential habitats has been identified, with the relevant terrains located and the environmental conditions deciphered. It is suggested that this era was followed by a period of global climatic change, towards a cold and dry environment that has lasted to the present day.

The Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA) instrument on Mars Express is a visible/near-infrared hyperspectral imager, built under the responsibility of the Institut d'Astrophysique Spatiale (IAS), Orsay, France (Principal Investigator, PI, and Project Manager, PM), and the Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Meudon, France, in cooperation with the Istituto di Fisica dello Spazio Interplanetario (IFSI-INAF), Rome, Italy, and the Institute for Space Research (IKI), Moscow, Russia (Bibring et al., 2004a).

1. OMEGA Instrument

OMEGA couples an imaging capability, with an instantaneous field of view (IFOV) of 1.2 mrad, and a spectral capability, in acquiring for each pixel the spectrum from 0.35 to 5.1 μ m, in 352 contiguous spectral channels ('spectels'), with a spectral sampling of 7, 13 and 20 nm in the spectral ranges 0.35-1.0, 0.93-2.65 and 2.51-5.1 µm, respectively. OMEGA includes three spectrometers, one for the visible and near-infrared (VNIR) range 0.35-1.0 µm, and two covering the near-infrared (NIR) range 0.93-5.1 µm. Two dedicated and co-aligned telescopes are used to illuminate the VNIR and NIR channels separately. VNIR operates in the push-broom mode; it images a given line of Mars, perpendicular to the drift velocity of the spacecraft, along one direction of a bi-dimensional CCD detector array, with the spectrum of each pixel spread over the other direction of the array by a concave holographic grating. The infrared channel operates in a whisk-broom mode: one pixel of Mars is imaged at a time, and its spectrum is acquired on two IR linear arrays, from 0.93 to 2.65 µm (short-wavelength IR, SWIR), and from 2.51 to 5.1 µm (long-wavelength IR, LWIR), respectively. A scanning mirror ahead of the NIR telescope enables contiguous pixel imaging in the cross-track direction, perpendicular to the spacecraft drift velocity. For VNIR, SWIR and LWIR, the second spatial dimension is provided by the movement of the spacecraft. Over time, three-dimensional (two spatial and one spectral) image cubes are built up, which constitute the OMEGA dataset.

The imaging performance can be summarised as follows. With an IFOV of 1.2 mrad, the spatial sampling (cross-track pixel size) is ~300 m when the observation is made close to periapsis, up to 4.8 km from an altitude of 4000 km. OMEGA's prime goal is to perform a global coverage of Mars with a 1.5-4.8 km footprint, and to map selected areas amounting to ~5% of the surface at high resolution (footprint <400 m), although the initial goal of the mission design was to acquire global high-resolution (100 m) coverage. The instrument design allows a total field of view of 128 pixels cross-track, or 8.8°, for both the VNIR push-broom and the NIR whisk-broom channels. However, building the images requires synchronising the duration of a swath with the drift of the spacecraft in order to avoid both under- and oversampling. With an infrared integration time of typically 5 ms, chosen to secure a signal to noise ratio (SNR) >100, the swath varies from 16 pixels when acquired at periapsis (high spacecraft orbital velocity, ~4 km/s), to 128 pixels when operating above 1500 km (slower spacecraft drift, <2 km/s). Thus the high-resolution mode consists of strips some 5-8 km wide, and hundreds of kilometres long, while the global coverage is made of strips 300-500 km wide and thousands of kilometres long.

The nominal pointing mode is nadir. In order to target given units of interest, nadir pointing with a constant cross-track offset angle must be implemented. In addition, some observations have been made in inertial mode (3-axis stabilised), in particular to acquire limb profiling, and in a 'spot pointing' or emission phase function (EPF) mode, to enhance the detection of atmospheric constituents. Due to severe mission resource constraints, mainly on energy and downlink capabilities, ESA imposed a strict sharing with other investigations, and assigned OMEGA an average data volume cap of 15%. This means that OMEGA operates during less than one out of four orbits on average, and for <60 min per orbit. As a consequence, a large number of specific targets were missed, with very little multiple coverage of the same area to monitor seasonal changes in the first three (terrestrial) years of operation.

2. Identification of Atmospheric Constituents

Because OMEGA analyses the solar radiation diffused by Mars, its spectral images always include signatures of the atmospheric constituents, both gases and aerosols. Their retrieval is mandatory for identifying surface features, and gives access to unique atmospheric properties, with the highest spatial sampling on Mars Express (300 m from periapsis altitude). However, given the limited spectral sampling (7–20 nm), only the major (CO₂) and a few minor species (CO, H₂O and O₂) are unambiguously detected. Examples are given in the following.

2.1 CO₂

An accurate radiative transfer model devoted to the retrieval of the three components (surface, gas, aerosols) is essentially complex and iterative. At first order, it is possible to calculate the atmospheric absorption independently. A dedicated model has been built for this purpose (Melchiorri et al., 2006), which computes a multiplicative component in the synthetic spectrum representative of the main atmospheric contributions (CO_2 , H_2O and CO) in the 1–2.7 µm range (corresponding to the SWIR-C channel). This model performs a line-by-line spectroscopic calculation of the atmospheric absorption, and a spectral atmospheric database is built up for each OMEGA session, with a one-to-one correspondence. *A priori* knowledge of the atmospheric pressure is taken from general circulation model (GCM) predictions (Forget et al., 1999), as well as a humidity factor and CO profile. Several spectra are calculated around the GCM-predicted position in parameter space, and a least-squares fit adjustment is made to retrieve the observed atmospheric pressure. Each calculation is performed at the exact illumination and elevation conditions corresponding to the OMEGA observations.

The pressure measured in this way is not the actual martian pressure, as at this stage no correction has been made for dust opacity. The 'effective pressure' measured in the model is nevertheless correlated with the actual pressure, in a way that can be constrained by a more sophisticated model, including the scattering which is developed as 'second-order' modelling (Forget et al., 2007).

Since pressure variations on Mars are primarily correlated with the altitude of the surface, CO_2 being the dominant atmospheric compound, a first output of the model is an altimetry map along the OMEGA observations. These altimetry measurements can be checked against the Mars Orbiter Laser Altimeter (MOLA) measurements; effective pressure measurements are found to be accurate to 0.044 mbar (standard deviation), corresponding to an altimetry accuracy of 100 m (1 σ). The instrumental noise itself is estimated to about 200 m. Therefore, OMEGA atmospheric observation gives an altimetry measurement that is spatially better resolved than the *a priori* MOLA measurement, to an accuracy of a few hundred metres. This first step allows us to study pressure fluctuations beyond the altimetry variations. This second-order study enables us to search for global or local wave variations, at the 0.1 mbar pressure range, corresponding to the martian meteorology. Similar searches have been tentatively performed using Phobos imaging spectrometer (ISM) observations (Gendrin et al., 2003).

2.2 H₂O and CO variations

A second step in the study of atmospheric features from OMEGA observations is the H_2O and CO retrieval. Despite faint absorption at OMEGA resolution, the sensitivity of the instrument gives access to a good accuracy of the column density of these minor constituents. The spatial variations in the abundance ratio of H_2O and CO can therefore be studied, after a correction for the altitude of the surface is performed. The 2.6 µm band of H_2O is used, and water vapour maps have been obtained, for $L_s = 94-112^\circ$, corresponding to the sublimation of the northern polar cap. A mixing ratio of H_2O in the range $2-3 \times 10^{-4}$ is obtained at 40°N, corresponding to 25 pr-µm, and $5-10 \times 10^{-4}$ at 60–80°N, corresponding to 40–60 pr-µm. These results are consistent with previous Mars Atmospheric Water Detector (MAWD/Viking) and Thermal Emission Spectrometer (TES/MGS) observations below 60°N (Encrenaz et al., 2005).

The CO abundance is measured with only a low accuracy, due to the low intensity of the (2–0) band at 2.3 μ m. Nevertheless, spatial variations have been positively observed over Hellas at $L_s = 130-150^\circ$, by a factor of 2 compared with $L_s = 330-350^\circ$ (Encrenaz et al., 2006). This result is consistent with GCM predictions (Forget et al., 2006), which indicate an enrichment of non-condensable species over Hellas during the southern winter, due to the effects of local topography on the global circulation. Similar variations in argon abundance have been observed on Hellas at similar L_s (Sprague et al., 2004).



Fig. 1. (a) Average of OMEGA spectra taken at the limb over altitudes in the range 50-90 km, exhibiting the fluorescence of CO₂ and CO in the martian atmosphere. (b) Integrated emission on the spectral bands for CO₂, CO and the continuum, showing the maximum emission along the line of sight.

2.3 CO₂ fluorescence

Strong non-LTE emissions of the martian atmosphere are observed above the limb in the OMEGA observations in 3-axis stabilised mode. These emissions are identified as CO₂ at 4.3 μ m, with a maximum at ~90 km altitude, and CO at 4.7 μ m, with a peak emission at ~50 km. The CO₂ emission is observed at altitudes well above any dust contamination, since dust opacity reflections typically occur well below 60 km. Although no direct observations of the CO₂ emission in imaging mode had been made before Mars Express, its interpretation was well understood in advance from non-LTE modelling of the martian atmosphere, with models developed in particular for atmospheric profile accuracy measurements (Lopez-Valverde et al., 1998). An example of a spectrum of the fluorescence is given in Fig. 1(a), and the vertical variation in the integrated emissions in the CO₂ and CO bands are plotted in Fig. 1(b). The main value of OMEGA observations is that they provide simultaneously the spectral information on CO₂ and accurate imaging of the emissions. For the first time, the altitudes of these emissions can be directly evaluated from the spectral images, and compared with the model. The model has been improved to fit the data (Drossart et al., 2004).

2.4 Clouds and aerosols

OMEGA has clearly identified both H_2O and CO_2 clouds, through specific spectral features. In particular, high-altitude CO_2 clouds show up via resonant absorption at 3.24 µm, within the otherwise saturated band; they also appear through enhanced reflection in the visible in both the OMEGA VNIR data, and HRSC coordinated observations. Their occurrence has been mapped over the entire planet and all seasons: these clouds are highly localised in both space and time, emphasising the coupled role of thermodynamics and nucleation processes to account for their formation (Montmessin, 2008). In parallel, Monte Carlo based modelling has been conducted to derive aerosol properties from the near-infrared spectra in a variety of areas observed under different dust opacities (Vincendon et al., 2007).

2.5 The O₂ Dayglow

The O₂ emission at 1.27 μ m was observed on the dayside by OMEGA in both nadir and inertial modes of observation. In spite of the limited spectral sampling, it is possible to monitor the O₂ emission, as it does not overlap with emission or absorption features at a percent level. The O₂ dayglow at 1.27 μ m is excited by the photolysis of ozone. About 90% of O₂ molecules are produced on the excited level $a^1\Delta_g$, which decays either by emitting 1.27 μ m photons or by colliding with CO₂ molecules. From nadir observations, the distributions of the ozone abundances at different latitudes, local times and seasons are obtained. For the first time the signature of gravity waves in the O₂ emission, as well as CO₂ ice and H₂O ice clouds, have been observed simultaneously in the northern polar region at the end of winter. The OMEGA limb observations have been used to determine the vertical distribution of the O2 emission and the derived apparent ozone abundance, and to retrieve the vertical profile of the ozone number density. The O₂ emission profiles vary significantly with latitude, season and local time, but are usually observed below 40-60 km. To estimate the vertical profile of the O₃ number density, the quenching effect was taken into account. From the limb profile of the O₂ emission, the quenching parameter was found to be $k = (0.7-1) e^{-20} \text{ cm}^3 \text{ s}^{-1}$, which is about 2–3 times lower than the existing upper limit. In order to take into consideration the collisions between O₂ and CO₂ molecules, we used the vertical CO₂ profiles simultaneously obtained from the Mars Express/PFS LWC data. Below 10 km the aerosol absorption becomes significant even at low dust loading in the atmosphere, which obscures the O_2 emission. An example of a vertical profile of ozone is shown in Fig. 2.

In order to retrieve the diagnostic signatures of surface constituents, several steps are followed, and a variety of data reduction techniques are used. The first steps involve removing the instrumental effects and the atmospheric contribution, dominated by the CO₂ bands (see section 2.1). Then, the spectrum is divided by a synthetic solar reference spectrum. The resulting radiance factor or *I/F* spectral values (where *I* is the measured radiance and πF is the incident solar radiance at the top of the martian atmosphere at the time of observation) include all potential surface features.

Most features of interest can be enhanced by spectral band ratios, dividing the I/F at a wavelength position corresponding to the supposed maximum absorption (band centre) to that of the nearby continuum. More sophisticated techniques are available, which for example search for coupled absorptions of a single component. The modified Gaussian model (MGM) is well suited for identifying constituents exhibiting features that can be reproduced by a small number of Gaussians, such as pyroxene (see section 5).

The OMEGA spectral characteristics and performance are very favourable for identifying H_2O and CO_2 ice and frost features in the SWIR channel, by the absorptions centred at (1.25, 1.5, 2 µm) and (1.435, 2 µm) for H_2O and CO_2 , respectively. Moreover, the band shapes (width and depth) are direct indicators of the texture and mean size of the icy grains, which enable their qualitative assessment (Fig. 3). Consequently, OMEGA has been able to monitor the seasonal evolution of both polar caps over one martian year (Bibring et al., 2005; Langevin et al., 2005a; Douté et al., 2006).

Figure 4 illustrates the seasonal evolution of the northern polar cap. Condensation of both H_2O and CO_2 are roughly symmetrical in longitude, with H_2O frost observed down to 4°S of the CO_2 frost. When the sublimation is completed, all CO_2 disappears, leaving a pure H_2O -rich perennial ice cap.

Previous observations in the visible (e.g. Benson & James, 2005) and in the thermal IR (Kieffer et al., 2000) provided detailed information on the retreat of the southern seasonal ice cap. In mid-spring, a cold and dark region (the 'cryptic region') develops over part of the cap (Kieffer et al., 2000). The OMEGA observations have demonstrated that the southern seasonal cap is almost free of water ice during most of the spring and summer, unlike the northern seasonal cap. Furthermore, contrary to expectations, most of the cryptic region has been shown to be dominated by dust contamination of the surface (Langevin et al., 2006) with a possible link with a complex atmospheric circulation driven by the presence of the Hellas basin.

The bright southern perennial ice cap consists of a thin veneer of annealed CO_2 ice, containing trace amounts (~0.03 wt%) of dust and H₂O ice, which is probably trapped



Fig. 2. Vertical profile of ozone above Argire (44°S, 318°E) at L_s =16°, Lt=10.8h.

3. Identification of Surface Constituents

4. Observations of Frost and Ice



Fig. 3. Model spectra of CO_2 ice with grain sizes of 1 mm (orange) and 5 cm (red), and H_2O ice with grain sizes of 10 μ m (green) and 1000 μ m (blue). The three dashed lines correspond to the OMEGA spectels at 1.385, 1.5 and 1.77 μ m, which are used to determine the strength of the H_2O ice absorption at 1.5 μ m, as this is the only weak CO₂ absorption at these wavelengths.



Fig. 4. Seasonal evolution of the northern polar cap: spatial distribution of spectral signatures of H_2O ice and CO_2 ice observed by OMEGA in early northern spring (L_s 22°, March 2006). (a) Band depth of the H_2O ice absorption feature at 1.5 µm. The rainbow scale covers the range from 60% (black) to 0% (red). (b) Band depth of the CO_2 ice absorption feature at 1.43 µm, also from 60% (black) to 0% (red). The annulus observed by TES between the boundary of bright regions (black line in b) and that of regions at the equilibrium temperature of CO_2 ice (crocus line, white dashes, from Titus & Kieffer, 2003) is confirmed as consisting of H_2O frost. At this season, the strongest CO_2 ice signatures, corresponding to large mean grain sizes, are observed over regions corresponding to the central parts of the permanent northern ice cap.





Fig. 5. OMEGA global mapping of low-Ca pyroxene (LCP), for latitudes between -50° and +50°.

Fig. 6. OMEGA global mapping of high-Ca pyroxene (HCP), for latitudes between -50° and +50°.

during the southern winter (Douté et al., 2006). It covers an extended H_2O -rich glacier (Bibring et al., 2004b) where the water ice, unambiguously identified by OMEGA, is mixed with dust and does not show up in visible images.

As a consequence, the two perennial caps constitute a major reservoir of the presently known inventory of H_2O on Mars. Perennial CO_2 ice is apparently only a very minor constituent of the southern cap, and does not account for more than a small fraction of the present atmospheric mass of CO_2 .

The visible and near-infrared spectral range has long been recognised as very favourable for identifying diagnostic features of rock-forming minerals, such as Fe electronic crystal field transitions in olivines and pyroxenes (e.g. Adams & Filice, 1967; Soderblom, 1992, and references therein). Consequently, most olivine and pyroxene minerals can be identified from VNIR observations. Low-Fe silicates such as plagioclase feldspar, however, are nearly featureless in the VNIR and are thus not readily identifiable with an instrument like OMEGA.

Pyroxenes [(Ca,Fe,Mg)₂Si₂O₆] are identified by the presence of two broad but distinct absorptions centred near 1 and 2 μ m, with the band positions varying in a systematic pattern as a function of the pyroxene chemistry (Fe, Mg and Ca abundance) and crystal structure: the band centres shift towards longer wavelengths with increasing calcium content. Low-calcium pyroxenes (LCPs, e.g. orthopyroxene) have short-wavelength band centres (~0.9 and ~1.85 μ m), while high-calcium pyroxenes (HCPs, e.g. clinopyroxene) have their band centres at longer wavelengths (1.05 and 2.3 μ m). Because silicate rocks typical of terrestrial planet surfaces are mixtures of different minerals, the region around 1 μ m can also exhibit absorption features that may originate from the presence of other minerals such as olivine (with a broad absorption centred at ~1.05 μ m) and ferric oxides (with typical absorptions near ~0.9 μ m). Most other minerals do not exhibit broad features near 2 μ m, however. Therefore, it can be more definitive to detect pyroxenes through their ~2 μ m features rather than those at ~1 μ m.

We have defined a spectral index based on band ratios that enables the detection of pyroxenes independent of their Ca content (Poulet et al., 2007). The resulting maps of this mineral at a global scale reveal the contrast between the units where their pristine mafic composition has been preserved (the heavily cratered highlands crust and volcanic outflows), and large areas such as the northern plains that have apparently been altered to or covered by pyroxene-free materials. In parallel, we have developed an algorithm based on the MGM, which is well suited to identifying the pyroxene features, to discriminate between HCPs and LCPs and to weight their relative abundance (Figs. 5 and 6) (Sunshine & Pieters, 1993).

Generally, LCP is enriched in the older Noachian crust, while HCP is enriched in more recent lava flows (Mustard et al., 2005). Figure 7 illustrates this pattern in the Syrtis major region (Nili Fossae/Nili Patera areas), where the volcanic shield exhibits the highest HCP/LCP abundance ratio found on Mars. HCP-rich areas are darker and generally more sandy (Fig. 8). The HCP enrichment of the lava outflows might indicate partial melting or a low level of mixing within the magma chamber, since HCPs (e.g. diopside) melt first, while LCPs (e.g. enstatite) require higher temperatures to melt. By contrast, the Noachian crust appears to have crystallised out of a fully melted magma, mixing LCP and HCP.

Olivine $[(Mg,Fe)_2SiO_4]$ has a broad complex absorption centred near 1 µm, which extends from 0.8 to 1.5 µm; it broadens and deepens with increasing Fe content in olivine, from forsterite Mg₂SiO₄ (Fo100) to fayalite Fe₂SiO₄ (Fo0) (King & Ridley, 1987). For example, in USGS samples (Clark et al., 1993), the absorption extends to about 1.55 µm for Fo89 and to 1.8 µm for Fo11. In addition, there are systematic variations in the shape of the 1 µm absorption with grain size. Increasing the grain size broadens the bottom of the band and shifts the right wing towards longer wavelengths, so that forsterite with very large grains (>100 µm) and fayalite with smaller grains have similar spectra. Therefore, a precise olivine composition in terms of Mg/Fe ratio is

5. Observations of Mafic Minerals

Fig. 7. OMEGA mineralogical mapping of the Syrtis Major area (square in Fig. 6), exhibiting the HCP-rich lava outflows surrounded by the LCP-rich Noachian crust and olivine-rich spots.





difficult to assess from NIR spectral data only. Olivine is primarily found in a variety of localised areas, including Nili Fossae and Terra Meridiani; in low-albedo regions such as Aonia terra, Nereidum Montes, Terra Tyrrhena and Oenotria Scopulus; in several unnamed and named craters, including Gale, Herschel, Huyghens, Schroeter, Pollack, Schiaparelli, Herschel and Moreux (Fig. 9); and in Valles Marineris (Ius, Hebes, Capri, Melas and Ganges). A large number of isolated olivine-rich spots have been detected around the rims of Isidis, Hellas and Argyre (Fig. 10). In addition to these olivine-rich

Fig. 8. Mineralogical (OMEGA) and optical (MOC, HRSC) mapping of Hebes Chasma. The HCP band depth (top left) is higher in the dark areas (top right), which appear as sand dunes (bottom right).



Fig. 9 Olivine-rich dunes within Moreux crater, located at 41.5°N and 44.5°E, as identified by OMEGA (blue = olivine, right), in the MOLA (left) and THEMIS (middle) context.



Fig. 10. Olivine-rich spots surrounding the Argyre impact basin, centred at 50°S, 320°E), as identified by OMEGA (turquoise = olivine).

areas, detailed radiative transfer modelling (Poulet et al., 2007) indicates that olivine is likely present together with pyroxene in the large mafic areas, mainly as forsterite of small grain sizes (<10 μ m), possibly with concentrations of up to 20%.

Ferric-rich minerals can be detected through features in the visible and in the nearinfrared (e.g. Burns, 1993): the electronic transitions of ferrous iron, which lead to absorption band centres from 0.95 to 1.05 depending on composition, shift towards smaller wavelengths (at ~0.85–0.9 μ m) when the oxidation state varies from ferrous to ferric. In addition, the spectrum of ferric-rich phases exhibits some specific features in the visible, with in particular a shallow absorption at ~0.6 μ m with an edge at ~0.53 μ m. Several indices have therefore been defined to identify ferric minerals. However, they do not lead to identical maps, which indicates that the surface of Mars contains a variety of ferric minerals that differ in composition, structure, crystallinity, and/or mean grain size, and therefore may possibly record distinct formation processes.

The index based on the 0.53 μ m absorption edge integrates all ferric-rich phases (Bell et al., 1990; Morris et al., 2000). The corresponding ferric mineral map (Fig. 11b) shows a positive detection all over the martian surface, with a high variation in intensity, well correlated with the near-infrared albedo (measured at 1.1 μ m) (Fig. 11a). Smaller concentrations are detected in the low-albedo mafic units, which could correspond to the presence of ferric minerals in the bulk of the crust.

Higher concentrations of ferric minerals are found in the vast areas that do not exhibit mafic signatures: they may result from the alteration of these mafic regions, and appear as a bright reddish soil ('dust'). These areas correspond also to a positive detection when another spectral index, a ratio of the reflectance at 0.98 and 0.8 μ m, is used. This index is sensitive to the presence of so-called nanophase hematite (nanometre-sized particles of α -Fe₂O₃), as shown by Morris et al. (2000) (Fig. 11c). The dust is subjected to atmospheric transport, resulting in the coverage of wide areas such as the Olympus Mons and Tharsis volcances. However, this mobility does not affect the entire Mars surface, as demonstrated by the high mineralogical diversity still

6. Observations of Ferric Oxides





Fig. 12. Typical OMEGA spectra of oxide-rich areas: Aram Chaos (red), Candor Chasma (green), Capri Chasma (blue), compared to that of dust (black).

Fig. 11. Global maps of (a) the NIR albedo, (b) ferric oxides and (c) nanophase ferric oxides.



Fig. 13. Spatial coupling of sulphates and oxides in Candor Chasma. *Left*: 1.9 μ m band depth identified as polyhydrated sulphates (blue = 2%, red = >5%). *Centre*: 2.1 μ m band depth, identified as kieserite (green = 2%, red = >5%). *Right*: oxide band depth, as modelled using the MGM of Sunshine and Pieters (1993) (orange = 10%, red = >30%). observed at all resolutions. An important observation made by OMEGA is that these ferric oxides, as shown in section 7, are strictly anhydrous. On this basis, the OMEGA team has proposed that they result from alteration by atmospheric peroxides rather than by liquid water (Bibring et al., 2006).

A third and distinct class of ferric phases is detected by the occurrence of a deep 0.9 μ m band and a strong reflectance increase to 1.3 μ m (Fig. 12). Such features are located in a few areas only, and appear coupled to the presence of hydrated minerals, mostly sulphates. This class of ferric phases has been found in Terra Meridiani, Aram Chaos, and in association with layered deposits in Valles Marineris (Fig. 13) (Bibring et al., 2007).



Fig. 14. Distribution of hydrated minerals detected so far by OMEGA at the surface of Mars, for latitudes from -50° to +50°. Blue: kieserite; green: polyhydrated sulphates; red: phyllosilicates; yellow: other hydrated minerals.

Minerals with water molecules either adsorbed or in their crystal structure exhibit relatively well defined absorptions near 1.4, 1.9 and 3.0 μ m, and are thus readily accessible to OMEGA detection. O–H stretching, either symmetric (v₁) or asymmetric (v₃), has its fundamental absorption band at 2.9 μ m, with overtones and combinations at 1.4 μ m (v₁ + v₃). The H–O–H bending fundamental at ~6 μ m (v₂) has its first overtone at 3.1 μ m, and a combined resulting feature (v₂ + v₃) at ~1.9 μ m. These near-IR features have been studied previously in lower spatial and spectral resolution Mars datasets (e.g. Houck et al., 1973; Pimentel et al., 1974; Calvin, 1997).

All hydrated phases do exhibit a broad 3 µm band, which is thus not diagnostic of specific minerals. However, it can be used to evaluate the amount of water stored in the mineral structure (Jouglet et al., 2007; Milliken et al., 2007). Hydrated minerals are thus identified by features resulting from O-H and/or H₂O related vibrations, at \sim 1.4 and \sim 1.9 µm, together with those resulting from the coupling between OH and/or H_2O to metal (e.g. Al, Mg, Fe or Ca) or to anionic complexes such as SO_4^{2-} , CO_3^{2-} (e.g. Clark et al., 1990a, 1990b; Swayze & Clark, 1990). Minerals containing hydroxyls exhibit the 1.4 µm band, as well as narrow absorptions between 2.0 and 2.4 µm, which are typically combination overtones of an OH stretch and a metal-OH bend, and can be very diagnostic of mineralogy (e.g. Bishop et al. 1993, 1994; Roush et al., 1993; Bell et al., 1994). Hydrated sulphates have specific features resulting from the SO stretches (fundamentals at $\sim 10 \mu m$), with overtones in the 2.2–2.5 μm region when in presence of water (e.g. Crowley 1991; Cloutis et al., 2006). Their precise position and shape of the sulphate near-IR bands vary with composition, and for hydrated sulphates result in features at 2.2 and 2.4 µm. An important exception is that of monohydrated sulphate (e.g. kieserite MgSO₄, H₂O), for which the 1.4 and 1.9 µm bands are shifted towards longer wavelengths, at 1.6 and 2.1 µm, respectively.

OMEGA has identified and mapped two classes of hydrated minerals: sulphates (section 7.1) and phyllosilicates (section 7.2). In contrast, carbonates (section 7.3), which have two strong absorption features at ~3.5 and ~3.9 μ m, have not been detected so far, above the detection limit of ~1–2% in volume, demonstrated by ground calibration.

One key outcome of OMEGA detection of hydrated species is that they are found only in very localised areas (Fig. 14). In particular, the ferric oxides that constitute the bright dust covering most of the northern plains and Tharsis, are strictly anhydrous (see section 6).

7.1 Hydrated Sulphates

OMEGA has detected hydrated sulphates at the surface of Mars at three locations: in the layered deposits of Valles Marineris (Gendrin et al., 2005), in Terra Meridiani (Arvidson et al., 2005) up to Aram Chaos, and in dark dunes of the northern polar cap (Langevin et al., 2005b). In most cases, mixtures of sulphates are present. In a few cases however, due to their diagnostic signatures, specific sulphates have been identified with a high level of confidence: kieserite (MgSO₄, H₂O) and gypsum (CaSO₄, 2 H₂O).

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Fig. 15. Red curve: OMEGA spectrum from 1.2 to 2.6 μm of a sulphaterich region within the dark dunes of Olympia Planitia, within the northern polar cap, ratioed to a reference spectrum of a nearby dark area, normalised to 1 at 1.25 μm. Blue curve: normalised ratio of two spectra obtained during ground calibration: that of a pure gypsum powder (<40 μm grain size) and that of an aluminium oxide powder, which is spectrally featureless in this wavelength range. Features are observed in both spectral ratios at 1.445, 1.535, 1.745, 1.94, 2.22, 2.26, 2.42 and 2.48 μm (dashed lines).



Fig. 16. Area interpreted to be gypsum rich within Olympia Planitia, illustrated by a false-colour composite showing the distribution of the absorption at 1.93 μ m relative to a continuum defined from 1.86 and 2.14 μ m. The colour code is a rainbow scale from black (<4% band depth) through blue, green and yellow to red (>25% band depth). A strong absorption at 1.93 μ m is observed on an extended dark area centred at 240°E, 80°N. White areas correspond to the regions with permanent water ice at the surface.



Fig. 17. Hydrated sulphate spectra identified in the OMEGA observations. Green: library spectrum. Black: OMEGA spectrum. Blue: reference spectrum. Red: spectral ratio. *Left*: kieserite (MgSO₄, H₂O). *Middle*: gypsum (CaSO₄, 2H₂O). *Right*: polyhydrated sulphate; the library spectrum corresponds to epsomite (MgSO₄, 7H₂O) but other polyhydrated sulphates are good spectral analogues.



Fig. 18. Spatial distribution of the kieserite, identified in OMEGA spectra, plotted over the HRSC 3D perspective model of Candor Chasma.



In its 1.2–2.6 μ m spectrum, gypsum exhibits six unique spectral features, at 1.45, 1.75, 1.94, 2.22, 2.26 and 2.48 μ m, which makes its potential for identification quite robust (Fig. 15). OMEGA could at the same time (Langevin et al., 2005a): (i) identify H₂O as the dominant constituent of the permanent (residual) northern cap, excluding CO₂ ice; (ii) map its spatial distribution; and (iii) identify gypsum as the major constituent of the dark terrains of Olympia Planitia intermixed with the bright ice (Fig. 16).

Kieserite also has specific features in terms of position and shapes, at 1.6, 2.1 and 2.4 μ m (Fig. 17). Its presence in a few locations on the surface of Mars is important as this monohydrated mineral is known to be easily hydrated into epsomite (MgSO₄, 7H₂O), which can eventually dehydrate to hexahydrite (MgSO₄, 6H₂O) and amorphous Mg sulphate (MgSO₄, 1.2H₂O). Kieserite has been identified in several layered deposits within Valles Marineris (Fig. 18), as well as in a small spot northeast of the Mars Exploration Rover (MER) *Opportunity* landing site, in Terra Meridiani (Fig. 19).

Most of hydrated sulphates detected by OMEGA appear to be polyhydrated, possibly including the amorphous Mg sulphate phase. Poulet et al. (2007) have shown that some of the sulphates detected in Terra Meridiani could be Fe-rich sulphates, such as amarantite $(Fe^{3+})(SO_4)(OH)\cdot 3(H_2O)$ or schwertmannite $(Fe^{3+}_{16}O_{16}(OH)_{12}(SO_4)_2 \cdot nH_2O)$. However, jarosite $((K,Na,H_3O)Fe_3(SO_4)_2(OH)_6)$, detected by *Opportunity*, has a specific NIR spectrum that is not observed in the OMEGA data.

7.2 Hydrated Phyllosilicates

As shown in Fig. 14, OMEGA has detected a variety of phyllosilicates in localised areas, with the two largest ones located in the Nili Fossae and Mawrth Vallis areas (Poulet et al., 2005). These detections constitute the best evidence that Mars once hosted liquid water over long periods, enabling the formation of these hydrated alteration phases.

The composition of the phyllosilicates is not identical at all locations (Fig. 20). Mg/Fe smectites are always present, in particular as nontronite, and dominate in the

Fig. 19. Distribution of kieserite (red), polyhydrated sulphates (green) and other hydrated minerals (pink) in Terra Meridiani. The *Opportunity* site is indicated.



Fig. 20. Spectra of hydrated phyllosilicates, as detected by OMEGA, compared with laboratory spectra, showing the diagnostic shift of the M–OH feature from 2.2 μm for Al-rich (a,b) to 2.28 μm Fe-rich (c), and 2.35 μm Mg/Fe-rich (d) species. Nili Fossae/Syrtis Major complex. Al-rich phyllosilicates, such as montmorillonite or chlorite, are also found, in particular in the Mawrth Vallis area. However, kaolinite appears to be rare. This is an indication that the process responsible for the formation of the phyllosilicates, although it implies liquid water likely over long periods, was characterised by a rather low level of leaching (Chevrier et al., 2007). With reference to conditions prevailing in terrestrial environments, or during laboratory simulations when similar minerals are formed, the martian fluids in which these smectites formed were neutral to alkaline rather than acidic at the time the aqueous alteration took place (Chevrier et al., 2007).

The sites where the phyllosilicates have been mapped are all very ancient, and have been exposed to the surface either by impact or erosion. In the Nili Fossae area (Mustard et al., 2007; Mangold et al., 2007), the phyllosilicate-rich terrains all appear to predate the first lava flows from Nili Patera and Syrtis Major Planum, dated early Hesperian by crater counting. Phyllosilicate-rich sites include both ancient heavily cratered terrains that have not been buried by the lava flows, and recently excavated ones (Fig. 21). Apparently the impact process did not destroy or dehydrate these minerals, but might rather have triggered their formation. It is important to note that by contrast, the lobate ejecta craters within the Nili Patera lava floor do not exhibit hydrated minerals, which strongly indicates that this lava material was essentially dry.



Fig. 21. Hydrated phyllosilicates in Nili Fossae. The intensity of the 1.93 μ m feature (*right*) indicates the location of the hydrated clays, found in the ancient terrains not buried by lava flows.

In Mawrth Vallis (Poulet et al., 2005, Loizeau et al., 2007), as in all similar outflow channels, no hydrated minerals are found within the bed or the mouth of the channel (Fig. 22). In contrast, hydrated minerals are found on the highly etched terrains along the flanks of the channel. One interpretation of this observation is that the phyllosilicates were formed prior to the outflow. The outflows themselves do not appear to have lasted long enough, nor constituted a sufficiently sustained degree of fluvial activity, to form hydrated minerals such as clays. Rather, the outflow channels may result from transient episodes (e.g. Baker et al., 1974) that were violent enough to erode their flanks and expose ancient materials that happen to have been processed by liquid water in earlier times. Those earlier phyllosilicates have remained preserved as such until the present day.

7.3 Hydrated carbonates, and other CO₂ sinks

We have searched the OMEGA data for carbonates in a wide variety of potential sites all over the planet. In particular, we have performed a systematic characterisation of the material related to impact craters within the northern plains, with the following rationale. If Mars once hosted a large ocean at a time when the atmosphere was dense enough for CO_2 to dissolve, ionise and precipitate (as on Earth) sedimentary layers of hydrated carbonates might have accumulated on the hypothetical ocean floor prior to these low-altitude terrains filling with lava. Large enough impact craters could have reached down into these older layers and exposed in their ejecta some of their constituent materials. In fact, in their OMEGA spectra, most craters with diameters larger than ~20 km exhibit a clear signature of the crustal (mafic) bedrock (Bibring et al., 2005). However, none of the ejecta, nor the central peaks, show the spectral signature of carbonates, nor even of any hydrated minerals. This is a strong indication that these terrains probably never hosted long-standing water bodies in the presence of a dense CO_2 -rich atmosphere.

As described in section 4, OMEGA has shown that the two perennial polar caps are massive water ice glaciers, but do not constitute significant CO_2 traps. With the lack of detection of abundant carbonates, it seems very likely that the atmosphere, although extremely tenuous, is the dominant CO_2 reservoir at present. This constitutes a major constraint on the long-term evolution of the climate of Mars.



Fig. 22. Hydrated phylloslicates in Mawrth Vallis. Distribution, over an HRSC mosaic (three contiguous maps), of the minerals identified by OMEGA through their 1.93 μ m (hydration, blue), 2.20 μ m (montmorillonite, green) and 2.30 μ m (Mg/Fe-rich smectites, red) features.

8. A Derived Mars Mineralogical History: Identification and Characterisation of an Early Global Change

The identification and mapping of both primary igneous and secondary altered minerals, put into their geomorphological context, reveals some major features relevant to the history of Mars (Bibring et al., 2006). Well preserved mafic minerals are still observed on a wide scale, in the oldest crust and, in places, even in impact craters. By contrast, the northern lowlands are dominated by an alteration product (dust) characterised by anhydrous ferric oxide. Hydrated minerals have been detected, in a restricted number of localised areas. They consist of two classes, phyllosilicates and sulphates, which are found in distinct terrains, formed by distinct processes, at distinct times. They trace distinct eras, 'phyllosian' and theilkian' respectively to reflect the names, in Greek, of their dominant minerals. Stratigraphic relationships suggest that the phyllosilicates formed first, in a neutral to alkaline environment, followed by the sulphates (*theilkos* in Greek), in an acidic environment. We are thus led to propose that in between the two eras, Mars underwent global-scale climatic change. We attribute this major environmental evolution to the volcanic activity that led to the building of Tharsis and the filling of the northern plains (Fig. 23).

Since phyllosilicates usually require water over long duration to form, Mars likely hosted conditions sustaining liquid water on geological timescales in its very early history. This in turn requires that there were abundant greenhouse gases, given the predicted low luminosity of the early Sun (e.g. Pollack et al., 1987). However, like most young stars, the early Sun was likely an extreme ultraviolet emitter, with high ionising efficiency, and with an intense solar wind. A planetary magnetic shield was thus critical to protect against atmospheric loss. As demonstrated by the findings of the Magnetometer and Electron Reflectometer (MAG/ER) investigation of remnant crustal magnetism on Mars Global Surveyor, early Mars appears to have supported a global dynamo, which could have efficiently protected its atmosphere. The absence of magnetised minerals over Tharsis and in the northern plains is a strong indication that this dynamo shut off before the onset of volcanism that raised Tharsis and filled the plains.

A possible explanation is that mantle convection could not sustain a sufficient temperature difference between the core and the mantle, required to maintain core convection: the dynamo and its associated magnetic shield dropped. Cold plumes could have started to form and to sink within the mantle and accumulate at the core/ mantle boundary. This, in turn, could have triggered thermal instabilities, leading to the formation of degree 1 hot plumes, ascending to form Tharsis after some tens of millions years. In such a scheme, the formation of Tharsis would have happened long after the magnetic field had faded, and long after most of the atmosphere had been lost by solar wind erosion or other processes. In the tenuous resulting atmosphere, the massive outgassing coupled to the volcanic activity could have injected S-rich compounds as dominant species, which then rapidly oxidised into sulphuric compounds, leading the environment (including any groundwater) to become highly acidic. These S-rich species precipitated widely over the planet, possibly in the form of nanophase S-rich grains, accounting for the large concentration of S detected by elemental Alpha Particle X-ray Spectrometer (APXS) analyses at all rover and lander sites since Viking.

The present composition of the martian atmosphere has an N_2/CO_2 value close to those of both Venus and Earth (~3%), if one takes into account that most of the initial terrestrial CO₂ is presently trapped as carbonates. The N_2/CO_2 ratio is consistent with such an early physical loss mechanism. If the initial volatile reservoirs of Mars, Venus and Earth were similar, and given that CO₂ can be sequestered into carbonates whereas N_2 hardly ever condenses into minerals, one would not expect a massive depletion of both constituents (more than 99.9%) with identical efficiencies (Bibring & Erard, 2001). OMEGA data support a model in which most of the atmosphere escaped prior to the Theiikian; today's atmosphere would result from an equilibrium between the present (very limited) loss mechanisms, for example as measured by Mars Express/ASPERA (Barabash et al., 2007), and the supply of volatiles by residual internal activity.



In such a model, the Phyllosian era would have ended when the surface water could longer remain stable as a liquid, and instead evaporated and/or percolated and froze subsurface permafrost. The large-scale tectonic effects that followed the building of harsis, such as the opening of Valles Marineris and the tilt of Terra Meridiani, as well the localised rising of the geothermal water table, could have produced sequential pplies of liquid water to a variety of regions within these areas, for example, meanting the S rish mean have grained in the localised denosite. This process

Fig. 23. OMEGA derived Mars mineralogical history.

no longer remain stable as a liquid, and instead evaporated and/or percolated and froze as subsurface permafrost. The large-scale tectonic effects that followed the building of Tharsis, such as the opening of Valles Marineris and the tilt of Terra Meridiani, as well as the localised rising of the geothermal water table, could have produced sequential supplies of liquid water to a variety of regions within these areas, for example, cementing the S-rich nanophase grains into large sulphate deposits. This process would not necessarily require surface liquid water to be long-lasting, since sulphates can sediment even while water is evaporating. During this period, sulphate layers would have grown where surface water was supplied, in spatial and time relation with the Tharsis rise. The Theiikian era would have ended rapidly, leading to a long era (Siderikian), lasting until the present, dominated by anhydrous surface oxidation and the creation of nanophase ferric oxides (*siderikos* in Greek) in a highly rarefied atmosphere. This oxidation likely results from a very slow process (time scales of Gyr) operating on the very superficial layers (sub-millimetre scale) of surface grains.

Although one could have expected that the global circulation of dust would preclude the identification of distinct units on the surface of Mars, the OMEGA investigation has demonstrated a high degree of mineralogical diversity down to a sub-kilometre scale. Units of all ages, from the most ancient to the most recently processed ones, have been identified by their composition. In particular, the oldest units, although subjected to a longer period of potential weathering, still preserve their igneous content. In parallel, the detection and mapping of alteration products provide key clues for deciphering the evolution of the Mars environment.

Two classes of hydrated phases have been identified. Placed in their geological context, and in relation to the *in situ* findings of the two NASA Mars Exploration Rovers, they enable a profoundly new model of the past martian climate to be envisioned. Thirty years after the pioneering measurements of the Viking landers, the OMEGA orbital near-infrared survey indicates that Mars might indeed have hosted, once in its earlier past, conditions that favoured liquid water to remain stable over long periods of time. The sites where one might search for these potential habitats are not necessarily located where the optical images would have led us to consider, since phyllosilicates are not directly associated with fluvial or other water-related landforms. OMEGA results so far suggest that the most favourable sites for preserving evidence of this early epoch are those characterised by a mineralogical signature of hydrated phyllosilicates. Most of the largest of these targets may have already been identified. A refined analysis by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument on the Mars Reconnaissance Orbiter mission, with

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similar spectral coverage but a tenfold higher spatial sampling than OMEGA, will greatly enhance the characterisation of these regions.

It is our deep conviction that if ever life once emerged on Mars, these phyllosilicaterich sites are the targets in which future *in situ* laboratories (for example the NASA Mars Science Laboratory and ESA/ExoMars missions) have the best chances of finding potential biorelics at a microscopic scale.

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