

MARS CLIMATIC AND GEOLOGICAL HISTORY, DERIVED FROM THE OMEGA/MEX DATA.

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Introduction: On board the Mars Express ESA mission [1], OMEGA [2] acquires spectral images of the surface and atmosphere of Mars since January 2004. Its 1.2 mrad IFOV provides a footprint varying from 300 m (high resolution mode, when imaged close to periapsis) up to ~5 km (global mode, up to 4000 km altitude). The spectral range (0.35 μm to 5.1 μm) is covered in 352 contiguous spectral channels, with spectral sampling varying from 7 nm (in the visible) to 13 nm (from 1 μm to 2.5 μm) and 20 nm (from 2.5 μm to 5.1 μm). Its very high SNR enables the retrieval of features down to 1 % in absorption. The constraints in energy and downlink at mission level lead to a severe limitation of the number of observations OMEGA can acquire, with a cap of 15% of the total data volume imposed by ESA from the mission start, for the benefit of the other investigations. As a consequence, only a very limited high resolution coverage has been achieved so far.

The OMEGA spectral domain, dominated by solar reflectance with a limited thermal contribution, has confirmed to be well adapted to characterize the composition of both the Martian surface (minerals, frosts and ices) and atmosphere (CO_2 , H_2O , CO, O_2 , aerosols). Coupling the compositional identification (spectral performance) to their mapping (imaging performance) has a huge potential to trace back the evolution of Mars over the variety of its timescales: diurnal to seasonal circulation, seasonal to secular fluctuations, climatic to geological variations.

An important specific of OMEGA is to enable the discrimination between i) the various potential phases in which H_2O and CO_2 may be stored, e.g. as clouds, frosts, ices, hydrated minerals; ii) their molecular composition, H_2O and CO_2 exhibiting distinct diagnostic features; and iii) some physical properties, such as the mean grain size, the temperature, their bounding (e.g. O-H vs H_2O). As a consequence, the Martian H_2O and CO_2 cycles can be monitored through the space/time variations of the diverse phases, which has led to major breakthroughs in the understanding of small to medium timescale evolution, presented in companion papers. In this talk, we focus on the long-term (climatic/geological) evolution, with an emphasis on the role liquid water might have played over the Mars History.

The OMEGA spectral images reveal that at all spatial scales large fractions of the surface of Mars exhibit a wide diversity, despite dust transportation. As a consequence, major compositional units can be identified, and located in distinct geomorphological contexts: this relationship opens the possibility to trace back the environmental changes that modeled the planet history. This requires to couple the occurrence of given minerals to the thermodynamical properties favouring their formation. In a few instances, specific calculations have been conducted to constrain the Mars environment at the relevant epochs.

Pristine materials: OMEGA has shown that the dichotomy between the cratered highlands of Noachian age and the more recent units, derived from surface structures, is also reflected in their composition: a large fraction of the ancient terrains have preserved their pristine composition, with no global alteration having modified their mafic content. OMEGA identifies the crust primarily through its pyroxene content [3,4,5], with a mixing of low to high calcium species representative of crystallization out of a highly fused magma. By contrast, the lava flows from the later volcanic activity are enriched in high calcium pyroxenes, indicating a rather low level of fusion of the corresponding magma. The existence of preserved ancient terrains, from their compositional standpoint, requires a specific interpretation for their not having been altered although they are the oldest. It opens an exciting possibility to still access materials dating from an era contemporary with the emergence of life on the Earth, in the search for similar processes having taken place at Mars.

Altered materials: On a global scale, the large areas having been altered as not exhibiting their primordial mafic content are covered by a reddish and bright dust: OMEGA identifies its composition dominated by ferric oxides [6]. The spectral signature is similar to that of $\alpha\text{-Fe}_2\text{O}_3$, supporting the suggestion that it is constituted of nanophase hematite [7]. As discussed below, OMEGA capability to identify hydrated minerals has led to the important assessment that these ferric oxides are anhydrous, and are likely not resulting from alteration by liquid water [8]. They rather would have been formed by interaction with atmospheric peroxides as trace elements, which would account for its being

very shallow (sub-mm) and requiring long time scales (Gy), precluding the highlands to yet be highly altered.

A major discovery of OMEGA is the identification and mapping of hydrated minerals. By contrast with the occurrence of large areas covered with ferric oxides, the hydrated minerals are observed in localized areas. Two classes have been found: sulfates and phyllosilicates, while carbonates have not (see below). Specific companion papers [9,10] summarize these findings. As this discovery constitutes a key driver to trace back Mars history, a brief reminder is given hereafter.

Hydrated sulfates have been identified in two main types of location: 1. in the dunes of Olympia Planitia, within the Northern polar cap [11]; 2. in a variety of areas within Valles Marineris ([10,12], Aram Chaos [10,12] and Terra Meridiani [12,14]). The OMEGA spectra do not enable the retrieval of the specific composition of these hydrated sulfates quite unambiguously, as many of them have very similar NIR spectrum: the most robust discrimination is that of monohydrated sulfates (e.g. kieserite $\text{MgSO}_4 \cdot \text{H}_2\text{O}$) and of gypsum ($\text{CaSO}_4 \cdot 2 \text{H}_2\text{O}$). The context in which these hydrated sulfates are found suggests a very distinct origin for the two types of location. In the Northern polar cap, the sulfates would be associated with the recent supply of sulfur from outgassing, followed by in situ reaction with water and Ca-rich mafic minerals (volcanic ash), in the form of gypsum wind-transported and deposited as dunes. All other hydrated sulfates would be much older; it is important to note, though, that sulfates are not found within the highly cratered Noachian areas. They would record the massive surface water supply coupled to the tectonic activity that followed the building of Tharsis (see below). In particular, sulfates are found in layered deposits within Valles Marineris.

The discovery, identification and mapping of hydrated phyllosilicates is a major outcome of OMEGA [9,15]. As for the sulfates, the phyllosilicates are only found in localized areas. These areas are all distinct from those in which sulfates are found, spread over the ancient cratered crust, with higher concentrations found in two sites: within the Syrtis Major/Nili Fossae complex, and around the Marwth Vallis outflow channel. Phyllosilicate-rich areas have been exposed, either by wind and/or liquid erosion, or by impact. It is noteworthy that impact actually did not destroy the hydrated minerals, but rather might have triggered their formation [3,8]. The composition of these minerals is not identical in all locations. Mg/Fe smectites are present systematically, and dominate in the Nili/Syrtis area. Of particular importance is the detection of nontronite, as it implies a neutral to alkaline environment

to form. In Marwth Vallis and other areas, Al-rich species, with montmorillonite and chlorite potential candidates, are also found: Al-rich and Mg/Fe-rich phyllosilicates seem then to be associated to structurally distinct context, as evidenced on the optical images [16], and with an increased spatial sampling by the CRISM/MRO spectral images [17]. Kaolinite, with its specific spectral signature, has been tentatively observed, in a very few occurrence only [9]. The fact that this species is rare indicates a rather low level of leaching during the alteration process.

The formation of hydrated sulfates and phyllosilicates requires very different aqueous conditions. Although one might conceive ways to form phyllosilicates in transient processes not implying liquid water, it is highly likely that the widely spread occurrence of phyllosilicates within the crust results from alteration with long standing liquid water, either at or below the surface. By contrast, sulfates might form while liquid water is not stable, deposited as salt during evaporation.

Where is the CO_2 ?: OMEGA spectral and radiometric performances are well suited to search for CO_2 in a variety of phases: gas, frost and ice, carbonates. In particular, the 3.4 μm and 3.9 μm features associated to most carbonates are readily detectable by OMEGA, as demonstrated during ground calibration with mixtures of carbonates within hydrated clays, down to abundance ratios of 1 weight % [3,18]. We have searched for carbonates in all potential locations at the surface of Mars, including the ejecta from craters in Vastitas Borealis, large enough to have exposed crustal material [3]: if an ocean had existed in presence of a CO_2 -rich atmosphere, prior to the lava filling of these lowlands, one would have expected some carbonates to have sedimented, and been later exposed by impact. So far, OMEGA has not detected carbonates in any of the areas mapped. The absence of carbonates is consistent with the N_2/CO_2 atmospheric abundance: if the present low atmospheric pressure results from gaseous loss, with CO_2 primarily trapped as carbonates (as on the Earth) while N_2 hardly precipitates as a mineral, one would not expect both species to be depleted so heavily (by almost a factor of 10^4 with respect to a primordial atmosphere comparable to that of Venus or the Earth) with exactly the same efficiency, to account for the N_2/CO_2 ratio of $\sim 3\%$, identical in Mars and Venus (and the Earth if one considers that most primordial terrestrial CO_2 is in carbonates): the N_2 and CO_2 atmospheric depletion on Mars must have occurred through a process not involving the chemical structure of these molecules. To complete the evaluation of the CO_2 trap, OMEGA searched for icy reservoirs. The presence of CO_2 as a major constituent of

the bright Southern perennial cap was proposed on the basis of its surface temperature derived from thermal infrared observation (TES/MGS). OMEGA did map the polar cap after retreat, and discovered that although the bright material of the perennial cap is indeed made of CO_2 , it constitutes a very thin veneer, some meters in depth at most, covering a massive H_2O -rich glacier of some km in depth, not visible in optical images [19]: the CO_2 icy reservoir accounts for less than one mbar; the tenuous Mars atmosphere would constitute the major present CO_2 reservoir. Altogether, OMEGA observations would be consistent with an early and efficient atmospheric escape that led to the present properties some billion years ago, in agreement with recent evaluation [20].

Climatic History: The detection of well preserved mafic minerals within the cratered Noachian crust, of hydrated phyllosilicates exposed in crustal areas, of hydrated sulfates cemented in units surrounding the tectonic event triggered by the building of Tharsis, and of anhydrous ferric oxides covering the late Hesperian to Amazonian units, constitutes a mineralogical record of the Martian history [8]. This history appears as a sequence of three eras (figure 1), during which water played very distinct role. The earliest one is traced by the presence of hydrated phyllosilicates (“phyllosian”) within the pristine crust, suggesting a climate favoring water to remain stable along geological timescales, in a neutral to alkaline global pH. In a subsequent era, no phyllosilicates formed, but hydrated sulfates (“theiikian”), in localized areas characterized by a highly acidic environment, and large surface supplies of liquid water, possibly unstable so as to leave precipitates of sulfates. The next era, lasting until now, is dry and cold; with an alteration at a global scale dominated by gaseous oxidation in ferric oxides of the surficial dust (“siderikian”). During these two last eras, space and time localized events, triggered by either impacts or transient obliquity changes, might have injected water in the atmosphere and at the surface, resulting in spectacular fluvial structures without having hydrated the associated minerals.

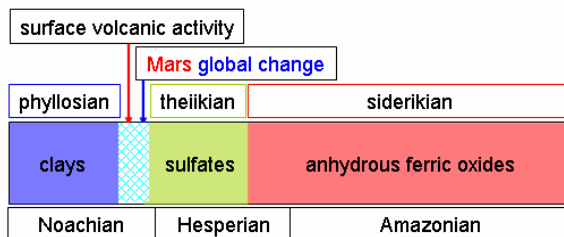


Fig. 1: OMEGA derived Mars Mineralogical History

The Mars global change: The mineralogical history suggests that the Martian environment changed drastically between the phyllosian and the theiikian, both in its global pH and its ability to sustain stable liquid water. This Mars global change (figure 1), indicated and characterized by the OMEGA identification and mapping of its surface altered minerals, could be directly coupled to the onset of volcanic activity constituted by the formation of the Tharsis buldge. Moreover, this event could itself be coupled to the drop of global magnetic dynamo, as a result of the specific evolution of the core/mantle interaction. A sequence such as follows would account for OMEGA observations.

While the dynamo operated, providing an efficient magnetic shield against the ionization and sputtering atmospheric effects of the early Sun, Mars sustained an atmosphere well above the water triple point conditions: surface or subsurface water could remain liquid long enough to alter efficiently the mafic crust into hydrated phyllosilicates. However, for the core to remain convective requires a large thermal gradient at the core/mantle interface to cool efficiently the outer core and induce downswelling cold plumes. The decrease in mantle convection thus led to the drop of the core convection, and its associated magnetic shield: unprotected, the Mars atmosphere suffered an efficient escape, resulting in a depletion of greenhouse gases precluding water to remain stable. Phyllosilicate formation stopped, surface water both percolated and evaporated, with the later followed by its escape, together with that of CO_2 and N_2 : this constituted the end of the phyllosian era. In the mantle, cold plumes started to form and to sink, accumulating at the core/mantle boundary: this in turn triggered thermal instabilities, leading to the formation of degree 1 hot plumes, ascending to form the Tharsis buldge after some tens of million years. As a consequence, this happened long after the magnetic field had faded, and most the atmosphere had gone. In the tenuous resulting atmosphere, the massive outgassing coupled to this volcanic activity injected as dominant species S-rich compounds, rapidly oxidized into sulfuric ones, leading the environment to become highly acidic. These species precipitated widely over the surface, possibly in the form of nanophase S-rich grains, which accounts for the large sulfur concentrations detected by elemental analyses at all rover and lander sites since Viking. The large scale tectonic events that followed the building of Tharsis, such as the opening of Valles Marineris, the tilt of Terra Meridiani, the localized raise of the geothermal water table, produced sequential supplies of surface liquid water in a variety of spots within these areas, cementing the S-rich nanophase into large

sulfate deposits. This process though did not require water to constitute long standing liquid structures, since sulfates could sediment while water evaporated. Theiikian is this period during which sulfate layers grew where surface water was supplied, in spatial and time relation with the Tharsis raise. It ended rapidly, opening a long era (siderikian), dominated by the anhydrous surface oxidation in nanophase ferric oxides in a highly rarefied atmosphere.

Conclusion: The detection and mapping by OMEGA of pristine and altered surface minerals give key clues to decipher the evolution of the Mars environment. Placed in their geological context, they model a profoundly renewed vision of the past Martian climate. 30 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 favouring liquid water to remain stable over long durations.

The sites in which one might search for these potential habitats are not located where the optical images would have led us to consider, that is primarily in relation with fluvial or other water-driven structures. OMEGA suggests that the most favourable sites are those characterized by their mineralogical content of hydrated phyllosilicates. Most of these targets have already been identified. A refined analysis by MRO/CRISM, with a ten-fold higher spatial sampling, greatly increases their characterization. It is our deep conviction that if ever life once emerged on Mars, these phyllosilicate-rich sites are the targets in which future in situ laboratories (NASA/MSL and ESA/ExoMars) have the best chances of finding potential biorelics, at a microscopic scale.

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