

**AN OVERVIEW OF THE SULFATES DETECTED IN THE EQUATORIAL REGIONS BY THE OMEGA/MEX SPECTROMETER.** N. Mangold<sup>1</sup>, A. Gendrin<sup>2</sup>, C. Quantin<sup>1</sup>, J.-P. Bibring<sup>2</sup>, B. Gondet<sup>2</sup>, Y. Langevin<sup>2</sup>, F. Poulet<sup>2</sup>, R. Arvidson<sup>3</sup>, J. L. Griffes<sup>3</sup>, H. Hauber<sup>4</sup>, Ph. Masson<sup>1</sup>, G. Neukum<sup>5</sup>, and the OMEGA and HRSC Co- Investigator Teams (1) IDES-Orsay, UMR 8148, CNRS and Université Paris-Sud, Bat. 509, 91405 ORSAY Cedex, France, nicolas.mangold@u-psud.fr, (2) IAS, Université Paris-Sud, France (3) DEPS, Washington University, St Louis, MO, USA (4) DLR, Berlin, Germany (5) FU, Berlin, Germany.

**Introduction:** Sulfates are detected with the spectral data OMEGA (Observatoire pour la Minéralogie, L'Eau, Les Glaces et l'Activité) onboard Mars Express on many areas of the Valles Marineris-Xanthe Terra chaos and Terra Meridiani regions. They are present uniquely on the light toned layered deposits present inside canyons, in chaos and over the Meridiani Planum area [1 to 6]. Sulfates require the presence of liquid water in their formation. As a consequence, sulfates in layered deposits have been interpreted either as deposition through evaporitic processes or alteration of preexisting material through groundwater circulation, or eventually acid fog alteration [1], but many issues remain open concerning their formation. Here we provide an overview of the different locations that are sulfate-rich in the equatorial regions and we detail their geologic context, by comparing the sulfate mapping with the geology, the topography, the thermal inertia and the presence of other minerals.

**OMEGA Analysis:** Kieserite is detected using three main absorption bands at 1.6, 2.1 and 2.4  $\mu\text{m}$ . These bands are due, in monohydrated sulfates, to the single, strongly hydrogen bonded, water molecule. A second group of minerals is detected with absorption bands at 1.4 and 1.9  $\mu\text{m}$  and a drop at 2.4  $\mu\text{m}$ . Such associations are observed in spectra of polyhydrated sulfate minerals which can correspond to any sulfates (with Fe-, Na-, Ca-, Mg- cations) with more than one water molecule. Gypsum is locally identified using the doublet at 2.22-2.28 microns and an additional band at 1.7 micron. Additionally, Fe-sulfates are locally detected in the Terra Meridiani region from their strong absorption around 1 micron coupled with other sulfate features [3].

Other minerals are also detected together sulfates. A drop between 1 and 1.3 micron suggests the frequent occurrence of iron oxides close to the locations where sulfates are detected in many locations of Valles Marineris [4] and locally in Terra Meridiani where ferric hydroxides might be present too [3]. Pyroxenes are detected in the same region than sulfates, but they are usually not mixed together sulfates. Notice also that sulfate minerals might not be the only minerals present in the sulfate-rich outcrops, especially if the rocks contain minerals that are spectrally neutral in the NIR wavelengths (halite salt or silica for example).

**Sulfates in Terra Meridiani and chaos region:** In the chaos region, Aram Chaos exhibits a large area of sulfate-rich deposits corresponding to a part of the Aram Chaos spectacular layered deposits (Fig. 1). These sulfates surround, and are locally found together, a location with a strong absorption of iron oxides. This iron oxide rich region fits the location where TES discovered gray hematite. This leads to a similar context than Meridiani Planum, but, here, iron oxides are present beneath the sulfates as a result of erosion of material and eolian sorting into sand dunes at the foothill of scarps. In addition, the largest part of sulfate deposits in the central part of the canyon are not enriched in sulfates. These layers lie topographically above the sulfate-rich layers. It is possible that the stratigraphic column in Aram chaos corresponds to sulfates in the lowermost units and sulfate-free material in the uppermost unit.

In Terra Meridiani, sulfates are associated with the so called "etched terrains" exposed to the east and north of the hematite bearing plains where the rover Opportunity landed. The etched terrains are intensively eroded layered material [2]. The geomorphology, spectral properties and stratigraphy indicate that a well defined sequence of units (~1 km thick) was deposited unconformably over cratered plains in the area studied in northern Meridiani Planum [2, 3, 5]. Erosion has exposed these materials. The outcrops explored by Opportunity (located ~390 km to the southwest of the study site) are interpreted to be the uppermost layer of etched terrains similar in nature to the Upper Etched Plains materials [5]. The differences in mineralogy and hydration found for the lower section of these units regards to the uppermost one imply that the aqueous conditions varied during emplacement and/or alteration of the ~1 km layered materials.

These two regions also behave other hydrated minerals identified with the 1.9 micron band but lacking any other bands of sulfates [1, 2]. In Terra Meridiani, some of these hydrated minerals have locally a 2.3 micron band typical of Fe-OH bond which signs the presence of Fe-rich clay minerals [4]. The local association of clays and sulfates might sign different conditions than those expected for strongly acidic fluids expected at the Opportunity landing site [4]. Nevertheless, clays are not predominant in regions with large sulfate-rich outcrops.

**Sulfates in Valles Marineris region:** In Valles Marineris, this is clearly visible on the map of Interior Layered Deposits (ILD) of Lucchitta [7]. The mapping of polyhydrated sulfates relative to kieserite does not show some specific geographic organization: both are found in the different canyons except in Ganges and Tithonium Chasma where only kieserite exists (Fig. 2). Gypsum is only significantly present in two canyons such as Juventae and Capri Chasma. There is no obvious correlation between morphology and sulfate signatures that can match all the deposits. Nevertheless, kieserite is found preferentially over outcrops that are very eroded, with many grooves typical of wind erosion. Layering at this scale is often difficult to assess but usually exists when looking at the highest resolution. In contrast, the polyhydrated sulfates are often found on much darker surfaces, with less strong erosion and layering better visible. Elevations can be checked in the West Candor–Ophir Chasma canyons. Here, the difference in elevation from the floor to the plateau is of about 8 km, from  $-5$  km for the lowermost floor at the SE edge of West Candor and center of Ophir to 4.3 km on the plateau. The top of the westernmost lies at about 3.6 km above datum, thus only 700 m below plateau level. Assuming a subhorizontal layering for the overall interior layered deposits, the difference of elevation found in West Candor Chasma corresponds to a thickness of layered deposits of about 7 to 8 km; a thickness consistent with estimations made using Viking data [7]. Sulfates are found over elevations from  $-3.6$  km to  $+3.1$  km, thus over much of the layered deposits sequence. The mapping of the two sulfates types can be compared to TES thermal inertia [8] (Fig. 3). The TES map is shown for values  $> 200$  SI. Beneath 200 SI, the surface material corresponds to mobile dust. We can see that most canyons have floors above this limit, suggesting indurated or coarse grains that might lead to a detection in NIR spectroscopy. Nevertheless, large parts of West Melas, Ophir and East Candor Chasma are beneath the limit. We see in these canyons that sulfates have limited exposures (see Ledoit et al., this issue). Hereafter we detail the presence of sulfates in several canyons of Valles Marineris.

*West Candor Chasma characteristics:* West Candor Chasma lies in the central area of the Valles Marineris canyon system (Fig. 4). Sulfates signatures are mostly developed on the scarp of mesas, and some other escarpments. In contrast, pyroxene is found mainly in the low lying areas of dark tone and a few areas at higher elevations such as the top of the eastern mesa. These areas correspond to dark sand dunes, never to ILD. Thus, sulfates and pyroxene do not follow the same overall distribution. This conclusion is verified in all canyons. At MOC scale,

the surface texture of bright deposits displays flutes and yardangs typical of eolian erosion in weakly consolidated material. They are also devoid of small impact craters ( $<100$  m), which does not mean that the layers formed recently, but that they were exhumed recently. Slope statistics show a continuous increase in the relative proportion of kieserite with the increase of the slope [6]. This is an evidence that kieserite is directly present in the bedrock and does not come from surface interactions.

*Ophir Chasma:* In Ophir Chasma, a strong patch of kieserite exists at a place not mapped as ILD by Lucchitta [7]. At this location (Fig. 5), the THEMIS visible images show that this sulfate-rich unit is part of layered deposits exposing a very strongly eroded patterns with eolian grooves through all the surfaces. This location is therefore a layered deposit present on the floor of the canyons. Its strong erosion might explain the lack of signature on surrounding walls which have a lower thermal inertia.

*Ganges Chasma:* In Ganges Chasma, sulfate signatures can be followed all around the thick central mesa (Fig. 6). The kieserite is observed at same elevation on the different sides of the mound. It might sign the presence of kieserite in a specific layer about 1.5 km thick at the base of the 3 km thick mesa. Nevertheless, the basal part of the mesa is also a location of night temperatures higher than the uppermost part, and of a steeper slopes to the basal scarp than on the uppermost layers. Thus, the presence of kieserite in the basal part can also be biased by the more eroded texture of the layered deposits visible from the higher thermal inertia and partly due to steeper slopes.

*Tithonium Chasma:* The part of Tithonium canyon containing sulfates is located at the western edge of Valles Marineris. Most sulfates consist of kieserite found on a hill of height of about 3 km. This hill is not the unique ILD present here. The HRSC image enable us to see other bright material corresponding to ILD, but they display few or none sulfates. The sulfates are mainly detected on the flanks of the central hill. Two effects might explain this distribution. Firstly, the hill has two strong slopes ( $10$  to  $20^\circ$ ) on the side where sulfates are detected. Secondly, the THEMIS night time image shows a brighter surface at the base of these hills relative to the summit and to the two other ILD to the north. A higher tone on night time image corresponds more or less to a higher thermal inertia, therefore a material coarser or more indurated that might be a better terrain for spectral detection. Thus, erosion from slopes and higher thermal inertia might be responsible of the distribution observed in Tithonium Chasma, suggesting sulfates are more widespread in the butte.

**Implications:** From the observation of these different regions, it is clear that sulfates are correlated to layered deposits, but a few parameters are important to take into account:

Sulfates are present at very different elevations, up to 3.1 km above datum. In order to form sulfates as lacustrine deposits or alteration of preexisting layers, liquid water should have reached, either at surface or in aquifers, the elevation of 3.1 km to explain the presence close to the summit of the two mesas. This elevation is high with respect to Valles Marineris eastern limit located at  $-4$  km. Terra Meridiani is located below 0 km, implying a lower hydraulic head compared to Valles Marineris.

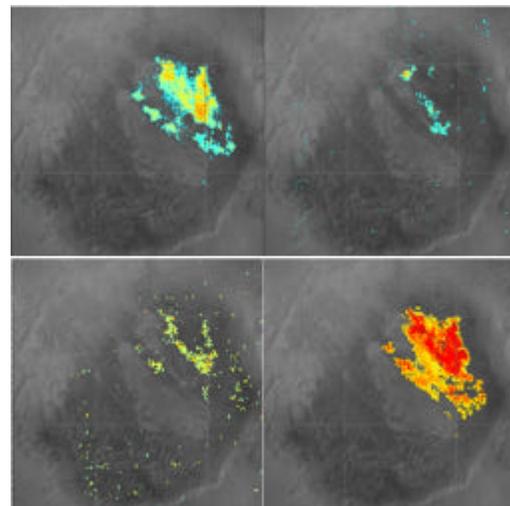
We also observe that the effect of slope is very important. Clear sulfate signatures are often found on slopes steeper than  $10^\circ$ . This might be related to the freshness of the outcrop, or the grain size. This effect is important to take in account in the interpretation, because it can modify the view interpretations when layers are present at different steepness.

Sulfates are observed when thermal inertia  $> 200$  SI, a value higher than dust deposits. Depending on locations, sulfates are also found on outcrops with the highest thermal inertia relative to the surroundings (as in Ophir Chasma for example).

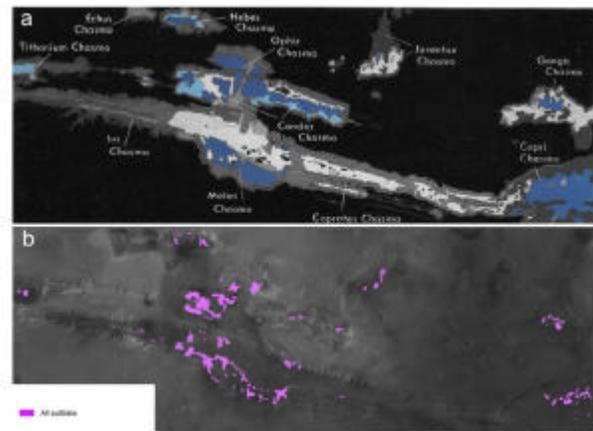
The lack of sulfates on several layered deposits can be questioned. Why do we not detect sulfates on all layered deposits? Are sulfates dominant or a minor component of the layered deposits? On one hand, sulfates are better seen on high thermal inertia areas, on steep slopes and strongly eroded area. This suggests that ILD without these characteristics might also contain sulfates, but they are not detected due to these limitations. However, a few layered deposits, such as in Hebes Chasma or Aram Chaos central part, show very few sulfates despite layers are of high thermal inertia, suggesting this explanation does not match all outcrops. Sulfates have also small absorption bands (2-10%) with regards to library spectra, showing either that the grain size is not adequate for detection or that sulfates are mixed with other material. Nevertheless, pyroxenes and olivine, two minerals very well detected by OMEGA, are not detected as a major component of layered deposits, if not completely absent of them. This is also the case over layered deposits outcrops where no sulfates are detected. In summary, it is likely that sulfates are mixed with other components, with some of them detected such as ferric oxides or ferric hydroxides and perhaps others not detected. This study does not allow us to discriminate between the two main hypothesis of formation (aqueous precipitation or alteration of preexisting material by fluid circulation) and both might have occurred, but the determination of these missing phases and the in depth comparison

of regions would probably be critical to understand better their formation. In any cases, sulfates are strongly associated to layered deposits, but these rocks display a variety of compositions from canyon to canyon and from Valles Marineris to Meridiani Planum which might sign regional variations in the chemical environment of formation of these materials that are not explained by a single aqueous environment.

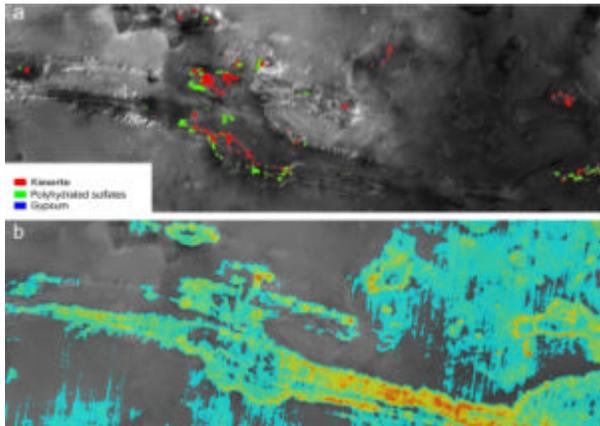
**References:** [1] Gendrin et al, Science, 307, 1587-1591, 2005. [2] Arvidson et al., Science, 1591-1594, 2005. [3] Poulet et al., Icarus, submitted, [4] Gendrin et al., LPSC, 2006. [5] Griffes et al., JGR, in press [6] Mangold et al, Workshop on sulfates on Mars, Houston, 2006 [7] Lucchitta, JGR, 1994.[8] Putzig et al., Icarus, 2005.



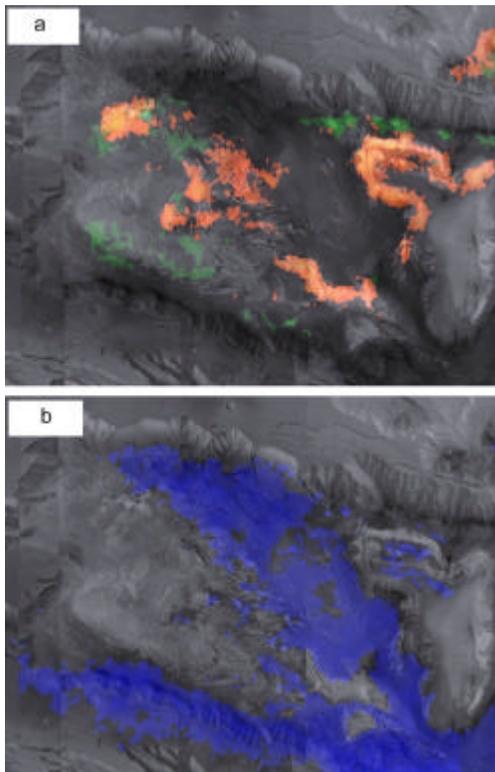
**Fig. 1:** Aram chaos. Top left: 1.9 micron band from 2 to 5%. Top right/ Ibid with 2.1 micron. Bottom left: 2.4 micron band. Bottom right: Iron oxides.



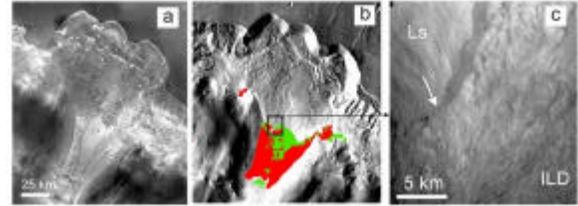
**Fig. 2** Identification of sulfates by OMEGA/MEX (pink) in (b) compared to the geologic mapping of interior layered deposits by Lucchitta [5] in (a).



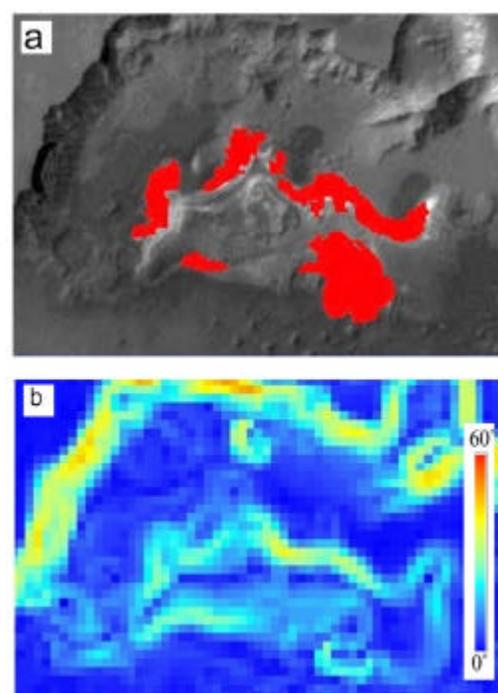
**Fig. 3:** Identification of polyhydrated sulfates (green) and kieserite (red) by OMEGA/MEx (pink) in (a) compared to the thermal inertia as mapped by Putzig et al. [6] in (b).



**Fig. 4:** OMEGA map of kieserite (red), polyhydrated sulfates (green) and pyroxene (blue) over HRSC mosaic of West Candor Chasma



**Fig. 5:** (a) THEMIS night time image of Ophir Chasma. (b) OMEGA detection of kieserite and polyhydrated sulfates. (c) Close-up on THEMIS visible image of the contact between a landslide (free of sulfates) and strongly eroded layered deposits at the bottom of the canyon.



**Fig. 6:** (a) Ganges Chasma kieserite detection. (b) Slope map using MOLA of the same area.