

# LITHOLOGIC UNIT MAPPING BASED ON OMEGA/MARS EXPRESS DATA

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## ABSTRACT:

This paper develops a procedure for mapping Martian lithologic units, using the OMEGA/Mars Express data. The procedure consists of correcting Martian atmospheric absorptions based on an empirical transmission function method, noise-free principle components analysis based on a minimum noise fraction (MNF) method, lithologic unit delineation, and spectral matching of the units to spectral libraries using spectral feature fitting (SFF) and spectral angle mapper (SAM) methods. Two areas, Meridiani Planum and Ophir-Candor Chasma for their mostly-known lithologic and chemical compositions, were chosen for testing the approach. It is found that the MNF band 1 (accounting for ~50% of total information from 114 bands between 0.926 to 2.55  $\mu\text{m}$ ) is mostly correlated (positively or negatively) to the albedo (correlation coefficient  $r$  up to 0.83 - 0.98) of the OMEGA imagery, while the MNF bands 2, 3, and 4 contain most lithological information for making an informative and useful geologic unit map. The two spectral matching methods (SFF and SAM) emphasize different criteria and should be used together to achieve confident results.

## 1. INTRODUCTION

Existing Martian geologic map and its geologic units were based on their geomorphology, crater features and density, albedo, multi-spectral properties, and thermal characteristics (USGS, 1986 and 1987). It was the best geologic map though it was no way to tell really what minerals and lithologies for each unit. Since January 2004, Europe Space Agency's (ESA) Mars Express satellite has been successfully operated for two Martian years of data acquisition. OMEGA imaging spectrometer, one of the sensors on board Mars Express, has revealed a diverse and complex Martian surface mineralogy and composition (Bibring et al. 2005). OMEGA/Mars Express imagery can be used to map not only individual minerals, but also corresponding lithologic units. The result will provide better information on the Martian crustal composition and evolution.

The purpose of this study is to develop a procedure that can be used to delineate the lithologic units based on the OMEGA imagery. Two study areas, Meridiani Planum and Ophir-Candor Chasma, were chosen to test our methods, since many previous works based on TES, THEMIS, OMEGA, or Opportunity Rover have been carried out in these two areas. This procedure would make it possible to produce a new globe Martian geologic map by merging the lithologic unit maps derived from individual OMEGA orbit imagery.

## 2. DATASET

OMEGA onboard Mars Express provides unprecedented mineral and lithologic information in 352 bands with a spatial resolution of 300 m/pixel to 4 km/pixel and spectral resolution of 7 nm in the visible and near-infrared range of 0.364 – 1.070  $\mu\text{m}$ , 13 nm in infrared range of 0.926 - 2.695  $\mu\text{m}$ , and 20 nm in infrared range of 2.527 - 5.089  $\mu\text{m}$  (Bibring, J.P., et al. 2005). The spectral range and resolution allow the identification of major surface and atmospheric species by their diagnostic spectral absorption feature. The OMEGA data (ORB0529\_3 and ORB548\_3) for the two areas (Meridiani Planum and Ophir-Candor Chasma) were downloaded from ESA's Planetary Science Archive. In this study, we mainly examined the spectral range between 0.926 to 2.55  $\mu\text{m}$  (114 bands), which includes the diagnostic spectral absorption feature of minerals and lithologies. The data was pre-processed using a modified IDL program initially provided by ESA to a relative reflectance image (I/F).

## 3. MAPPING PROCEDURE

### 3.1 Atmospheric correction

Atmospheric correction is required for the OMEGA data before it is used to identify surface minerals, rocks and other materials. Compare to Earth atmosphere, Mars has a very thin atmosphere (0.006 bar) which is principally composed of CO<sub>2</sub> (95.3% by volume). The atmospheric effect on the OMEGA imagery is

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characterized by several absorption bands of CO<sub>2</sub>. The existing atmospheric correction method to removed atmospheric absorptions is to use empirical transmission functions based on the ratio of two spectra acquired at the top and base of the Olympus Mons scaled to the CO<sub>2</sub> absorption depth at 2 μm (Bibring, J.P., et al., 1989; Maustard, J.F. et al. 2005).

### 3.2 Minimum Noise Fraction

The atmospherically corrected image was then further processed using a called minimum noise fraction (MNF) transformation method. Figure 1 illustrates the atmospherically corrected I/F images and the MNF resulting images in the Maridiani Planum area. It is clear that the albedo image (Figure 1b) reflects very similar information as the true color image (Figure 1a). The most interesting thing found is that the MNF band 1 (Figure 1c) is almost identical with the albedo image, while other bands are very different from the albedo image. This is consistent with the scatter plots and correlation coefficients shown in Figure 2: very good correlation coefficient ( $r = 0.988$ ) between the albedo image and the MNF band 1, no correlation between albedo image and other bands.

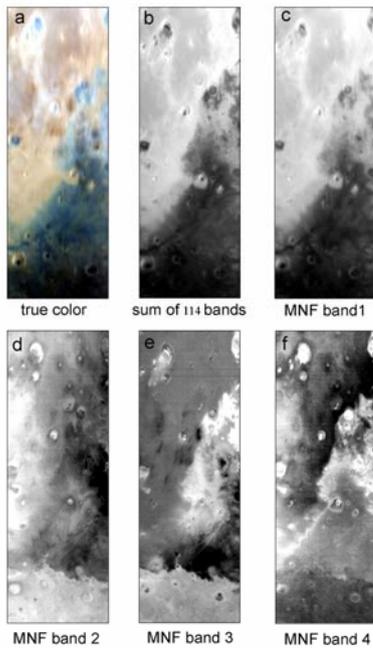


Figure 1. Atmospherically corrected I/F images (OMEGA image ID ORB0529\_3, Meridiani Planum region) and MNF resulting images: a: The true-color composition image (bands 0.66, 0.55, and 0.47 μm); b: Albedo (sum of reflectance of 114 bands from 0.969 to 2.553 μm); c, d, e, f are images of MNF bands 1, 2, 3, and 4, respectively.

The first six MNF bands of the ORB548\_3 at the Ophir-Candor Chasma area account for about 77 % of information from all 114 bands (0.926 to 2.55 μm) together. In particular, the MNF band 1 (Figure 3) accounts for ~47 % of total information and has an inverse relation with the albedo image ( $r = -0.91$ ), differing from Maridiani Planum image. Due to dramatically changing of the topography in this area, the MNF band 2, which accounts for 21% of total information, represents the terrain information. The bands 2, 3, 4 together account for ~27% of total information and contain most of geological unit

information. A false color image of MNF band 432 composite can be produced to delineate the lithologic units.

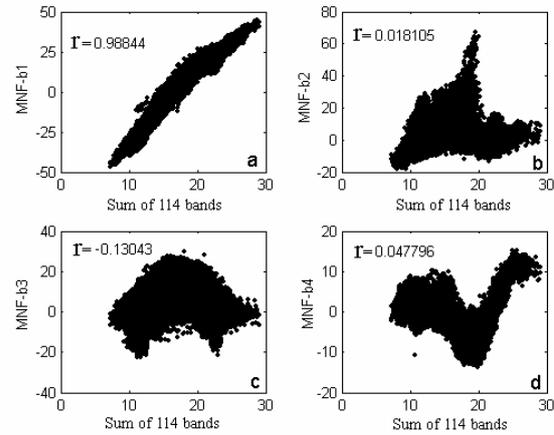


Figure 2. Scatter plots between albedo (sum of reflectance of 114 bands) and MNF bands 1, 2, 3, and 4, respectively (data from Figure 1), with  $r$  as the correlation coefficient of two variables.

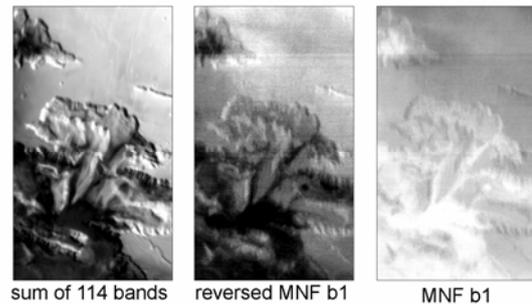


Figure 3. Atmospherically corrected I/F images (ORB548\_3, part of the Ophir-Candor Chasma) and MNF resulting images: left: Albedo image (sum of reflectance of 114 bands); middle: reversed MNF band 1; right: MNF band 1.

So the MNF band 1 is mostly correlated (positively or negatively) to the albedo ( $r$  up to 0.83 - 0.98) of the OMEGA imagery, while the MNF bands 2, 3, and 4 contained almost lithologies information for making an informative and useful geologic unit map. A false color image of MNF bands 2, 3, 4 could then be produced to represent major geological information for the delineation of lithologic units.

### 3.3 Lithologic unit delineation

Based on the false color image generated from above method, the lithologic units could be delineated by distinct tonal difference. These unit can also be reference to and compared with existing Martian “geologic units” based on geomorphology, crater features and density, albedo, multi-spectral properties, and thermal characteristics (USGS. 1986 and 1987, Arvidson, R. E., et al. 2003).

### 3.4 Spectral matching

Representative spectrum of these units was then processed to match with various mineral and rock standard spectral libraries

from USGS, John Hopkins University, and Brown University. Two spectral matching methods, spectral angle mapper (SAM) (Kruse et al. 1993) and spectral feature fitting (SFF) (Clark et al. 1990), were applied based on both spectra and/or continuum removed spectra for scoring each individual minerals and lithological classes from libraries with individual representative spectrum of each unit.

The highest scores of matched minerals and lithological units were then recorded for each unit. It should be realized that the representative spectrum, an average spectrum of an area, may well represent the lithologic information for the area but not the mineral information for the area due to extremely mixing feature. So matched minerals recorded here are only for reference purposes.

#### 4. EXPERIMENT RESULTS

##### 4.1 Maridiani Planum area

The Maridiani Planum area is the Opportunity Rover landing site and has been studied in a great detail (i.e., Arvidson et al, 2003; Christensen et al. 2001; Squyer, et al, 2004). Figure 4a is the RGB composition of MNF bands 4, 3, and 2, showing four major geologic units in the region. Figure 4b shows the representative spectra (atmospheric corrected I/F) for each unit (unit number and color corresponding to the number and color in Figure 4a). Figure 4c is the geologic unit map based on morphology, topography, and hematite index (Arvidson et al, 2003), with the red frame area representing the footprint of the ORB0529-3 image (Figure 4a). In comparison of the geologic units mapped by the OMEGA false-color image and those from Arvidson et al. (2003), it is clear that they matched very well. Unit-1 (in Figure 4a) corresponds to unit DCT (in Figure 4c) named Noachian dissected cratered terrain. Unit-2 corresponds to unit Ph named hematite-bearing plains deposit. Unit-3 corresponds to etched terrain unit E and unit P. Unit-4 corresponds to unit MCT named aeolian deposits mantled terrain.

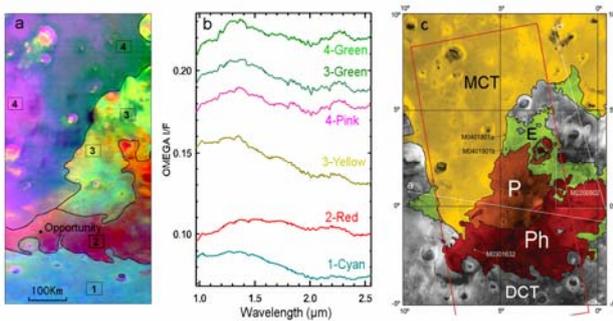


Figure 4. a: Geologic unit map (4 units) based on RGB image of MNF band 4, 3 and 2 of Figure 1. b: Representative unit spectrum corresponding to the units and colors in the left image, by averaging the spectra within the square area of each unit. c: "Geologic unit" map from Arvidson et al. (2003), with the red frame representing the footprint of ORB0529-3 [DCT: Noachian dissected cratered terrain; Ph: Hematite-bearing plain deposit that transitions to unit P; E: Etched terrain; MCT: Aeolian deposits mantled terrain].

Except for the unit Ph well-known as hematite-bearing plains (Christensen et al. 2001), there was no way to tell minerals and rock compositions for other units by using traditional topography, morphology, and albedo-based datasets. With spectral matching, it is possible to estimate the dominant minerals with hyperspectral data. Table 1 lists the spectral matching scores for each unit spectrum shown in Figure 4b as to the best possible lithologic (and mineral types as reference only), based on spectral feature fitting (SFF) and spectral angle mapper (SAM) methods.

unit	MNF b432	Lithologic matching			Minerals spectral matching		
		Lithologic	SFF	SAM	Minerals	SFF	SAM
Unit -1	1-Cyan	Diabase-h1	0.89	0.98	Pyroxene-cldd8	0.89	0.86
		Basalt-cdrs83	0.89	0.91	Pigeonite	0.88	0.86
Unit -2	2-Red	Basalt-h5	0.90	0.88	Goethite ws220	0.91	0.76
		Basalt-clrb34	0.91	0.82	Limonite hs41	0.91	0.63
Unit -3	3-yellow	Basaltic andesite	0.82	0.97	Hematite-cjb496	0.90	0.95
					Hematite-lahe03	0.90	0.94
Unit -4	4-pink	Basalt-cers83	0.85	0.98	Pyroxene-cldd6	0.92	0.75
					Monticellite	0.89	0.98
Unit -3	3-green	Basalt-cers83	0.90	0.96	Hematite-cjb496	0.91	0.95
					Monticellite	0.89	0.98
Unit -4	4-Green	Basalt-cers83	0.88	0.98	Hematite-cjb496	0.90	0.95
					Monticellite	0.89	0.96
Unit -4	4-pink	Basalt-cdrs83	0.85	0.98	Pyroxene-cers85	0.86	0.94
					Copiapite-gds21	0.93	0.29
Unit -4	4-pink	Basalt-cdrs83	0.85	0.98	Pyroxene-clsb58	0.91	0.76
					Hematite-cjb496	0.89	0.95

Table 1. The spectral matching score for each lithologic unit of OMEGA image (ORB0529\_3) at Meridiani Planum

The Unit-1 colored as cyan, located in the most-southern portion of the OMEGA image, is distinct from the Unit-2 colored as dark-red. Both units are dark in the true-color, albedo, and MNF band 1 images (Figure 1) due to the same low albedo characteristics. However, the Unit-1, named as Crater Unit and Dissected Unit of Plateau Sequence in the USGS "geologic" maps, best matches with mafic basalt, possible diabase and minerals of pyroxene and pigeonite as reference (Table 1). While the Unit-2, including the Opportunity landing site, best matches with basaltic rock and possible minerals of goethite, limonite and ferrihydrite, hydrated iron oxide minerals. These mineral types differ from the TES results (Christensen et al. 2001; Hynek, 2004) in which hematite, non-hydrated iron oxide mineral, was found rich in this unit. The major reason as mentioned earlier is that the representative spectrum got here is extremely mixed and barely tell individual minerals, but do give some hint about the compositions here. For example, all possible minerals seem to be iron-oxide minerals. In addition, the Opportunity's multispectral images show a stronger kink spectra near 530 nm and a shallow absorption near 900 - 950 nm, indicating the possible existence of ferrihydrite and goethite (Bell et al. 2004). The weak absorption near 900-950 nm is consistent with the presence of fine-grained, crystalline hematite alone (Bell et al. 2004). However, if the presence of goethite is true, it would support that the hematite formed in watery conditions, since the goethite only forms in the presence of water (liquid, ice or gaseous form), while hematite usually, but not always, forms in the presence of water. The Opportunity's other instruments suggested that the soil consists of fine-grained basaltic sand and hematite-rich spherules and that the finely laminated rocks, siliciclastic sediments, contain abundant sulfate salts with embedded hematite-rich spherules (Squyer, et al, 2004).

In Unit-3, two major representative spectra were identified: 3-yellow and 3-green. The best matched lithologies are basaltic andesite for 3-yellow and basalt for 3-green. The possible minerals matched are hematite for 3-yellow and pyroxene, hematite, and monticellite for 3-green. The Unit-3 consists of well developed basaltic sediments named as etched terrain and layered terrain (Hynek, et al, 2002) that, together with the Unit-2, overlies the oldest dissected crater terrain (DCT) unit and partly covered by hematite-bearing soil or dune (Arvidson, et al, 2003). They may originate from the erosion of the south highlands (Edgett, 2005). Although the unit-4 shows variable colors from pink to green, the two major representative spectra (4-green and 4-pink) best match with basalt. Possible minerals matched are copiapite, hematite and pyroxene. Copiapite is a poly-hydrated sulfate mineral and was also found in an area of the etched terrain (Unit-3), just east of this OMEGA image (Gendrin et al., 2005). The unit-4 corresponds to the mantled terrain that mantled by tens of meters of aeolian deposits (Arvidson et al., 2003).

**4.2. Ophir-Candor Chasma area**

Ophir-Candor Chasma area is the widest portion of the Valles Mariner and the biggest canyon on Mars. A false color image of MNF band 4, 3 and 2 composite can be produced to delineate the geologic units. As a result, Ophir-Candor Chasmas area can be divided into 3 geologic units (Figure 5a) and the representative spectrum of each unit is shown on the Figure 5b. Figure 5c is the USGS “geologic” unit map, in which 9 different units were mapped (relative or estimated ages also indicated in the map). The best matched lithologies for each unit are shown in Table 2, while best matched minerals are listed as reference only. More details described as follows.

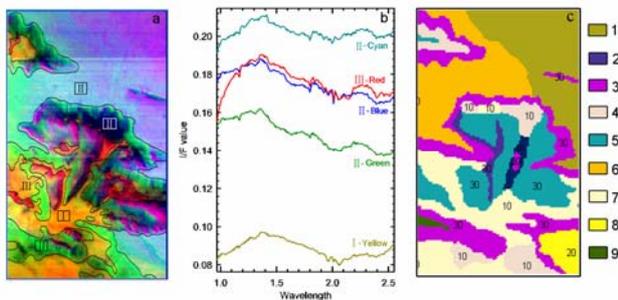


Figure 5. a. Geologic unit map (3 units) based on false-color image of MNF band 4, 3, and 2 of ORB548\_3 at the Ophir-Candor Chasma area; b. Representative unit spectrum corresponding to the units and colors in the left image, by averaging the spectra within the square area of each unit. c. USGS “geologic” map of the same area: colors and numbers on the legend are 1-Ridged Plains Material; 2-Older Channel Material; 3-Undivided Material of Highly Deformed Terrain; 4-Silde Material; 5-Layered Member; 6-Smooth Unit; 7-Floor Member; 8-Subdued Cratered Unit; 9-Yonger Fractured Material. Numbers in the “geologic” map are relative or estimated age (0.1 Ga) of the geologic units.

The Unit-I, at the chasmas floor with low albedo (Figure 3) and colored yellow in Figure 5a, best matches with mafic basalt. Possible minerals are pyroxene and hematite. Typical ferrous absorptions (such as 1.04 μm) and broad pyroxene absorption at 2.0 to 2.4 μm implicated that the low albedo areas in the

Chasma floor is mainly basaltic materials that possibly have large basaltic bedrock exposure (Bibring et al., 2001). Polyhydrated sulfate was also mapped in some small areas of the Chasmas floor (Gendrin, et al., 2005). Unit- I is well corresponding to Floor Member (7) and Older Channel Material (2) in the USGS geologic map (Figure 5c). Some parts of the Layered Member (5) in the USGS map are also part of the Unit-I.

Unit	MNF b432	Lithologic spectral matching			Minerals spectral matching		
		Lithologic	SFF	SAM	Minerals	SFF	SAM
Unit-1	1-yellow	Basalt-cdrs83	0.87	0.96	Pyroxene-cdrs85	0.85	0.96
					Hematite-cjb496	0.78	0.94
Unit-2	2-green (pink)	Basaltic andesite	0.80	0.97	Copiapite-gds21	0.93	0.34
					Hematite-lahe03	0.90	0.85
	3-blue	Basaltic andesite	0.83	0.95	Hematite-lahe03	0.88	0.95
					Hematite-cdrh07	0.84	0.95
	4-cyan	Basaltic andesite	0.81	0.97	Copiapite-gds21	0.93	0.29
					Hematite-c1cy11	0.92	0.84
Unit-3	5-red	Basalt-cars83	0.85	0.98	Kieserite	0.90	0.37
					Hematite-lahe03	0.87	0.97

Table 2. The spectral matching score of lithologic unit of ORB0548\_3 at Ophir-Candor Chasma area

The Unit-II includes three sub-units: green (and pink) areas (II-green) at the cliff edge (corresponding to Undivided Material of Highly Deformed Terrain (3) and Yonger Fractured Material (9) in the USGS map), blue or dark blue areas (II-blue) at the northern of Ophir Chasma (Slide Materials (4) of the USGS map), and cyan areas (II-cyan) at the top of planum (corresponding to Ridged Plains Material (1), Smooth Unit (6), and Subdued Cratered Unit (8) in the USGS map). All of them best match with the basaltic andesite. This means that they are actually the same geologic units: II-green is actually the cliff edge of the II-cyan, while II-blue is just the slide materials from the cliff edge of the planum (II-cyan). The color differences of this same unit are the combined effect of topography, terrain texture and solar illumination. The topographic difference is huge in this area, i.e. the elevation of the flat (planum) area (II-cyan) is about 3.5 - 4 km, while the elevation of slide materials (II-blue) changes from -3.8 - -4.5 km. Best matched possible minerals are hematite and copiapite, though the SAM scores for copiapite are very low (only 0.29-0.34 in Table 2).

The Unit-III colored red or dark red, corresponding to the Layered Member (5) in the USGS map, though the Unit- III consists of several isolated small areas compared with the large area of the unit 5 in the USGS map. Most part of the unit 5 actually belongs to the Unit-I in our delineation. The possible minerals are kieserite and hematite. But the kieserite does not get a high score (only 0.37) in the SAM method, though the best score from the SFF method. Gendrin et al. (2005) found wide distribution of kieserite and polyhydrated sulfate in the Unit area.

**5. CONCLUSION**

A four-step procedure are developed to delineate the geologic unit map using the ESA’s OMEGA/Mars Express data and proved the method to be efficient. Two areas (Meridiani Planum and Ophir-Candor Chasma) were chosen to test the methods, some good results have been achieved by compared with previously well-known rock and mineral compositions derived from TES, THEMIS, and Opportunity Rover as well as

the USGS “geologic” unit map. The minimum noise fraction (MNF) method is an efficient method to derive noise-free principle components that can be used to delineate the Martian geologic units. It is found that the MNF band 1 is mostly related (positively or negatively) to the albedo ( $r$  up to 0.83 - 0.98) of the hyperspectral imagery, while the MNF bands 2, 3, and 4 contained almost all lithologies information for making an informative and useful geologic unit map.

The two spectral matching methods (spectral feature fitting and spectral angle mapper) have different performances in matching lithologies and minerals. The SFF method especially emphasizes the overall similarity of positions and depths of absorption bands for two spectral curves, while the SAM method emphasizes the overall similarity of the two spectral curves and does not care much about the position and depth of absorption bands. Three good examples found in this study are seen in the Table 2, in which the copiapite and kieserite have the highest SFF scores (0.90 - 0.93), while the SAM matching scores for them are very low (0.29 - 0.37). This suggests that the existence of those two minerals are questionable, even kieserite was reported in the region by the Gendrin et al. (2005). But another explanation for the difference is that as mentioned in the method section, the unit spectrum used in the study is actually the spectral average of a small area. So the unit spectrum is extremely mixed spectral signature which might good for lithologic unit mapping but not for individual mineral identification. So the minerals matched using this method are only for reference only. This also explains that the Unit-2 of Meridiani Planum area, best matched mineral is not hematite, but hematite was found widely distributed in the area by the TES and Opportunity Rover. Overall, the two matching methods (SFF and SAM) complement each other and should be always used together. If both give a high score, the matching results should be much confident than only one high matching score.

## REFERENCES

- Arvidson, R. E., F. P. Seelos IV, S. Deal, et al., 2003. Mantled and exhumed terrains in Terra Meridiani, Mars, *J. Geophys. Res.*, Vol.108, No.E12, pp.14-1 to 14-20.
- Bibring, J.P., Combes, M., Langevin, Y., et al., 1989. Results from the ISM experiment. *Nature*, Vol.341, pp.591-593.
- Bibring, J. P., S. Erard, 2001. The Martian Surface Composition. *Space Science Reviews*. Vol.96, pp.197-230
- Bibring, J.P., Langevin, Y., et al. 2005. Mars Surface Diversity as Revealed by the OMEGA/Mars Express Observations, *Science*, Vol.307, pp.1576-1630.
- Bell, J.F., Squyres, S., Arvidson, R.E, et al. 2004. Pancam Multispectral Imaging Results from the Opportunity Rover at Meridiani Planum. *Science*, Vol.306, pp.1703-1709
- Christensen, P.R., Morris, R.V., Lane, M.D., and Bandfield, J.L., and Malin, M.C.. 2001. Global mapping of Martian hematite mineral deposits: remnants of water-driven processes on early Mars. *Journal of Geophysical Research*, Vol.106, pp. 23, 873-23, 885.
- Clark, R. N., A. J. Gallagher, G. A. Swayze, 1990. Material absorption band depth mapping of imaging spectrometer data using the complete band shape least-squares algorithm simultaneously fit to multiple spectral features from multiple materials. *Proceedings of the Third Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Workshop*. JPL Publication, Vol. 90-54, pp. 176-186.
- Edgett, K.S.. 2005. The sedimentary rocks of Sinus Meridiani: Five key observations from data acquired by the Mars Global Surveyor and Mars Odyssey orbiters, *Mars*, No.1, pp.5-58
- Gendrin, A., Mangold, N., et al. 2005. Sulfates in Martian Layered Terrains: The OMEGA/Mars Express View. *Science*, Vol. 307, pp.1587-1591.
- Kruse, F. A., Lefkoff, A. B., Boardman, J. B., Heidebrecht, K. B., Shapiro, A. T., Barloon, P. J., et al. (1993). The spectral image processing system (SIPS) -- Interactive visualization and analysis of imaging spectrometer data. *Remote Sensing of Environment*, Vol.44, pp.145-163.
- Hynek, B.M., Arvidson, R.E., et al. 2002. Geologic setting and origin of Terra Meridiani hematite deposit on Mars. *Journal of Geophysical Research*, Vol.107, No.E10, pp.18-1 to 18-14.
- Hynek, B.M.. 2004. Implications for hydrologic processes on Mars from extensive bedrock outcrops throughout Terra Meridiani. *Nature*, Vol.431, pp.156-159
- Maustard, J.F., Poulet, F. et al. 2005. Olivine and Pyroxene Diversity in the Crust of Mars. *Science*, Vol.307, pp.1594-1597.
- Squyres, S., Arvidson, R.E et al. 2004. The Opportunity rover's Athena Science Investigation at Meridiani Planum, Mars. *Science* Vol.306, pp.1698-1703.
- USGS. 1986 and 1987. Geologic map of the eastern, western, and polar regions of Mars. Available at: <http://astrogeology.usgs.gov/Projects/webgis/>.

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