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Article

Meridiani Planum Mineralogy Along Part of the Opportunity Rover Track Based on the Mini-TES Spectrum

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Abstract: The research uses data from the Mini-TES infrared spectrometer of the Opportunity rover taken at selected locations along its route on Meridiani Planum on Mars. Using emissivity data, the corresponding mineralogical compositions were calculated. Generally, the results are consistent with previous works, in particular they indicate the widespread occurrence of clay minerals and minerals from basaltic rocks. However, several interesting facts were also noted. Among other things, clear changes in the hematite content were found, suggesting that on certain area spherical concretions (known as blueberries) may be devoid of hematite. A similar phenomenon is known from studies of terrestrial concretions. Moreover the possibility of pyrite existence was found on a certain section of the route. On Earth, pyrite often occurs with economically valuable minerals.

Keywords: Meridiani Planum; opportunity rover; Mini-TES; mineralogy; hematite; pyrite; spherule

1. Introduction

1.1. Opportunity Rover Mission

The Opportunity rover landed in Meridiani Planum on January 25, 2004, three weeks after its twin, Spirit. Due to the landing time, Opportunity is designated Mars Exploration Rover – B (MER-B). However, Opportunity was produced before Spirit, so the designation MER-1 is also used. The Spirit rover is designated MER-A or MER-2, respectively. Opportunity was active on Mars from 2004 until 2018 for 5111 sols (14 years, 138 days on Earth). During this time the rover had traveled a distance of 45.16 km [1].

Mission included finding meteorites (e.g., Heat Shield Rock [2]) and exploration of Victoria crater [3]. In 2011 it reached Endeavour crater [4]. Eventually the mission is considered one of the NASA's great success.

Three instruments on the Opportunity rover are the most important for our analysis. They are: Miniature Thermal Emission Spectrometer (Mini-TES, e.g., [5], [6]), the Alpha Particle X-Ray Spectrometer (APXS), and the Mossbauer spectrometer (MB) - Figure 1.

The Mini-TES provides the mineralogy and thermophysical properties of the regolith. It is a Fourier transform spectrometer. It covers the wavelength range of 5-29 μm (corresponding to the wave number range from 339.50 to 1997.06 cm^{-1}). The Mini-TES telescope is a 6.35 cm diameter Cassegrain telescope that provides a resolution of 20 mrad (it could be reduced to 8 mrad). The Mini-TES and 2 cameras (pancamera and navigation camera) are mounted on the Pancam Mast Assembly (PMA) and are located ~1.5 m above the ground. The PMA provides possibility 360° of azimuthal rotation and view from 30° upwards to -50° downwards.

APXS determines the elemental composition of the regolith. Alpha particles and X-rays (generated by radioactive sources) excite X-rays in the sample. The X-ray spectrum shows elements from sodium to yttrium. In addition, back-scattered alpha particles provide data on oxygen and carbon. Finally, the concentrations of the elements are obtained [7].

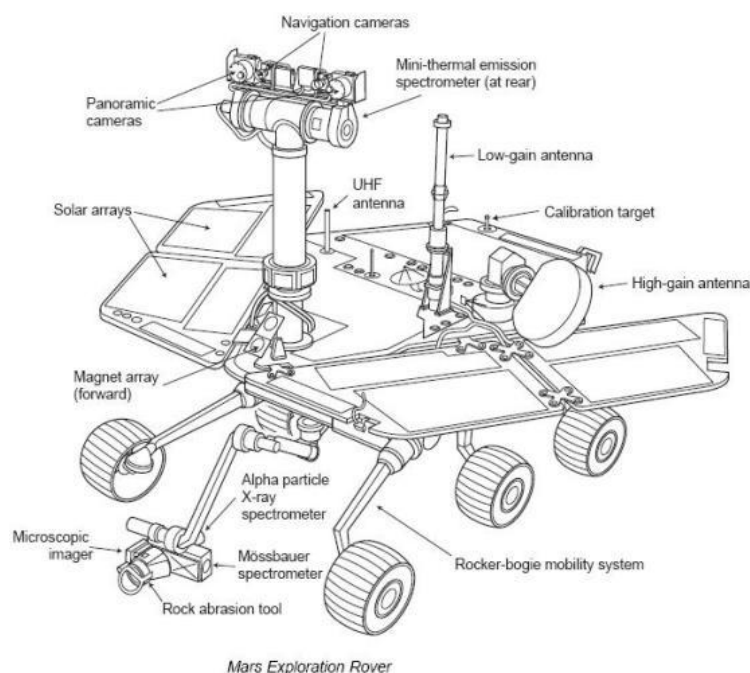


Figure 1. Schematic drawing of Mars Exploration Rover. Image by NASA. Source: <http://marsrovers.jpl.nasa.gov/newsroom/merlandings.pdf>. Note positions of Mini-TES mounted on the Pancam Mast Assembly (PMA, on the upper part of the rover). The microscopic camera, rock abrasion tool, MB, and APXS are mounted on a moving arm known as the Instrument Deployment Device (IDD, just above the ground).

Mossbauer spectroscopy (MB) is a method for quantitative analysis of iron-bearing minerals. In the Opportunity mission, the goal was to identify minerals containing iron (e.g. silicates, oxides, sulfates, carbonates, and sulfides). It can also determine the distribution of iron in different oxidation states (e.g. Fe^{3+} , Fe^{2+}) and measure the proportion of iron in some basaltic minerals (e.g. pyroxene, magnetite, olivine, ilmenite) [8].

The microscopic camera, rock abrasion tool, MB, and APXS are mounted on a moving arm known as the Instrument Deployment Device (IDD). To measure, MB and APXS sensors must be placed close to the surface of the selected sample (by the IDD).

1.2. Meridiani Planum

Meridiani Planum is a plain lying within the boundaries of: Arabia Terra to the north, Noachis Terra to the south, Terra Sabaea to the east, and Ares Vallis to the west. The plain is covering an area of almost 175 000 km². On the surface of Meridiani Planum there are extensive sandy areas of various fractions. There are also spherical concretions with a diameter of several mm to 1 cm, known as blueberries (Figure 2A).



Figure 2. Examples of spherules: A. Martian spherules. Microscopic camera. Visible spherules on the surface sol 319. Image size 3x3 cm. B. Utah spherules from the Dakota Formation (Lower Cretaceous), with leached iron oxides. Visible spherules fused due to mineralization and single ones. Spherule diameter about 1 cm. C. Moqui marbles spherules from the Navajo Formation (Upper Jurassic) covered with iron oxides. Spherule diameter about 4-5 cm. Photos B, C - Natalia Zalewska.

On Mars, there are 3 basic geological eras of the formation of the surface of Mars: Noachian, Hesperian, and Amazonian. On Meridiani Planum, the geological history was shaped in the following way [9] [10]:

Noachian - rivers bring large amounts of basaltic mud,

Hesperian - volcanism on Tharsis delivers large amounts of volcanic ash and sulfur acidifying the Meridiani reservoir,

Amazonian - water gradually began to dry out, leaving sedimentary minerals on the surface, wind erosion began to dominate. It was during this period that concretions called blueberries were formed.

Meridiani Planum is a plateau covered with a variety of sediments - Figures 3 and 4. The area is characterized by the presence of rock layers that are formed by long-term sedimentary processes. Analysis of orbital images and data from the Opportunity rover reveal the presence of sedimentary rocks, e.g. sandstones and mudstones. The region may have been subject to hydrothermal processes and of extensive volcanism during the Hesperian. Some structures and minerals, such as jarosite, may have been formed by the circulation of hot water beneath the surface, which could have influenced the deposition of sulfate minerals and the formation of sedimentary layers.

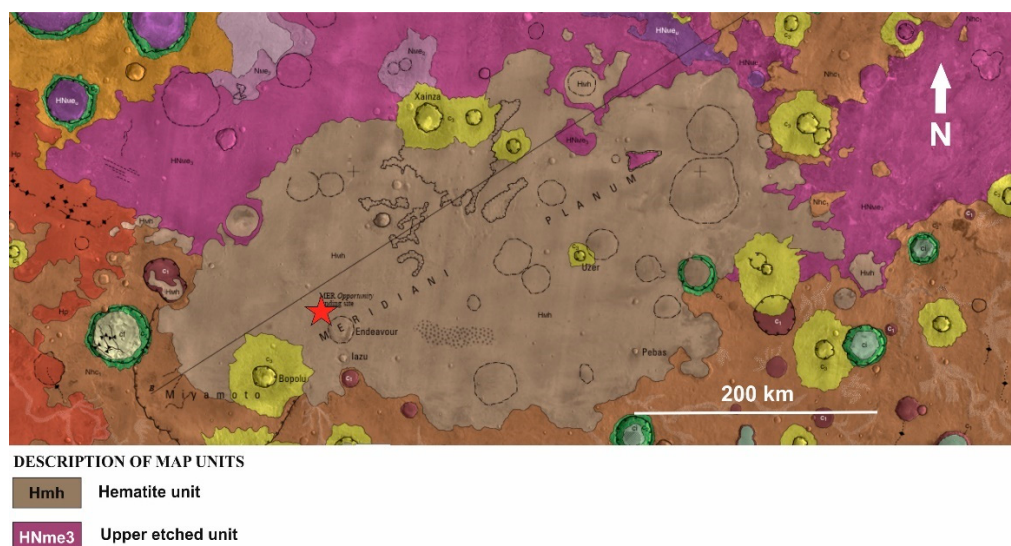


Figure 3. Geologic Map of Meridiani Planum, Mars by Brian Hynek and Gaetano Di Achille (2017) - [11]. The red star marks the landing site of the Opportunity rover. Credit USGS.

Today, dunes and aeolian ripples are common on Meridiani. The surface is covered with partially buried or filled impact craters (up to 50 km in diameter). The Hmh- Hematite unit (early Hesperian) unconformably overlies the heavily eroded HNMe3- Upper etched unit (Middle to late Noachian), characterized by local knobs, mesas, and outliers. The spherules most likely formed by chemical precipitation from iron-bearing groundwater or by volcanic processes. This suggest that the spherules formed in the upper etched (leached) unit (HNMe3), forming extensive surface deposits. Isolated, smaller exposures around the central, larger exposures suggest that the unit had a larger former extent [11].

Many scientists believe that there were thermal springs or water reservoirs in the Meridiani Planum region. This is indicated by data from the Mars Global Surveyor (MGS) probe's Thermal Emission Spectrometer (TES), which identified elevated amounts of hematite on Meridiani.

Based on data from the Gamma Ray Spectrometer (GRS), a high hydrogen content was discovered. The GRS, installed on board NASA's Mars Odyssey, allowed mapping the chemical composition of Mars at a depth of 10 cm to 1 m below the surface by measuring gamma rays from space and their interactions with various surface materials. The GRS consists of the Gamma Sensor (GS), the Neutron Spectrometer (NS), and the High-Energy Neutron Detector (HEND). Neutron

detection equipment, such as NS and HEND, measures neutrons of different energies released from the near surface of Mars by cosmic rays.

According to the interpretation of scientists [12] (Mars Advanced Radar for Subsurface and Ionosphere Sounding) MARSIS radar (Mars Express probe) data indicates that the relatively low derived dielectric constant of Meridiani Planum sediments ($\sim 3.6 \pm 0.6$) is consistent with a sequence of thick, low-density porous basaltic sand. As can be seen, pore-filling water ice is therefore not necessary to explain the low dielectric constant of Meridiani Planum sediments [12].

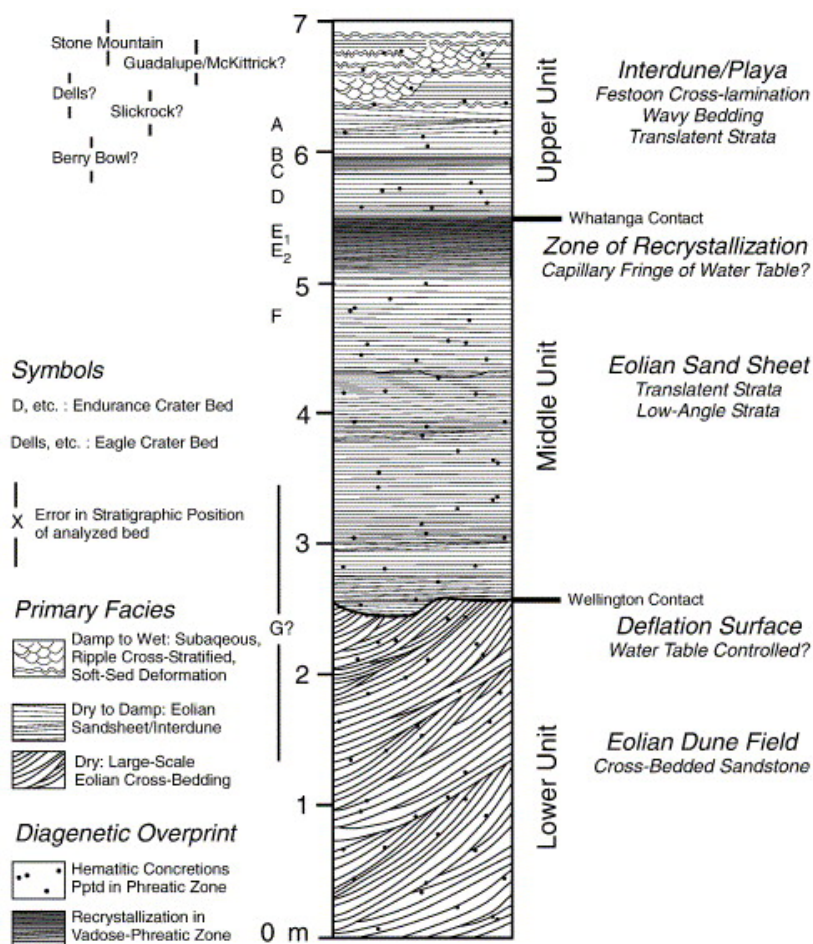


Figure 4. Geologic cross-section of the Endurance Crater cliff, Burns Formation by [13].

2. Methods

The Mini-TES is designed for remote determination of the mineral composition of the regolith of planetary bodies. In addition, it can be used to determine the surface temperature and/or properties of the atmosphere -Figure 1. The Mini-TES is a miniaturized version of TES, installed on the orbiter Mars Global Surveyor (MGS). Mini-TES is placed on 2 rovers exploring Mars (Spirit and Opportunity).

Mini-TES provides high resolution infrared spectra over some range of wavelengths. By making measurements in the thermal infrared part of the electromagnetic spectrum, it has some ability to penetrate layers of dust. Such layers are common on the surface of Mars and pose a problem for remote observations. The range of Mini-TES spectrum corresponds to some characteristic bands of vibration spectra. They allow us to identify certain crystal structures of minerals. This makes it often possible to determine the mineralogy and various properties. In particular, detection of the following groups of minerals is possible: hydroxides, sulfates, phosphates, silicates, carbonates, and oxides [5].

Mini-TES covers the spectral range from 1997.06 cm^{-1} to 339.50 cm^{-1} with a spectral sampling of 9.99 cm^{-1} (at 167 points). The extreme ends of each spectrum were excluded from deconvolution due to the lower signal to noise ratio (SNR) in these spectral regions.

The mission of the Opportunity rover lasted 5111 sols. However, the number and quality of late measurements were lower. We focus on data from the Mini-TES spectrometer taken from sol 313 to sol 395. We chose less discussed parts of the route of the rover. In these parts there are less other data (e.g. from APXS and MB). We do not average the results over a larger area. Our results concern the local differences that occur in a selected sectors of the rover's route Opportunity.

The position of the object being measured by Mini-TES is determined by the direction in which the instrument is facing. This direction is given by elevation and azimuth. Elevation is an angle counted from the horizontal level (downwards it has negative values). Since we are interested in the spectrum of the planet's surface, we use data with negative elevation (Figure 5). In general, the elevation values ranged from approx. -50° to approx. $+30^\circ$. For the height of PMA $\sim 1.5 \text{ m}$ the distance to the measured object is $\sim 86 \text{ m}$ for an elevation angle -1° and $\sim 1.25 \text{ m}$ for an elevation angle -50° . Of course, the exact distance depends on the inclination of the rover itself and the topography of the terrain.

We often also have photos from some cameras taken in the same direction (Figure 6), which allows us to determine the general characteristics of the terrain. In some places along the rover's route, tests were also carried out with other instruments (such as APXS and the Mossbauer spectrometer). Moreover there are also results from the Mars orbiter available (TES). Orbital TES data have much lower resolution, but allow the determination of large-scale changes (e.g., gradients).

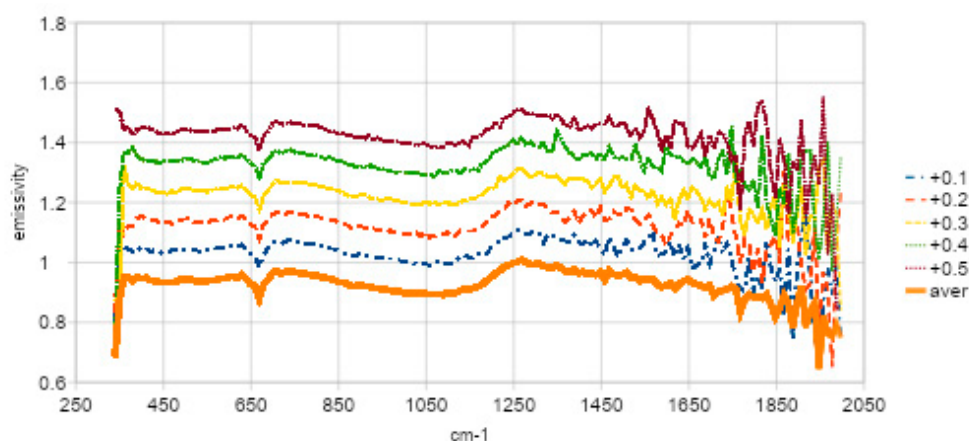


Figure 5. Five emissivity profiles for the measurement series 1t163157489emr4705p3575n0a1 made during sol 394. Elevation $-0.349100 \text{ rad} = -20^\circ$, azimuth $= 3.136937 \text{ rad} = 179.7^\circ$. For readability of the graphs, individual profiles are shifted vertically relative to each other by 0.1 (see legend). The lowest profile (thick line) is the average of the others and is not vertically shifted. Note the large fluctuations at the ends of the profiles, which make interpretation of these parts virtually impossible. Averaging reduces some of these fluctuations - see the lowest profile. The peak around 660 cm^{-1} is associated with atmospheric carbon dioxide and this part of the spectrum is removed before interpreting the spectrum of the planet's surface (see Figure 7).

In our work we use methods similar to those in [14]. However, unlike there, we focus on typical areas of Meridiani Planum, not the rather untypical areas of outcrops within Eagle crater. Note that the mineralogy of the outcrops may be significantly different from that of the loose regolith.

The measurements were performed in series (packages) containing from several to several hundred measurements - Table 1. Usually measurements in a given series were made for the same values of elevation and azimuth. In a few cases only, elevation and/or azimuth were changed systematically.

Table 1. Data from Mini-TES used in our research.

Our notation	Notation in PDS <u>Planetary Data System</u>	Our notation	Notation in PDS <u>Planetary Data System</u>
		(cont.)	
	https://pds-geosciences.wustl.edu/missions/mer/geo_mer_datasets.htm		https://pds-geosciences.wustl.edu/missions/mer/geo_mer_datasets.htm
	https://pds-geosciences.wustl.edu/mer/mer1-m-mtes-4-emr-v1/mer1mt_3xxx/data/		https://pds-geosciences.wustl.edu/mer/mer1-m-mtes-4-emr-v1/mer1mt_3xxx/data/
0313a	1t155968073emr38h7p3575n0a1	0384	1t162271126emr4403p3575n0a1
0313b	1t155970233emr38h7p3290n0a1	0385	1t162359900emr4503p3575n0a1
0313c	1t155971234emr38h7p3575n0a1.	0386	1t162448685emr4603p3575n0a1
0313d	1t155971951emr38h7p3575n0a1	0387a	1t162535829emr4603p3575n0a1
0314a	1t156055646emr38h7p3575n0a1	0387b	1t162537464emr4603p3575n0a1
0314b	1t156056856emr38h7p3575n0a1	0388a	1t162624808emr4700p3575n0a1
0315	1t156144440emr38h7p3575n0a1	0388b	1t162626234emr4700p3575n0a1
0319a	1t156500733emr3940p3575n0a1	0389a	1t162713380emr4700p3575n0a1
0319b	1t156499520emr3940p3575n0a1	0389b	1t162715024emr4700p3575n0a1
0321a	1t156677094emr3981p3575n0a1	0389c	1t162716469emr4700p3972n0a1
0321b	1t156678275emr3981p3575n0a1	0389d	1t162716917emr4700p3973n0a1
0322a	1t156765845emr4000p3575n0a1	0390a	1t162802322emr4700p3575n0a1
0322b	1t156767047emr4000p3575n0a1	0390b	1t162803779emr4700p3575n0a1
0323a	1t156859422emr4000p3575n0a1	0390c	1t162808419emr4700p3976n0a1
0323b	1t156860754emr4000p3575n0a1	0391a	1t162891150emr4705p3575n0a1
0323c	1t156862377emr4000p3575n0a1	0391b	1t162892555emr4705p3575n0a1
0324a	1t156943733emr4000p3575n0a1	0391c	1t162893249emr4705p3290n0a1
0324b	1t156944602emr4000p3575n0a1	0392a	1t162979928emr4705p3575n0a1
0324c	1t156950645emr4075p3715n0a1	0392b	1t162984295emr4705p3977n0a1
0325a	1t157032170emr4075p3575n0a1	0393a	1t163068603emr4705p3575n0a1
0325b	1t157033393emr4075p3575n0a1	0393b	1t163070132emr4705p3575n0a1
0329	1t157388477emr40a3p3575n0a1	0394a	1t163157489emr4705p3575n0a1
0331a	1t157570782emr40ajp3575n0a1	0394b	1t163158927emr4705p3575n0a1
0331b	1t157565012emr40ajp3575n0a1	0395a	1t163245881emr4786p3575n0a1
0331c	1t157566061emr40ajp3575n0a1	0395b	1t163246388emr4786p3575n0a1
0382a	1t162093577emr4336p3575n0a1	0395c	1t163247648emr4786p3575n0a1
0382b	1t162094557emr4336p3575n0a1	0395d	1t163252492emr4786p3575n0a1
0382c	1t162095419emr4336p3715n0a1	0395e	1t163254368emr4786p3575n0a1
0382d	1t162098649emr4336p3575n0a1	0395f	1t163255320emr4786p3575n0a1

0383a	1t162181197emr4336p3575n0a1	0395g	1t163256838emr4786p3575n0a1
0383b	1t162182367emr4336p3575n0a1		

Figures 5 and 7 show examples of some of the problems when selecting data for interpretation. In Figure 5 there are 5 profiles of emissivity taken during sol 394. As one can see, for the extreme values of wavelength the measurements show large fluctuations in values. Therefore, these profiles are averaged. Averaging reduces these fluctuations. Moreover we consider only spectra in the range 370-1500 cm⁻¹ excluding regions of largest fluctuations.

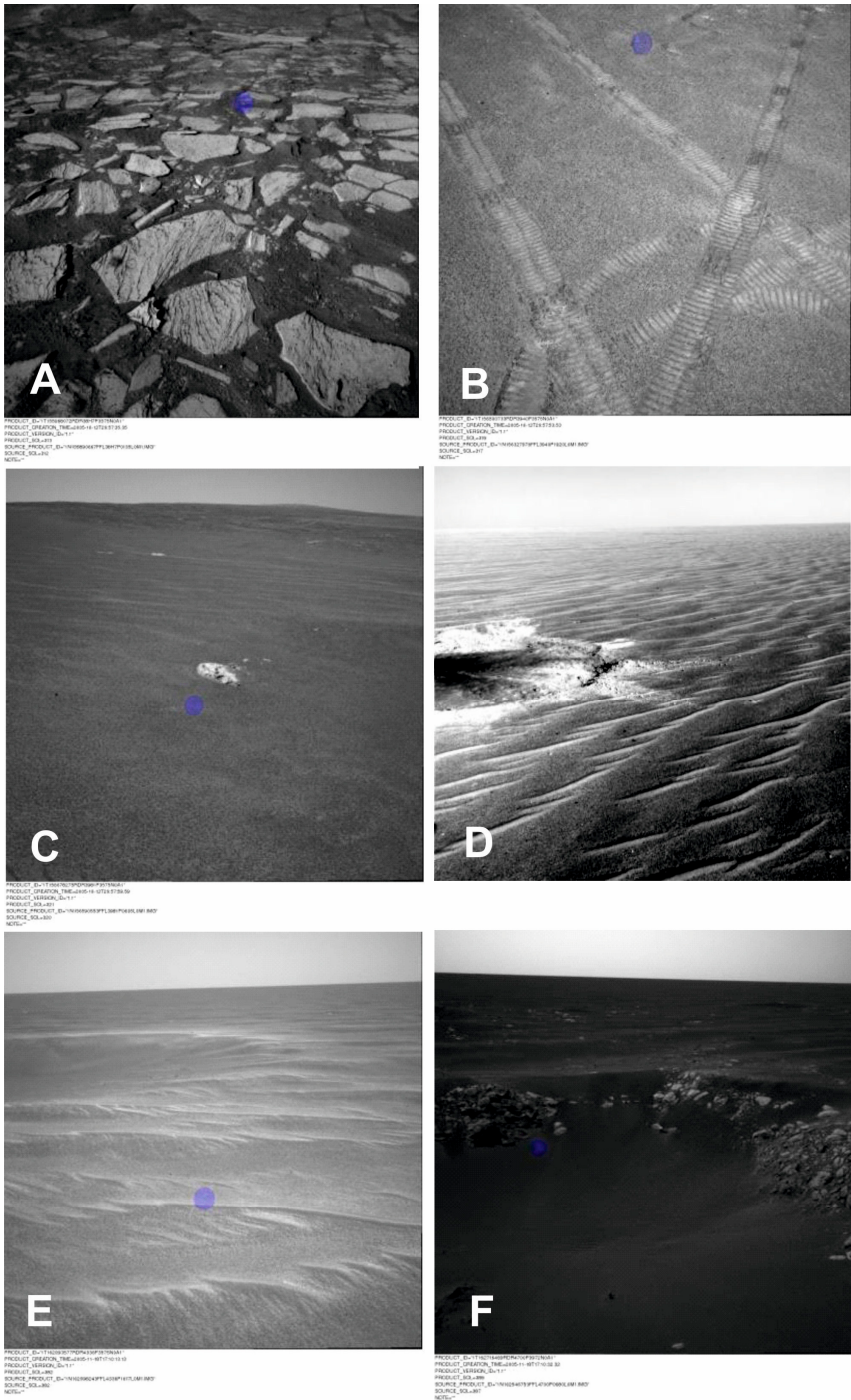


Figure 6. Sample images from the Opportunity rover's cameras. They show several types of geomorphologic context of sites where Mini-TES measurements were made. The purple spot (later added to the camera image) indicates very approximate locations of Mini-TES measurements. Sectors and measurements numbers: A- is

from sector 1, 1T156144440EMR38H7P3575N0A1. B, C, D from sector 2, 1T156500733EMR3940P3575N0A1, 1T156677094EMR3981P3575N0A1, 1N157047868RAD40A3P0685L0C1. E sector 3, 1t162093577EMR4336P3575N0A1. F sector 4, 1T162716469EMR4700P3972N0A.

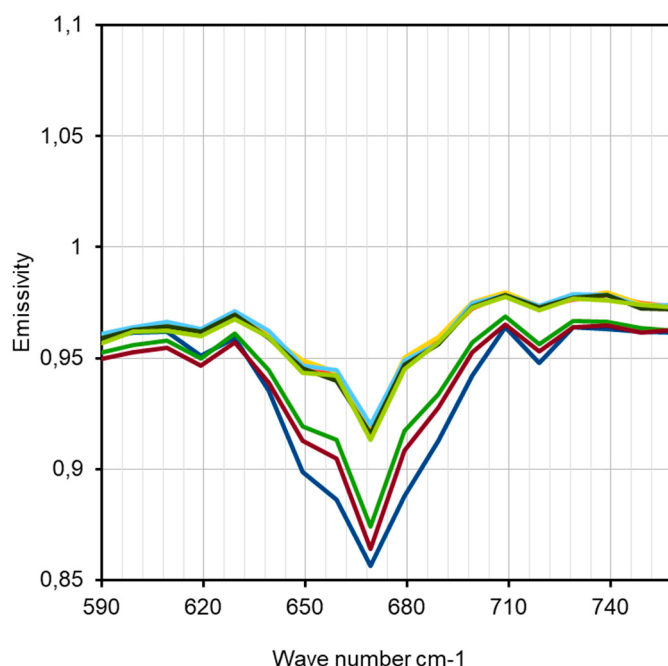


Figure 7. Range of emissivity obtained from Mini-TES around the CO₂ peak. In practice, we eliminate the range between 600 and 740 cm⁻¹ from the interpretation. We also considered other methods of treating this peak (see text). Horizontal scale (wave number) in cm⁻¹, vertical scale (emissivity) is dimensionless.

To remove the effect of the CO₂ peak a method of cutting out part of the spectrum is generally used, e.g. [14]. This is also the main method used in our work. We used a notch from 600 to 740 cm⁻¹. We determined the mineralogical composition using the least squares method, using a linear spectral approximation from a selected library of mineral spectra. All software, data import and calculations in the research was made by L. Czechowski.

Another possible method of treating the CO₂ peak is to approximate the spectrum in this range by an appropriate function. Of course, it would be best to use a function similar to the emissivity of the same minerals (without CO₂ in the atmosphere). Using the least squares method, one could come closer to reproducing the mineralogy. Unfortunately, until we have relatively accurate information about the surface composition, it is difficult to choose such an interpolation. In practice, we only examined the linear or second degree interpolations and compared them with the results of the excision method.

2.1. Solution Stability

One of the properties for a reliable solution is stability towards small disturbances of data and/or methods. In order to determine the stability of our solutions, we examined the stability in respect to:

- (i) relative to the initial solution approximation,
- (ii) in terms of the required accuracy of the solution approximation,
- (iii) relative to methods of data averaging (number or selection of averaged data),
- (iv) stability against excluded regions of largest fluctuations (see above),
- (v) stability towards different spectral libraries,
- (vi) controls for removing unrealistic minerals from the solution.

The result of solution instability may be artifacts, i.e., the appearance of minerals (in the numerical solution) that were not present in the studied location. Therefore, to obtain an acceptable solution we use more minerals than necessary, including some whose probability of occurrence is low. The percentage value of the artifact may reach a few percent. A single occurrence of such minerals should be treated with caution as an artifact. However, if it appears systematically, then there is a high probability that this mineral was indeed present in the studied location, i.e., we are not dealing with an artifact. See also problems of pyrite and quartz discussed below.

3. Results

3.1. Data Emissivity

Data from the Opportunity rover's Mini-TES (Mini-TES Science Emissivity Records (EMRs)) are available in the Planetary Data System at <https://pds-geosciences.wustl.edu>. We finally selected 61 series of measurements made between sol 313 and sol 395. We chose good quality data from typical sectors of the route. Therefore, we did not deal with unusual objects such as meteorites lying on the surface or interior of craters. Example photos of the studied sites are shown in Figure 6. A short description of the surface of the subsequent sectors of the route is included in the section Discussion. Note that practically along the entire selected route (Figures 8–11) there is a large number of spherical concretions on the surface – (Figures 2 A, 6 B, C). The measurement series that we selected in our work are marked with a sol number (and additionally with a letter (a, b, c, d, e, f, g), if several measurement series were made on the same Martian day. Table 1 shows our measurement notations and the corresponding notations used in the Planetary Data System database.

We have focused on the area from sols 313 to 325, 329–331 and 382–395 due to the small number of studies of this sectors of the rover's route in the literature. There is quite a rich interpretation of data from craters explored by the rover, but some typical parts of the route are not investigated using Mini-TES. The break between sols 331–382 results from the route of the rover, which examined the Heat Shield meteorite then. Since we are focusing on the properties of Mars itself, we omit data concerning the meteorite. We have also given up on some parts of the route. From sol 382, however, the terrain begins with a more morphologically diverse topography. For sols 392 and 393, we have used APXS and Mossbauer measurements, which provide additional information on the mineralogy.

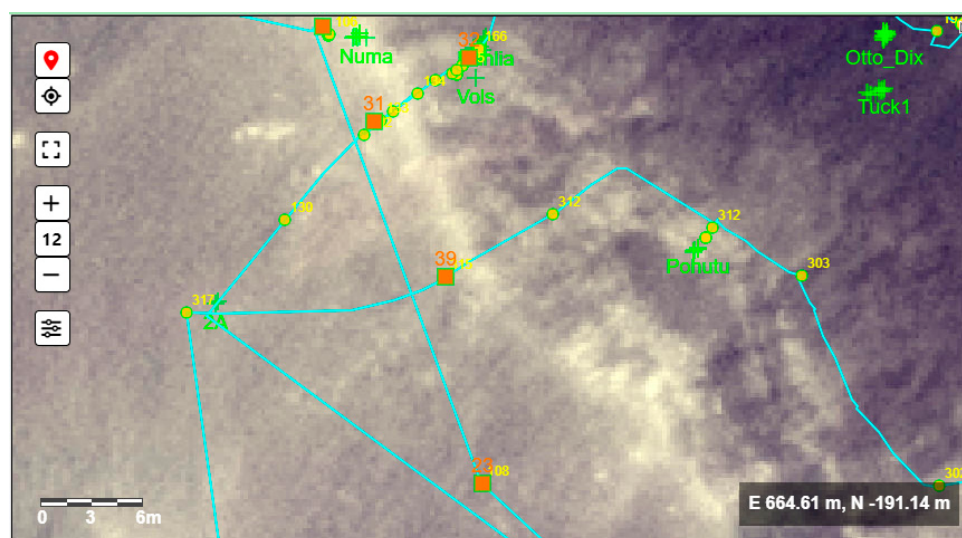


Figure 8. Part of the route Opportunity rover. We consider measurements performed from sol 313, when the rover had been approximately in the center of the above map (orange square indicating site 39). There is a substantial difference in mineralogy between sol 314 and sol 315. This is the boundary of the 130-meter Endurance crater. On the outer slope of the crater there is a lot of dust consisting fe-smectite and montmorillonite, with small amounts of jarosite and plagioclase, sector 1 of the route - see Table 3. Out of the

crater slope the amount of hematite starts to increase. Gypsum and carbonates appear, as well as hornblende and forsterite. The amounts of pyrite oscillate around a few percent. See chapter Results for more descriptions of mineralogy. Traverse map from: <https://an.rsl.wustl.edu/merb/AN/an3.aspx>.

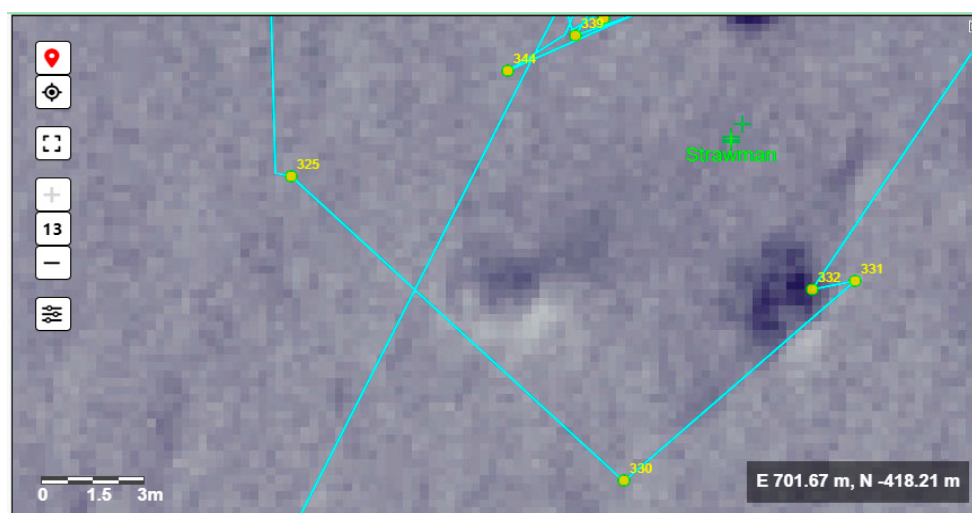


Figure 9. Fragment of sector 2 of the rover route – Table 3. From sol 323 mineralogy is similar to the previous one. From sol 329 the hematite and gypsum contents increase. The rover is located on the ejecta cover of the Endurance crater. We do not take into account sols 332-381 (see text). More descriptions of the mineralogy are in the Results section. Traverse map from: <https://an.rsl.wustl.edu/merb/AN/an3.aspx>.

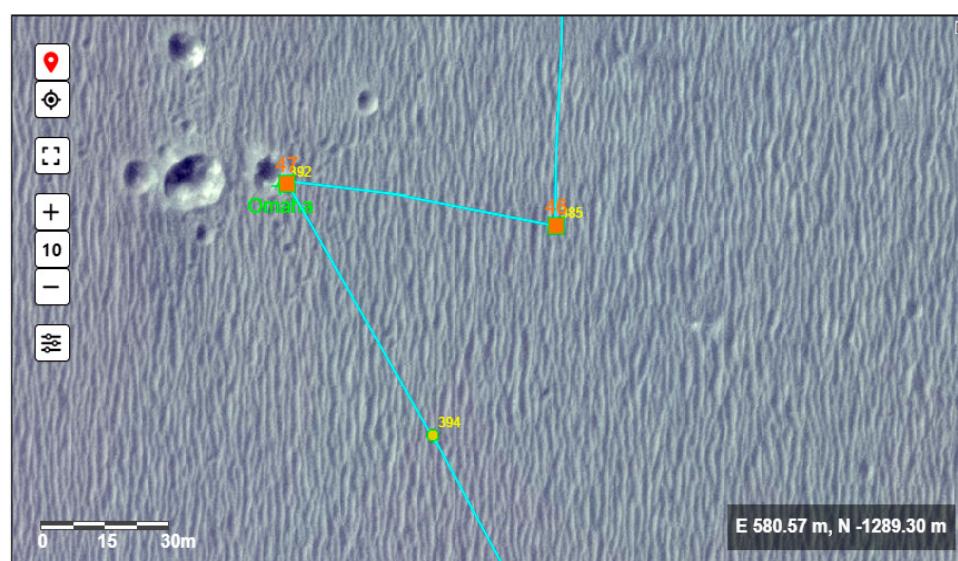


Figure 10. Parts of sectors 2 and 4 of the rover's route – Table 3. From sol 382 there is a large proportion of fe-smectite, gypsum and plagioclase. Some biotite and apatite also are found. From sol 388 the hematite virtually disappears, while fe-smectite increases. Biotite and apatite and gypsum disappears. The rover is located outside the area of the ejecta cover of the Endurance crater. More description of the mineralogy is in the Results section. Traverse map from: <https://an.rsl.wustl.edu/merb/AN/an3.aspx>.

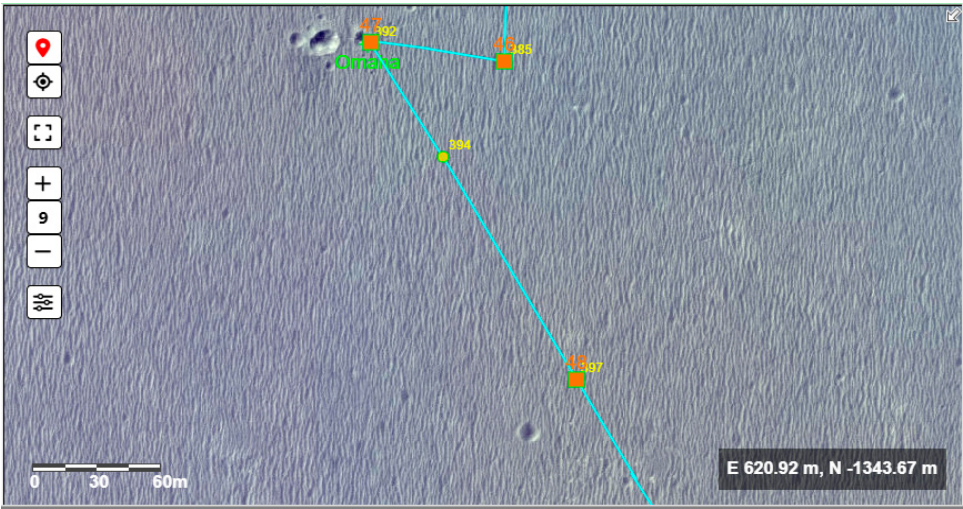


Figure 11. Fragments of sectors 4, 5, 6 of the rover route - Table 3. Note Omaha region, where APXS and MB measurements are made - see text. From 395a the hematite reappeared but it disappearing from 395e. Some ilmenite appears and the amount of fe-smectite increases. More description of mineralogy can be found in the Results section. Traverse map from: <https://an.rsl.wustl.edu/merb/AN/an3.aspx>.

3.2. Library Spectra

For the interpretation of the Mini-TES spectra we used 23 spectra of selected minerals - Table 2. Most of these spectra come from the ASU Spectral Library (<https://speclib.asu.edu/>). They are located in files with names given in Table 2. The latest spectrum of pyrite was taken from [15]. In selecting the spectra, we tried to use existing interpretations of spectra from Meridaini Planum. At the same time, we extended the study to spectra that were often not considered (to our knowledge) in some previous studies. Some spectra were introduced to check the stability of the method (see discussion in Section 2). The same library spectra and the same calculation process were used for all measurements in Table 1. The calculations were repeated under several random initial conditions. The stability of the solution can be used as an indication of the reliability of the results. The results indicate several confidence thresholds: ~2%, ~6%, and ~19%. If the results show a content below 2%, it is very possible that we are dealing with an artifact. For values above 19%, it is difficult to find reasons for the artifact and it should be assumed that the given mineral occurs in significant amounts.

Table 2. Names of mineral components in our paper and names of corresponding files in the library. Spectrum of pyrite was measured in laboratory of Institut für Planetenforschung, Deutsches Zentrum für Luft- und Raumfahrt (DLR). The rest are from ASU Spectral Library.

Name of file in librabry	
ASU Spectral Library	
https://speclib.asu.edu/ .	
Name in our paper and remarks	
Andesine BUR-240 1	andesine
Apatite ML-P1 86	apatite
Biotite BUR-840 25	biotite
Bronzite BUR-1920 6	bronzite
Calcite ML-C9 98	calcite
Chlorite WAR-1924 40	chlorite
Enstatite HS-9.4B 30	enstatite

Fe-smectite SWa-1 powder 205	fe-smectite
Gypsum (Selenite) ML-S8 83	gypsum
Hematite BUR-2600 50	hematite
Hornblende NMNH-R7208 173	hornblende
Ilmenite WAR-4119 35	ilmenite
Jarosite S51	jarosite
Labradorite WAR-4524 63	labradorite
Magnesite C55 132	magnesite
Magnetite WAR-0384 64	magnetite
Montmorillonite SCa-3 powder 198	montmorillonite
Quartz BUR-4120 55	quartz
Serpentine HS-8.4B 14	serpentine
Siderite130 Siderite C50 130	siderite
Goethite ASU	goethite
Forsterite038	forsterite
Emiss_pyrite_waven DLR	pyrite (see table caption)

3.3. Presentation of Results

The results for all measurements are presented in the form of bars - see the upper and lower parts of Figure 12. This form allows easy orientation in the content of the main minerals identified at the measurement site. The legend shows the colors corresponding to a given mineral. The height of the bar with this color is proportional to the mineral content. A discussion of the results is presented in the next section.

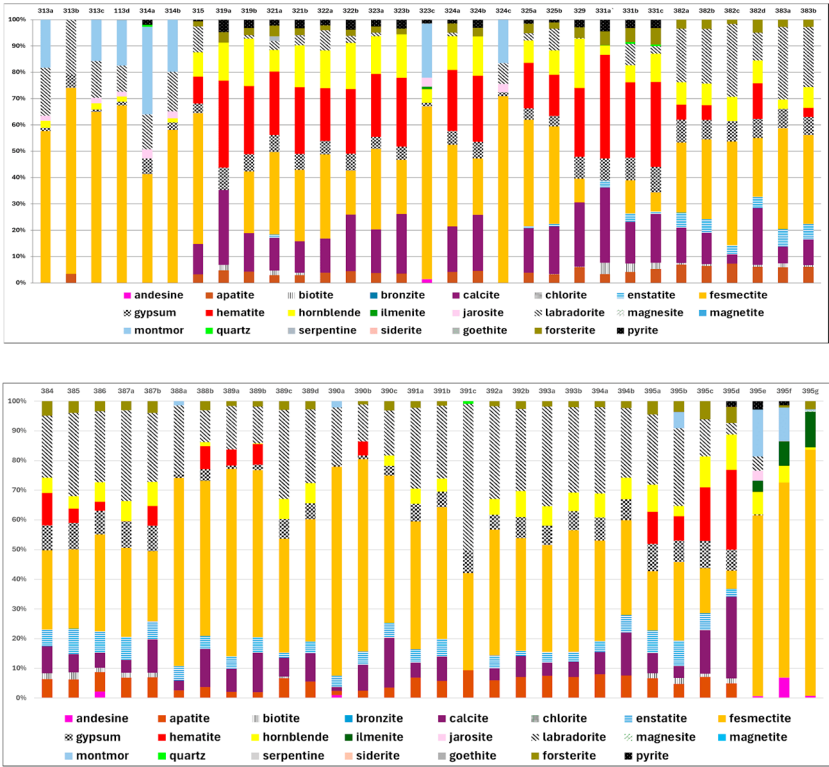


Figure 12. Our main results. Bar charts show the percentage of a given mineral. Each measurement is represented as a bar and labeled according to Table 1. The colour and/or pattern indicates the mineral, the size of the bar indicates the percentage.

4. Discussion

4.1. Mineralogy Along Rover’s Route

The calculations described in Section 3 have given the relative content of minerals whose library spectra were used in the calculations. Based on the mineralogy shown in Figure 12 (61 bars), we distinguished 6 sectors on the rover's route. Table 3 shows the average content of the considered minerals in each of the 6 sectors. Below we describe individual sectors of the route.

Table 3. Our results after averaging over individual sectors of the rover's route. Empty cells indicate very small values (less than 0.1%).

Range of sectors,		315-			395a-		
from:	313- 314b	331c	382a-389b	389c-394a	395d	395e-395g	
to:							Average for all measurements
Numbers of measurements	6	19	15	14	4	3	
Sector No	1	2	3	4	5	6	
andesine		0.1%	0.1%	0.1%		2.8%	0.21%
apatite	0.6%	3.6%	5.5%	6.1%	5.9%		4.31%
biotite		0.8%	0.9%		1.6%		0.57%
bronzite							0.00%
calcite		16.5%	9.3%	7.0%	13.3%		9.91%
chlorite							0.00%
enstatite		0.5%	5.7%	3.7%	6.1%		2.82%
fe-smectite	60.0%	27.7%	37.7%	43.4%	16.9%	69.8%	38.31%
gypsum	2.8%	5.8%	6.4%	5.4%	8.2%	0.1%	5.45%
hematite		22.2%	4.9%	0.3%	16.0%		9.24%
hornblende	1.4%	11.5%	5.2%	4.9%	8.7%	4.6%	6.94%
ilmenite		0.1%				8.0%	0.41%
jarosite	2.0%	0.3%				1.2%	0.36%
labradorite	15.2%	3.2%	21.1%	26.9%	16.6%	1.6%	15.04%
magnesite						0.2%	0.01%
magnetite							0.00%
montmorillonite	17.4%	2.0%	0.1%	0.1%	1.4%	9.2%	2.92%
quartz	0.1%	0.1%		0.1%			0.05%
serpentine		0.1%					0.03%
siderite							0.00%
goethite							0.00%
forsterite		3.0%	3.0%	1.9%	4.9%	1.2%	2.49%
pyrite	0.3%	2.6%			0.5%	1.4%	0.94%
SUM	99.98%	100.00%	100.00%	99.97%	100.00%	100.00%	100.00%

4.1.1. Sector 1, (Containing Measurements from sol 313a to sol 314b, 6 Measurements in Total)

Measurements in sector 1 were performed on the surface of bright, fractured rocks (with visible layering). Spherules are visible on the surface. They are usually stuck to the rock. In this sector, the geomorphology has changed only slightly.

The main minerals found in sector 1 are minerals from the smectite group: fe-smectite (smectite with Fe contain) and montmorillonite - together over 67%. These are phyllosilicates (sheet silicates). Smectites are usually formed from the weathering of basalt (or its chemically equivalent gabbro or some volcanic glasses). Many smectites are formed in volcanic hydrothermal systems (e.g., geyser). The hot water may percolate the volcanic ash through fissures or pores. It leads to replacing silica by phyllosilicates.

Labradorite is also present in significant amounts (~15%). The labradorite $((Ca, Na)(Al, Si)_4O_8)$ is a calcium-enriched feldspar mineral. It is an intermediate to calcic member of the plagioclase series. Labradorite occurs in mafic igneous rocks and is common in basalt and gabbro. The same rocks may also be responsible for hornblende.

Gypsum (2.8%) and jarosite (2%) are present in small amounts. They are sulfate minerals. Gypsum is evidence of water in the past on Meridiani Planum. It may have been created during the evaporation of water reservoirs during volcanic exhalations in geysers. It can also crystallize from groundwater in rock crevices. This is the type of fissure gypsum that the rover found on its way. Jarosite is an indicator of strongly oxidizing conditions prevailing at the surface of Mars.

From the above description, it can be seen that the minerals in this sector are the result of the interaction of basalt rocks in the aquatic environment and hydrothermal processes. Minerals that testify to the participation of water in the history of Meridiani Planum are minerals from the smectite group and gypsum. Other minerals present are mainly components of basalt (labradorite, hornblende).

Despite the presence of spherules, no hematite was found in this sector (see discussion below).

4.1.2. Sector 2, (sols 315-331c, 19 Measurements in Total)

Here the rover crossed the crater boundary (and mineralogical boundary, sols 314/315) and entered the ejecta cover. The rover's route seems monotonous in this region, but there are differences in the morphology and appearance of the surface. Measurements were first performed on light-colored fractured rocks with visible layering (sol 315). Spherical concretions are visible over the entire surface. Then the rover entered a flat area covered with weathered coarse material. Bright weathered rocks are visible in the distance (sol 321a). The terrain changes into a more dune surface with ripples (sol 322a). Bright material is visible on the dune ridges. From the side, a small crater with bright ejected material is visible (in the photo from the rear camera) (sol 329). The dune area, covered with spherical concretions extends further. There are ripple ridges with light surface material (sol 331a).

We observe large mineralogical differences between sectors 1 and 2. In sector 2, the content of clay minerals is much lower, falling from 67% to approximately 29%. The content of labradorite is also lower (from 15% to 3.2%). Hematite (22%) and calcite (16.5%) appear. The content of gypsum (up to 5.8%) and hornblende (up to 11.5%) is increasing. The higher contents of gypsum and calcite probably indicate a greater importance of evaporite/sedimentation processes. Minerals labradorite, hornblende, forsterite (olivine), biotite, enstatite are the components of basalt rocks. Apatite also appears (3.6%).

Note that our results also indicate the presence of pyrite at almost all measurement sites in sector 2. The average pyrite content is 2.6%. Similar content appeared in sol 314a, but there it could be an artifact. In the case of sector 2 however, it is rather not an artifact, because pyrite appears systematically. The presence of pyrite is known from Martian meteorites (e.g., [16]). However, there are problems with identifying pyrite from Martian artificial satellites. This is discussed, among others, in [15].

4.1.3. Sector 3, (sols 382a-389b, 15 Measurements in Total)

In the beginning of the sector there is the dune area (sols 384 - 388a) covered with spherical concretions. There are wrinkle ridges with bright material on the surface. Larger dunes and a dune-covered crater are visible (sol 382a). Later, outcrops of light rocks are seen (sol 384). Then rock rubble are visible. Later there is a dune area. Spherules are visible on the surface (sol 388a).

The composition of the mineralogy of this sector is similar to that of the previous sector but there is a radical reduction in the amount of hematite (below ~5%, on average). However, the contents of fe-smectite (~38%) and labradorite (up to 21%) increase. Enstatite appears in significant amounts (5.8%).

4.1.4. Sector 4, (sols 389c-394a, 14 Measurements)

The rover drove onto the slope of a small crater (sol 389c) covered with dark material. A breccia of light-colored cracked rocks is visible around the crater. Next, the rover enters a dune area with visible rock debris and outcrops of light rocks (sol 390a-393a). Spherules are visible everywhere on the surface. Among the sulfates, there is jarosite, which is confirmed by the Mossbauer spectrometer. The main minerals here are clay minerals (fe-smectite, average 43%, max. 70%) and labradorite (~27%, max. 49%). Apart from one point (sol 390b) there is no hematite. However, we find: apatite, calcite, gypsum (total average ~18%), as well as minerals related to basalt rocks: enstatite, hornblende and forsterite (total average ~10%). We also have trace amounts of quartz (0.1%), possible an artefact.

4.1.5. Sector 5, (sols 395a-395d, 4 Measurements)

Measurements were made on the surface with spherules. The amount of clay minerals decreases dramatically (in total they constitute only ~18%). Hematite appears again (16%). Basalt rock minerals dominate (labradorite, enstatite, hornblende, forsterite, biotite, total ~39%). They are accompanied by gypsum, calcite and apatite (together ~27%). Pyrite appears in the 395d measurement (below 2%, only).

4.1.6. Sector 6, (sols 395e -395g, 3 Measurements)

Measurements are taken on a surface with spherules. Stripes of light material are visible. In the last sector of the route there is a radical change in mineralogy. The mineralogy resembles that from sector 1. The share of clay minerals is very high (approximately 79%). There is no gypsum, calcite, or hematite. The difference from other sectors is the significant content of ilmenite (8%). Ilmenite, as a product of weathering of igneous rocks, often occurs in sands and gravels. Therefore, it is not strange that it appears in the dune area (where the rover was moving). Andesine, hornblende, jarosite and labradorite are also found in smaller quantities. Pyrite was observed in sol 395e and 395f (2.9% and 1.4%).

4.2. General Processes Along the Route

In the 5 sectors of rover's route considered, several groups of minerals were found: minerals that may be related to processes in the water reservoir (gypsum and calcite), phyllosilicates (fe-smectite and montmorillonite) and minerals occurring in rocks of basaltic composition (andesite, enstatite, labradorite, etc.). In the sector 6 neither gypsum nor calcite were observed. In the remaining sectors, the processes probably included hydrothermal processes, including the interaction of water and basaltic rocks leading to the formation of phyllosilicates and the processes of evaporation and/or precipitation of calcite and gypsum from aqueous solution. Similar processes occurred in other areas of Meridiani Planum. The absence of gypsum and calcite in the sector 6 indicates a lesser importance of evaporation and/or precipitation processes in this sector. Some other processes are discussed below.

4.2.1. Correlations

An inspection of Table 3 indicates a few correlations between some minerals. There are positive correlations between the contents of the following minerals: calcite - gypsum, fe-smectite - montmorillonite, enstatite - forsterite. The corresponding values of the sample Pearson correlation coefficient are: 0.45, 0.44, 0.35. These correlations may reflect similar conditions of formation due to sedimentation/evaporation, weathering processes leading to phyllosilicates, or content of basaltic minerals. Note also the strong negative correlation between contents fe-smectite - hematite: - 0.73. This may indicate some transfer of Fe.

4.3. Problems of Hematite and Spherical Concretions

One problem in our results that needs to be explained is the lack of hematite in some places (e.g., sector 1) and the significant amount of hematite (e.g., 22%) in sector 2. We can observe a similar situation in some areas on Earth. The spherical concretions from Utah are similar in shape and size to the Martian concretions (known as blueberries). However, the Utah concretions in the Dakota Formation do not have hematite. They probably once had a coating of iron oxides that were dissolved by flowing meteoric solutions [17]. The iron oxides were probably washed out of the concretions and recrystallized elsewhere. Indeed, in Utah, layers of red rocks with iron oxides are observed, alternating with white layers (from which the hematite was washed out). The solutions must have been acidic to dissolve the iron oxides. On the other hand, concretions from the Navajo Formation in Utah, called Moqui, preserve a layer of iron oxides. A similar explanation can be given for the absence of hematite in some places (and in concretions) in Meridiani Planum, despite the presence of hematite in concretions elsewhere. Such processes are investigated in our studies of the Utah concretions and other formations [18], (Figure 2 B, C).

Note also that observations of hematite made by the Thermal Emission Spectrometer on board the Mars Global Surveyor have shown that the region with hematite is not continuous and there are significant areas where the TES data do not show hematite. This is an analogy here to the situation we observed in some parts of Opportunity route, although MGS data are on another scale.

4.4. Problems of Pyrite and Quartz

Pyrite is a very interesting mineral, among others, because of its occurrence with various important minerals, including Au, Pt, Cu, Ni [19]. These metals may be crucial for the future Mars colonies. However, for some reasons pyrite detection by Mini-TES is difficult. This is mainly related to the spectrum in the IR range. An important characteristic peak in the pyrite spectrum is located close to 400 cm^{-1} . This is close to the border of the range of spectra considered in the current work. This cut-off is forced by the unstable behavior of measurements outside some range. In addition, the spectra of several minerals also have their peaks in this range, e.g., marcasite, chalcopyrite, clinopyroxene, magnesite, dolomite, etc - [15]. Despite these reservations, the presence of pyrite is very likely. In sector 2 it stays at the level 1.5%-3% (except for one measurement). This does not resemble the behavior of a random error. One can only have doubts about pyrite in sol 314a.

Note also that detecting pyrite from orbit is additionally difficult in the case of small size of the region with pyrite. Dust in the atmosphere of Mars can also distort the details of the spectrum.

Quartz also appears several times in our numerical solution. However, its amount is too low to consider this result reliable. It appears in minimal amount (average 0.05%) in quite random sols, so it may be an artifact.

4.5. Comparison with Mossbauer and APXS Results

The Opportunity rover was also equipped with a Mossbauer spectrometer (MB) and Alpha Particle X-ray Spectrometer (APXS). MB was to obtain the mineralogical identification of iron-bearing phases (e.g., oxides, silicates, sulfides, sulfates, and carbonates). The APXS is to determine the

elemental composition of Martian soils or rocks. We found two sols, during which Mini-TES as well as MB and APXS measurements were taken. These are sols: 392 and 393. We used data from [20].

Comparing the data from the Opportunity Mini-TES and APXS instruments, we can see a high SiO₂ content - (39.4% APXS). This is due to the fact that there is a large amount of clay minerals on the surface - aluminosilicates, plagioclase, pyroxene, amphiboles and olivines. According to our interpretations based on Mini-TES, the sols 392 and 393 contain about 40% fe-smectites, 40% plagioclase, 3% pyroxene, 7% amphibole and 2% olivine.

Similarly, MB detected olivine in the amount of 1%. APXS detected (in sol 393) phosphorus and calcium indicating apatite, carbonates and silicates, which are components of basalt. Magnesium indicates olivine, plagioclase and pyroxene. Aluminum indicates aluminosilicates plagioclase and amphiboles. Our results from Mini-TES confirm the occurrence of these minerals (see Table 4).

Table 4. Data for chosen sols for discussion in Section 4.5. Data from sols 392 and 393 are highlighted. Some data from sectors 5 and 6 are also presented.

	392a	392b	393a	393b	394a	394b	395a	395b	395f	395g	Average
andesine	0	0	0	0	0	0	0	0	0.0694	0.0075	0.002
apatite	0.0602	0.0707	0.0749	0.0714	0.0797	0.0758	0.0672	0.0471	0	0	0.043
biotite	0	0	0	0	0	0	0.016	0.0213	0	0	0.006
bronzite	0	0	0	0	0	0	0	0	0	0	0.000
calcite	0.0399	0.0713	0.0441	0.051	0.0756	0.1451	0.0691	0.0399	0	0	0.099
chlorite	0	0	0	0	0	0	0	0	0	0	0.000
enstatite	0.0435	0.017	0.0364	0.034	0.0368	0.0588	0.0754	0.0857	0	0	0.028
fe-smectite	0.4234	0.3796	0.3598	0.4091	0.3387	0.3198	0.1997	0.2637	0.6569	0.8294	0.383
gypsum	0.0505	0.0705	0.0657	0.0643	0.0771	0.0699	0.0921	0.0732	0	0	0.055
hematite	0	0	0	0	0	0	0.108	0.0817	0	0	0.092
hornblende	0.0534	0.0879	0.0651	0.0626	0.0811	0.0727	0.0914	0.0344	0.0556	0.0079	0.069
ilmenite	0	0	0	0	0	0	0	0	0.0829	0.1193	0.004
jarosite	0	0	0	0	0	0	0	0	0.0011	0	0.004
labradorite	0.3119	0.2765	0.3362	0.2873	0.291	0.2349	0.2365	0.262	0	0	0.150
magnesite	0	0	0	0	0	0	0	0	0	0.0045	0.000
magnetite	0	0	0	0	0	0	0	0	0	0	0.000
montmor	0	0	0	0	0	0	0	0.055	0.1132	0.0039	0.029
quartz	0	0	0	0	0	0	0	0	0	0	0.000
serpentine	0	0	0	0	0	0	0	0	0	0	0.000
siderite	0	0	0	0	0	0	0	0	0	0	0.000
goethite	0	0	0	0	0	0	0	0	0	0	0.000
forsterite	0.0173	0.0265	0.0178	0.0203	0.02	0.023	0.0446	0.0361	0.007	0.0275	0.025
pyrite	0	0	0	0	0	0	0	0	0.0138	0	0.009
Sector	4	4	4	4	4	4	5	5	6	6	

However, comparisons of sulfur and iron content give a more complicated picture. We must note here that APXS and MB results are difficult to directly compare with Mini-TES data. APXS and MB measurements are performed on a small fragment of the selected object (often rock). Rocks are usually cleaned beforehand. It is common to remove the weathered surface using an abrasive tool. In

the discussed case, Omaha (defined as RU, i.e. rock undisturbed) was examined. By its nature, such an object does not participate in the movement that loose material may undergo. Note that the loose material is also important object of our considerations. Therefore, direct comparisons of Mini-TES and APXS are not always appropriate.

The object examined by APXS and MB could have been the source of material eroded and transported to neighboring locations. So, for comparisons, it is worth using our results from neighboring sites where the Omaha material may be transported.

Sulfur detected by MB is indirectly interpreted as jarosite. Sulfur in our area (sols 392 and 393) indicates gypsum (see Table 4), but in neighboring sols the Mini-TES spectrum indicates jarosite (sol 395 – 3.36%).

Potassium identified by APXS may also indicate the presence of jarosite. The same is true for hematite, which occurs in significant quantities. In sector 5 of the rover's route (in measurements 395a-395d), Mini-TES indicates hematite occurring in 16% (average).

Titanium detected by APXS indicates ilmenite, which according to Mini-TES occurs in sol 395 in an amount of about 10%. In sols 392 and 393, according to Mini-TES analysis, there is no ilmenite.

5. Conclusions

In this work, we used some of the data from the Mini-TES of the Opportunity rover, which to our knowledge has been less interpreted so far - see Table 1. In general, the results show similarity of mineralogy from the neighboring parts of the rover route. This indicates a general similarity of processes in the Meridiani Planum area. However, along the part of the route we studied, we encounter also clear differences in mineralogy.

One of the significant differences is the variable content of hematite. Despite the occurrence of spherules practically along the entire part of the route we considered, we do not observe hematite in some sectors. We interpret this as the effect of hematite washing out from these concretions. We observe a similar phenomenon on terrestrial spherules. This indicates that terrestrial and Martian concretions may have an analogous origin.

Another interesting result is the finding of a small but systematic content of pyrite in sector 2. Pyrite often accompanies economically important minerals. Unfortunately, the current data are not sufficient to determine whether these minerals are indeed associated with the pyrite observed along the rover's path.

We will continue to study the remaining parts of the Opportunity and Spirit rover routes.

We also plan extension of the study to other areas (e.g. Chryse Planitia, [21]). Our current results on the interpretation of infrared spectra (e.g. TES) may help explain some structures observed there.

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