RAT magnet experiment on the Mars Exploration Rovers: Spirit and Opportunity beyond sol 500

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[1] The Rock Abrasion Tool (RAT) magnet experiment on the Mars Exploration Rovers was designed to collect dust from rocks ground by the RAT of the two rovers on the surface of Mars. The dust collected on the magnets is now a mixture of dust from many grindings. Here the new data from the experiment are presented. The findings from Mars are furthermore compared to simulation experiments performed on Earth. New experiments with analog rocks that mainly contain hematite indicate the likely presence of a stronger magnetic phase besides hematite in the outcrop rock formations found on Meridiani Planum, a phase which was hitherto not detected by other measurements (such as Mössbauer) on these rocks.

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1. Introduction

[2] The two Mars Exploration Rovers, Spirit and Opportunity [*Squyres et al.*, 2003], have explored two equatorial locations on Mars since 2004. Each rover carries a robotic arm, known as the instrument deployment device (IDD), on which four different payload elements are mounted. These elements are used to analyze rocks, surface soils and atmospheric dust – and even in some cases the atmosphere. The Rock Abrasion Tool (RAT) can brush and grind rocks and thereby expose unweathered parts of rocks, which can then be analyzed by the other three instruments: the Microscopic Imager (MI), the Mössbauer Spectrometer (MB) and the Alpha Particle X-ray Spectrometer (APXS) [*Herkenhoff et al.*, 2003; *Klingelhöfer et al.*, 2003; *Rieder et al.*, 2003]. Collectively, these four instruments constitute a powerful tool to study the geology on Mars and provide new insights into the evolution of the planet.

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[3] The Rock Abrasion Tool (RAT) [*Gorevan et al.*, 2003] has a spinning grinding tool and a spinning brush. The RAT is pictured in Figure 1. Close to the grinding head and the brush, four permanent magnets are built into the RAT housing. Two of the magnets have the same values of magnetic field strength and magnetic field gradient. These two strong magnets are called RAT Magnet1 (collectively RM1, individually called RM1_2 and RM1_3, respectively), while the two other magnets, RM2 and RM3, have a lower and much lower magnetic fields and magnetic field gradients, respectively (Table 1). RM1_2 is located close to RM2 while RM1_3 is located close to RM3 in the bottom plane of the RAT housing.

[4] The maximum values of the magnetic field and the maximum value of the magnetic field gradient for the different types of RAT magnets are provided in Table 1. When the RAT is operating, the active surface of these magnets is about 4 mm above the rock surface. Details on the magnets are given by *Gorevan et al.* [2003] and *Madsen et al.* [2003].

[5] The main goal for the RAT magnet experiment is to attract magnetic material from rocks ground by the RAT tool for further investigation with Pancam. This can provide additional information about the magnetic properties of the Martian surface rocks and thus be a supplement to the Mössbauer (MB) measurements. From the Pancam images it is to some extent possible to determine the amount (volume) of dust on the magnets, extract visible/NIR spectra of dust collected on the magnets and, perhaps most importantly, study the difference in amount of dust on the different types of magnets. The RM2 and RM3 are magnetically weak and therefore only highly magnetic particles can settle on these magnets. It is possible to collect some of the most magnetic particles, which may not be very abundant in the rock

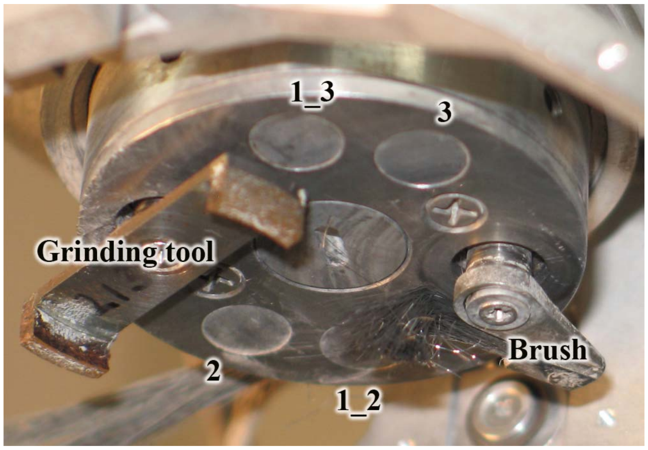

Figure 1. The RAT housing (33.4 mm in diameter) with its components: the grinding tool, the brush, and the RAT magnets. The two strong magnets are named 1_2 and 1_3 depending on whether their neighboring magnet is either 2 or 3. The maximum value of the magnetic field and the magnetic field gradient for the magnets are as follows: 1 (B = 0.27 T and *grad* B = 350 T/m), 2 (B = 0.1 T, *grad* B = 120 T/m), and 3 (B = 0.06 T and *grad* B = 80 T/m).

ground by the RAT. In this way the RAT magnet experiment can support the MB measurements and detect particles that represents maybe as little as 1 wt% of the rock. In the following discussion the rovers will be referred to as MER-A (Spirit) and MER-B (Opportunity).

2. Previous Work

[6] This paper examines RAT magnet data after sol 500 and some supporting experiments in addition to the main result of the first 500 sols reported by *Goetz et al.* [2008]. On both rovers, images from Pancam revealed dust on the strong RAT magnets early in the mission before grinding with the RAT. Grinding by the RAT resulted in further accumulation of dust on the other magnets. However, the color of the dust differed on the two sites. On MER-A the color of the first dust on the RAT magnets was relatively dark grayish. This was in good agreement with the MB findings of nonstoichiometric magnetite (probably titanomagnetite) [*Goetz et al.*, 2005] in airborne dust on the site. On the grindings performed at the Gusev crater floor (Adirondack sol 35, Humphrey sol 68 and Mazatzal sol 85) the dust collected on RM1 had a relatively flat optical/NIR spectrum, somewhat brighter than pure magnetite. However, during the grindings in rocks on the Colombia Hills RM1 collected more reddish dust that probably contained hematite and goethite. The spectra of RM1 were however darker than the spectra of pure hematite indicating a mixture of old (previously collected) dark material admixed with freshly collected hematite and/or goethite. For details on these results, see *Goetz et al.* [2008, chap. 3]. The MER-B landing site was chosen because hematite had been observed by TES [*Christensen et al.*, 2001] and this finding was later confirmed by MB data obtained on the surface of Mars [*Morris et al.*, 2006]. The MB experiment on MER-B site found hematite in spherules (known as "blueberries"), in sulfate-bearing outcrops and in the soil [*Squyres et al.*, 2004; *Grotzinger et al.*, 2005; *Klingelhöfer et al.*, 2004; *McLennan et al.*, 2005; *Calvin et al.*, 2008]. Other iron-bearing phases were also identified in the MB data from Opportunity, but most relevant for this paper was the occurrence of magnetite. Magnetite was found mainly in the loose dark soil believed to be a migrating component of the topsoil [*Morris et al.*, 2006] and not in the outcrops. It should be noted that MB data of a mixture of mainly hematite and only a few percent magnetite, would not necessarily reveal the magnetite since many peaks are partly overlapping. Therefore the RAT magnet experiment may serve as an independent support of the MB measurements.

[7] The spectra of the dust collected on the RAT magnets on MER-B turned out to be quite dynamic in the sense that the color of the dust on the magnets changed from one grinding to another. This proved that new material was collected on the magnets during grinding in different rocks. Material was not only collected on the strong magnet but also on the two weaker magnets.

3. RAT Magnets Beyond Sol 500

[8] The RAT can brush and grind selected target rocks; these two operations are referred to as RAT activities. In general the RAT activities have been slightly decreasing during the mission and therefore the imaging of the RAT and the RAT magnets has also been decreasing. The RAT is often imaged before and/or after RAT activities either by Pancam or Hazcam. Hazcam images are used to check the bits and lobes (Figure 1), so in these images the RAT is seen in profile (the grinding bits on edge) and it is therefore not possible to see the RAT magnets in these Hazcam images. Pancam images on the other hand show the RAT and RAT magnets in several viewing geometries (Figure 2). Usually these observations are taken in three Pancam filters (L257) making it possible to make false color images. After sol 500 there have been three of these observations on each rover, see Table 2 for details.

[9] On MER-A the lobes on the brush became more separated after several brushing activities, which for instance on sol A1442 clearly affects the dust layers on the RM1_2, RM2 and RM3. Here (and in the following) the term "dust" should not be confused with atmospheric dust, but is used as a synonym with "RAT cuttings." Dust was removed on these magnets by the brush. The RAT had no further activity until around sol 1830 and on the image from A2016 it seems that the RM2 collected dust again. However, the RM1_2 is clean again on A2016, so the brush had much influence on

Table 1. Properties of the RAT Magnets[a]

	Magnetic Characteristics \Magnet Type		
	RM1	RM2	RM3
Maximum value of magnetic field at surface [mT]	280	100	70
Maximum value of magnetic field gradient at surface [Tm^{-1}]	350	120	80

[a]There are two of the strong RM1, called RM1_2 and RM1_3 depending on whether it is the one close to RM2 or RM3.

Figure 2. False color Pancam images (L257) of the RAT. The arrow shows the RAT magnet RM1_3. The images labels refer to sol number for rover A and B. Photo credit: NASA/Cornell.

the experiment in the sense that dust is removed from the magnets by the brush.

[10] On MER-B there is lots of dust on all magnets in all images. There does not seem to be any conflict with the brush. Apparently the lobes were not separated very much on the MER-B brush even though the brush was used many times. When the lobes will become separated and make the brush affect the RAT magnet experiment is somewhat unpredictable. However, on B548 there is largely only dust on the magnets, whereas the rest of the RAT is more or less free of dust. On the two following images (B1373 and B1399 of Figure 2) there is still more and more dust accumulating on other parts of the RAT. As observed during the first 500 sols, the RAT magnet experiment is still dynamic and the dust on the magnets on B548 (Figure 2) is held by magnetic forces, indicating a relatively high saturation magnetization of the collected dust.

4. Simulation Experiment

[11] From laboratory experiments and model calculations, it seems unlikely that pure hematite with a saturation magnetization as low as Ms = 0.4 Am^2/kg is magnetically strong enough to be collected and retained during rover motion and vibration on all RAT magnets. For comparison, Ms = 92 Am^2/kg for pure magnetite [*Dunlop and Özdemir*, 1997]. In the work of *Goetz et al.* [2008], a simulation grinding was performed on a rock from Brazil herein named Ouro Preto, a sample which contains almost pure hematite (meaning that the iron-bearing phase was hematite). For the Ouro Preto rock, Ms = 0.8 Am^2/kg is a somewhat higher than the saturation magnetization for pure hematite. It was estimated that the rock thus contained about 0.9 wt % magnetite. The grinding experiment performed on this rock showed that the amount of dust collected on the magnets was comparable to what was observed on Mars. It was speculated, but not verified whether pure hematite as well could reproduce the observed dust collecting seen on the Opportunity RAT magnets. It was therefore deemed desirable to perform a new simulation grinding with a rock where the only iron-bearing phase was hematite. It could then be determined whether Meridiani outcrops are holding pure hematite as the only iron-oxide phase, or if there might instead be traces of a more magnetic phase which have not been identified using the MB.

4.1. Sample Conditions

[12] A good Martian analog for the desired experiment should fulfill at least two constraints: (1) The iron-bearing phase should be mainly pure hematite and if other potential phases are present they should not have higher saturation magnetization than hematite. (2) The sample should be suitable for RAT grinding, that is it should have a relatively smooth surface no less than 5–8 cm in diameter. It is difficult to grind smaller samples because of the dimensions of the RAT.

[13] For this study, a natural, diagenetic hematite sample (UT97–20B Jn) was chosen and it was determined that this rock does fulfill these constraints quite well. The sample is a cemented concretionary pipe form from the Jurassic Navajo Sandstone, Utah, described by *Chan et al.* [2000], *Beitler et al.* [2005], and *Chan et al.* [2007]. The concretion analog relationship to the geologic setting in the Meridiani region is discussed by *Ormö et al.* [2004] and *Chan et al.* [2004, 2005]. These terrestrial rock samples are mainly quartz arenites, typically with only a few percent hematite, but locally up to 15 wt % hematite The mass of the sample before grinding was 766 g and its density was 2.62×10^3 kg/m^3. This is a relatively low average density because hematite has

Table 2. RAT Activities Imaged by Pancam[a]

Sol	Activity
MER-A	
904	RAT diagnostic.
1442	RAT diagnostic before grind in target Freeman on sol 1445.
2016	RAT diagnostic at "Olive Leaf" target
MER-B	
548	In situ observation of "One Scoop" (ground about 6 mm).
1373	Grind "Smith 2" target about 1 mm. RAT magnet observation.
1399	In situ observation of "Lyell 1" in Victoria Crater.

[a]On MER-A, all three events were diagnostic before using the RAT. On MER-B all three RAT magnet observation are in connection with rock grindings. It should be noted that there were other RAT activities after sol 500, but those activities did not include Pancam imaging of the RAT.

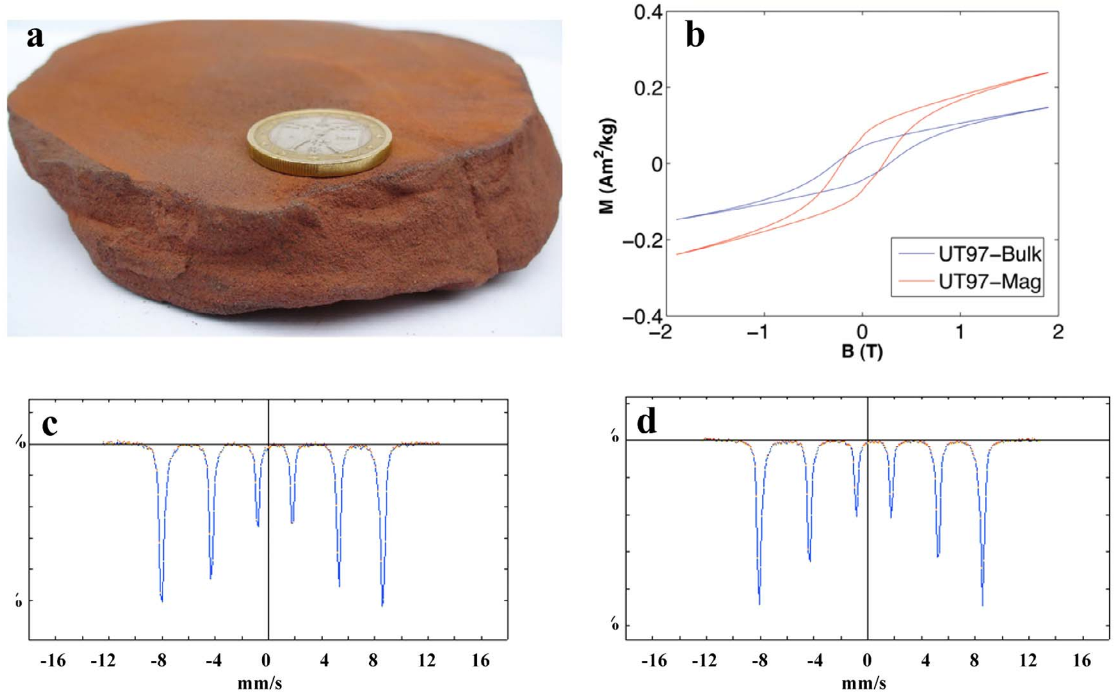

Figure 3. (a) Image of UT97–20B before any experiments were done. The ruler shows that the diameter of the sample is about 14 cm. (b) Magnetization curves of bulk (UT97 Bulk, Ms = 0.05 Am^2/kg) and a magnetically separated sample (UT97 Mag, Ms = 0.09 Am^2/kg). The magnetically separated sample is more magnetic than the bulk, which proves that it is possible at least partially to separate the sample. (c) Mössbauer spectrum of the bulk sample, showing hematite. (d) A separate of the bulk (note, not same as sample used for magnetization measurement in Figure 3b). The separated sample shows not only the same lines as the bulk but he two spectra have the same Mössbauer parameters (isometric shift, 0.35 mm/s; quadrupole shift, −0.11 mm/s; hyperfine field, 51.3 T), which corresponds very well to the parameters of hematite.

$\rho = 5.5 \times 10^3$ kg/m^3 and quartz has $\rho = 2.66 \times 103$ kg/m^3. The hematite composition for this sample was verified by X-ray diffraction in addition to the MB analysis discussed below.

[14] A small part of the rock was used for a magnetization measurement in a vibrating sample magnetometer (VSM). The bulk sample was ground to small particles (less than 1 mm in diameter). A magnetic separate was prepared by holding a small permanent magnet below a piece of paper where some of the bulk sample was located. Thereby it was possible to extract some particles slightly more magnetic than the average. Furthermore UT97–20 was examined by Mössbauer (MB) spectroscopy. Details on MB spectroscopy are not given here, because there is already an extensive literature on the topic. It is well established that MB spectroscopy is the tool par excellence for analyzing iron-containing samples.

[15] The MB data of UT97–20 (Figure 3) shows a hematite sextet, which of course was expected (Figure 3c). The question is if hematite is the only iron-oxide component in the sample. The outermost lines of the MB spectra (line 1 and 6) have a slight broadening at the bottom toward zero velocity. This can indicate the presence of another phase hidden by the main sextet, but at a much lower concentration. The magnetically separated sample was obtained by suspending a relatively fine-grained part of the sample in alcohol and extracting the most magnetic fraction of material by a permanent magnet. Based on MB spectroscopy there is no significant difference between the bulk sample (Figure 3c) and this wet separated sample (Figure 3d), which indicates that hematite is indeed the most magnetic phase in the sample. Candidates for a more magnetic phase should be either magnetite or maghemite (Ms = 70 Am^2/kg). The low value of Ms could be explained by about 10% hematite and no other magnetic phases. If on the other hand we assume that UT97–20 contains 2% wt of hematite the Ms value indicates a ratio between hematite and magnetite of about 40. Such a high amount of magnetite would still be difficult to detect in the MB data of the bulk sample, but it should be possible to separate it out, so the absence in the MB data of the separated sample of a magnetite component indicates that either hematite is the only iron-bearing phase or UT97–20 contains maghemite rather than magnetite.

4.2. Analogue Results

[16] The Utah rock UT97–20B was used for a simulation experiment performed at Honeybee Robotics, with an exact copy of the RAT that flew on the MERs. The RAT and the UT97–20B was placed in a vacuum chamber, which was evacuated to about 13 mbar. This is slightly higher than the pressure at the surface of Mars, but for technical reasons the pressure was kept at this level. Further evacuation would make the system shake, which was believed to be a problem. The small difference in pressure is however not likely to

Figure 4. The RAT after abrading the UT97–20B. (a and b) Two different positions of the RAT, (c) the RAT 1_3 magnet, and (d) the RAT2 magnet. These two magnets did not collect any piles of dust that are believed to be held by magnetism. It appears that the fine reddish dust on the RAT is mainly held by electrostatic forces. (e) The Ouro Preto used as hematite analog by *Goetz et al.* [2008]. Here dust is clearly collected on RM1_3.

have any major influence on the experiment. In the work of *Goetz et al.* [2008] an experiment was performed to evaluate the effect of pressure (i.e., ambient versus Mars pressure). It was found that the thicker atmosphere on Earth (1013 mbar versus 7 mbar on Mars) resulted in an increase in dust collection on the strong magnet with a factor of 2–3. The difference in pressure on Earth and Mars is about a factor 140. The pressure at this present experiment at Honeybee Robotics is about a factor of 2 higher than Martian pressure, so it is believed that the uncertainty from this pressure difference is minimal. The temperature was kept at room temperature and this is also insignificant for the experiment. After evacuation of the chamber, the rock was ground for about an hour, which made a 4.0 mm deep hole in the rock. The chamber was slowly filled with air again after the grinding. This backfilling had to be done slowly so that turbulence would not affect the experiment. After the experiment, the RAT was imaged again (see Figure 4). The RAT brush has unfortunately affected the RM1_2 and RM3, so any dust potentially present on these magnets has been removed. But RM1_3 and RM2 are not affected (Figures 4c and 4d, respectively). Around RM1_3 there is a lot dust, but this dust doesn't seem to be magnetically held, since the whole area around the magnet is covered in dust.

5. MER Results

[17] This section discusses the RAT grinding and the dust collection on the RAT magnets during the first 50 sols of the MER-B mission. The grinding on McKittrick-MiddleRAT on sol 30 is especially interesting for the following reasons: (1) It is the first grinding experiment performed, so there is no grinding material present on the RAT and the RAT magnets before this experiment. (2) The RAT was imaged in exactly the same position at the same time of day before and after the grinding experiment (on sol 29 and sol 31), see Figure 5. Therefore the images from before and after are directly comparable and visible/NIR spectra have been extracted for comparison.

[18] Also the images from sol 45 are discussed because here the RAT magnets have collected large piles of dust. Figures 5a and 5d from sol 29 show that a small amount of dust has been collected on RM1 and also a very small amount on RM2, i.e., before the RAT was ever used for grinding. This is confirmed by the Pancam spectra in Figure 6. The spectra are extracted from 10 to 15 pixels and shows that the stronger the magnet the more reddish it appears. There is a thin semitransparent dust layer on all magnets, but maybe almost no dust on the RM3. Because these images were acquired before any grinding had taken place, the collected dust on the magnets is expected to be atmospheric dust exclusively.

[19] On sol 30, the McKittrick rock was ground and on sol 31, the RAT was imaged again, which is shown on Figures 5b and 5e. In general, the whole RAT has been covered with reddish dust from the grinding. It is however possible to identify the magnets because they are slightly darker than the surroundings. It is a bit surprising to find that there seems to be more dust on RM2 than on RM1_2 (Figure 5e). The spectra (Figure 6b) show that the stronger the magnet the brighter is the dust collected. Similar observations are evident on the filter and capture magnets below the camera mast carrying the Pancam, *Madsen et al.* [2009]. The spectrum of dust on RM1 is almost identical to the spectrum of a reference sample of dust, which was extracted from the dust on the RAT. This indicates that there was some kind of sorting so that the most magnetic particles collected on the stronger magnets. If for instance magnetite is present as a strongly magnetic phase, this would make the dust darker and the concentration of magnetite would be relatively higher on the weaker magnets (which would not be able to retain weakly magnetic material as well), and this would give a dark spectrum as is indeed observed. Furthermore, the spectra have a small decrease from around 750 nm and out to 850 where the spectra tend to increase slightly again. This shape can be explained by hematite [*Farrand et al.*, 2007], which is in good agreement with the general understanding of the Meridiani Planum mineralogy [*Squyres et al.*, 2004; *Arvidson et al.*, 2006].

6. Comparison of Simulation Experiments and MER Results

[20] The simulation experiment with UT97–20 showed no small darker piles on the magnets. In general, there are no piles of dust in the simulation experiment with UT97–20 and the dust seen on the RAT in this simulation experiment is not magnetically held. As previously described, hematite

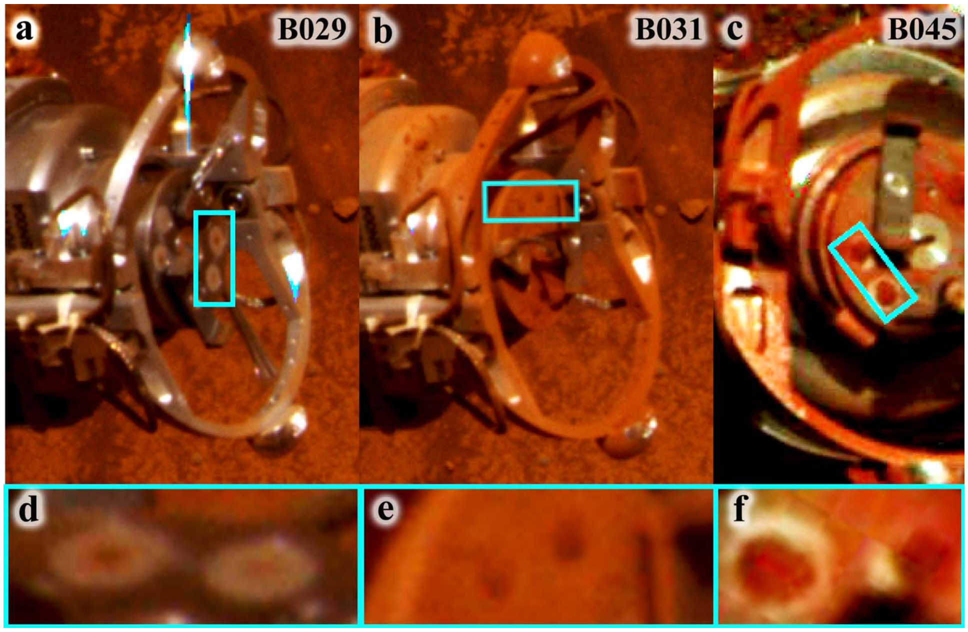

Figure 5. McKittrick-MiddleRAT: The first grinding by the RAT in Meridiani rocks. (a) The image is taken the sol before the first grinding. The RAT is still clean, but there are small piles of dust on the RM1_2 and RM1_3; the weaker magnets have not collected any dust. These small piles are presumably airborne dust. (b) The RAT after grinding a depth of 4.25 mm into the target McKittrick-MiddleRAT. The instrument collected a lot of red dust (hematite) and the magnets similarly collected a lot of dust during the grinding. RM1_3 is slightly in the shadow of the RAT grinding device, but there seems to be a shadow from a large pile of dust. There is a good view on RM1_2 and RM2 so they are compared. (c) The RAT after another 2 mm grinding in rocks in Eagle crater. (d and e) Magnifications of the RM1_2 and RM2 from sol 29 and sol 31, respectively. The RM1_2 is to the left, and RM2 is to the right. It is difficult to see if there is any dust on the RM3. The great change in dust on RM2 proves that most of the dust on the magnets originates from ground rocks and not airborne dust.

is the only magnetic phase in UT97–20 and therefore this experiment shows that it is not possible to hold pure hematite on the magnets by magnetic forces alone.

[21] Furthermore the spectra of the magnets on MER-B indicate that a significant sorting of the dust has taken place on the three different RAT magnets. Together this clearly shows that RAT magnets on Mars must have collected something more magnetic than hematite, probably magnetite since this mineral was detected in sand and atmospheric dust.

[22] Where did the strongly magnetic material collected on the RAT magnets come from? There are mainly three possible sources of magnetite (or other strongly magnetic phase): (1) atmospheric dust, (2) sand-sized particles migrating on the surface of Meridiani Planum, and (3) rock exposures and outcrops. It should be mentioned here that magnetite has only been detected in MB in dust and sand, for instance in the Meridiani sand on sol 11 [*Morris et al.*, 2006].

[23] On sol 29 (Figures 5a and 5d) only RM1_2 has collected small amounts of dust, while RM2 has traces of dust on it. As stated earlier, this dust is atmospheric dust collected during the first 29 sols and it is most unlikely that the magnets suddenly should collect lots of atmospheric dust during two sols. Likewise, it is not a realistic scenario that surface material should suddenly be able to get to the magnets during sol 29 and 30. If surface sand was likely to be lifted by the wind onto the magnets this could as well have happened during the first 29 sols, for instance (and with higher probability) on sol 11 when soil was investigated by the MB and APXS instruments. The most likely scenario is therefore that the dust collected on the magnets was liberated into the air during the grinding of McKittrick on sol 30 and then attracted to the magnets.

[24] On sol 45 the piles on the magnets have become much more pronounced. In Tables 2 and 3 the RAT activities in the period are listed. The list shows that there were two successful grindings in the period between sol 31 and 45 and one which failed. Furthermore, the other instruments on the IDD were used several times and there is an interesting result on sol 38 where the MB detected magnetite in a soil sample. So what is the origin for the dust seen on the RAT magnets on sol 45? It is still unlikely that the RAT magnets should start collecting lots of atmospheric dust since this was not really the case during the first 29 sols (Figure 5a). Sol 38 is the only time in the period where the IDD has definitely been in contact with magnetite (in the surface sand). This was detected by MB and more or less the same measurement and result was also found on sol 11. Clearly the positioning of the IDD on sol 11 did not result in sand being lifted to the magnets, since this sand would have been seen on the images of the RAT on sol 29. It is therefore

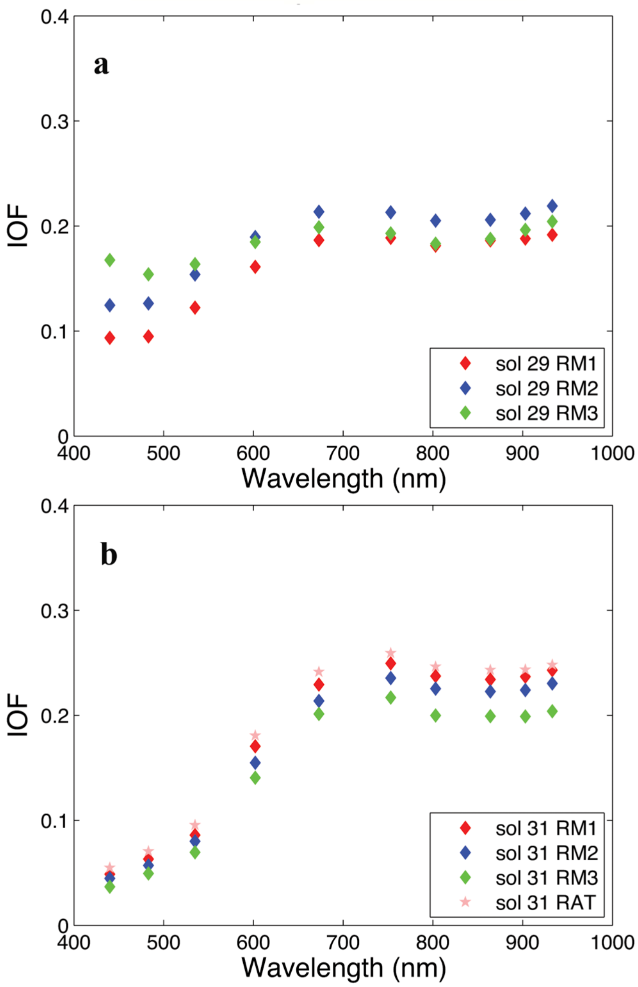

Figure 6. Optical/NIR spectra of the RAT magnets before and after the first grinding in Meridiani outcrops. (a) Sol 29 where a small amount of atmospheric dust has been collected, at least on RM1 and RM2. (b) All RAT magnets have collected dust after the grinding on sol 30. The RAT spectrum is reference spectrum of the dust on the RAT outside the magnets. The spectra of the dust on the magnets have the same shape as this reference spectrum but the dust on the magnets is darker. This indicates that the weaker the magnet the higher concentration of a dark mineral, probably magnetite.

not very plausible that sand-sized soil particles should have been lifted up on sol 38 either. The most likely explanation for the dust on the magnets on sol 45 is therefore that dust liberated during grindings (on sol 34 and sol 44) and maybe during RAT brushing on sol 45. It is therefore our interpretation of these results that the collected dust on the RAT magnets is material from the outcrops.

[25] If this conclusion is correct, it seems more than likely that hematite is not the only magnetic phase in the Meridiani outcrops. The simulation experiments performed and reported here show that hematite alone cannot settle and be retained on the magnets in a stable manner. *Goetz et al.* [2008] report a similar experiment performed on a rock from Brazil, Ouro Preto, as described in the Simulation experiment chapter. The grinding result by the RAT (Figure 4e) resulted in a pile of dust on RM1_3. Unfortunately RM1_2 does not have any pile visible because the brush has influenced the experiment and removed all dust collected on this magnet. RM2 did not collect any substantial amount of material, so these two simulation experiments show that it would be impossible for hematite to reproduce the dust piles seen on the RAT magnets after grindings on outcrop rocks at Meridiani Planum. The Ouro Preto rock is a BIF (banded iron formation) [*Goetz et al.*, 2008] and contains about 0.9 wt% magnetite, thus it is plausible that the Meridiani outcrops must contain an equivalent amount of magnetite or perhaps maghemite.

7. Implications for Mars

[26] The results presented here indicate that the Meridiani outcrops must contain a more strongly magnetic phase than hematite, a phase which has not been previously detected in the MB data obtained from these outcrop rocks. The abundance of this phase is probably very small, maybe 1–2% of the amount of hematite in the rocks. Note that even the presence of such a small amount of a strongly magnetic phase would raise the saturation magnetization of the outcrops by a factor of 2 or 3. The more strongly magnetic mineral could be either magnetite as also found in the soil, or maghemite which would be difficult to identify in a MB spectrum if present along with hematite. Since the RAT magnet experiment cannot distinguish between magnetite and maghemite, the interpretation of the result is somewhat speculative. If the magnetic phase is magnetite formed in liquid water in the environment of low oxidization, some kind of reducing mineral should have been present. It is also possible (or even more likely) that the putative magnetite phase was not produced in place, but was of magmatic

Table 3. IDD Activities Around the First Grindings in Meridiani Outcrops

Sol	IDD Activity
29	Positioning for Pancam imaging
30	Grinding in McKittrick-MiddleRAT. 4.25 mm after 2h
32	MB of McKittrick-MiddleRAT
34	Grinding in King3 (Guadalupe) 4.9 mm.
	Stronger than McKittrick. Three full ‘berries’ and one partial berry were abraded roughly halfway, and they all remained in place
35	MI/MB/APXS of Guadalupe
38	MI/MB of Pay Dirt. Soil Measurements.
	MB findings of magnetite
42	Attempt to grind Flatrock. Attempt failed only abrading away a small knob
44	Grinding 3.1 mm into Mojo2 on Flatrock.
	MB and APXS on RAT hole
45	Swept on hole with brush.
46	MI images show that lots of material was swept out of the hole yestersol.
48	Brushing of Berrybowl

origin and was transported to the Meridiani area by eolian or fluvial activity. If the phase is maghemite, this would probably imply some multistage process with the oxidation of magnetite as its final step.

8. Conclusions

[27] The Rock Abrasion Tool (RAT) magnet experiment was designed to support the interpretation of Mössbauer (MB) measurements of rocks on Mars. It was originally designed as a "one-shot" experiment and indeed the dust seen on the magnets today is a mixture and accumulation of many grindings. Interpretation of the most recent images are somewhat difficult. Two different simulation grindings have been performed with two hematite-rich terrestrial analog rocks to compare with RAT magnet experiments performed on Meridiani Planum. None of the chosen samples are perfect Mars analogs in the sense that their origin and history are significantly different from the formation of the Meridiani outcrops. However, the experiment shows how these different analog samples can still be used to help interpret images of the RAT magnet dust piles. Our interpretation of the experiments suggests that pure hematite can most likely *not* explain the amount of dust seen on the RAT magnets as observed on Opportunity at Meridiani Planum. MB measurements of the outcrops at Meridiani do not show any other magnetic phase than hematite, but it is plausible that the outcrops do contain a small amount (1–2 wt %) of magnetite or another strongly magnetic phase which because of the low concentration could not be detected by MB, but which has now been detected more indirectly by the RAT magnet experiment.

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