

# Magnetic properties of Martian olivine basalts studied by terrestrial analogues

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**Abstract** Here we present a comparison study of terrestrial olivine basalt and relatively un-weathered basalt studied by the Mars Exploration Rover Spirit on Mars. The Mössbauer spectra of terrestrial olivine basalt exhibit some characteristics that can also be seen in the Mars spectra. The results from Mössbauer spectroscopy on Mars indicate that the olivine in the rocks has undergone alteration at high temperatures (600–1,000°C), a process known to give rise to anomalously magnetic rocks on Earth. This suggests that if the rocks at Gusev crater had solidified in an external magnetic field of terrestrial magnitude, these would have become highly magnetic enough to explain the presence of magnetic anomalies on Mars.

**Key words** Mars · olivine basalt · Mössbauer spectroscopy · magnetic anomalies

## 1 Introduction

Among the major discoveries of the Mars Global Surveyor mission is the finding of strong magnetic remanent anomalies [1]. Models suggest magnetic rocks tens of kilometers in thickness with remanent magnetisation up to  $M_r \sim 20$  A/m [2], which is about an order of magnitude higher than average values for terrestrial mid-ocean ridge basalt (MORB). New results from the Mars Exploration Rovers (MER), in

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particular by Mössbauer spectroscopy, suggest that olivine-rich basalt lavas may constitute a significant portion of the Martian crust, and yet remain difficult to detect by means of orbital remote sensing [3].

With the aim to better constrain the Mars data and geology we have studied olivine basalt (<0.8 Ma) from Iceland. The Mössbauer data from Iceland lavas has proved a good analogue to the relatively un-weathered volcanic rocks at Gusev crater on Mars [4].

The MER Mössbauer data [5] yields two spectra: one from backscattered 14.4 keV  $\gamma$ -rays and one from backscattered 6.4 keV X-rays. The sampling depth varies with the energy of the radiation. For typical volcanic rocks ( $\rho \approx 3 \text{ g/cm}^3$ ) the 14.4 keV  $\gamma$ -rays give information from  $\sim 100 \mu\text{m}$  beneath the surface, while the 6.4 keV X-rays give information from  $\sim 50 \mu\text{m}$ . A difference in these spectra therefore provides information on the depth of oxidation processes and/or mechanical properties of the sample.

The rock abrasion tool (RAT) [6] on the MERs instrument deployment arm can be applied to either brush the surface of a rock sample or mechanically remove the surface by a grinding tool (ratting) to look beneath the weathered/dust coated top layer.

## 2 Iceland samples and experiments

A total of 31 samples were collected from <0.8 Ma olivine basalt from Reykjavik and the Reykjanes peninsula, Iceland, hereafter called the HRI series. The samples were collected either by drilling or by hammering. Following detailed measurements of the remanent magnetisation of the samples, they were ground into a homogeneous powder for use in other experiments. Magnetic separates were obtained by placing the sample on a piece of paper and applying hand magnets to collect the most strongly magnetic particles.

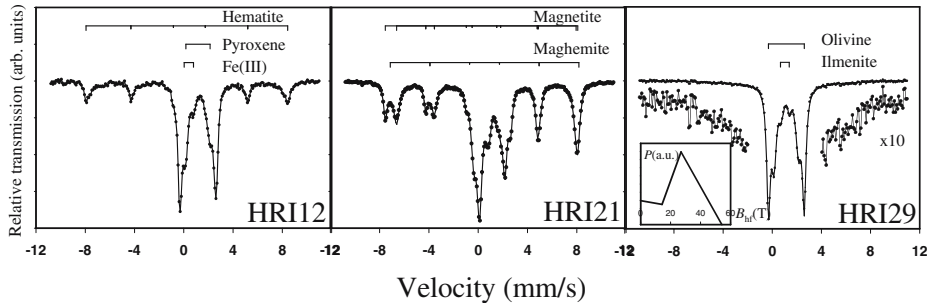
Mössbauer spectra were recorded at room temperature using 10–50 mCi  $^{57}\text{Co}$ :Rh sources moved relative to the sample on a conventional constant acceleration drive system. For conversion electron Mössbauer spectroscopy (CEMS) measurements, the bulk samples were placed on a double adhesive conduction tape and mounted as a cathode in a parallel plate avalanche detector. Velocities are given relative to  $\alpha$ -Fe at room temperature.

Mössbauer spectra of samples from Mars spectra were acquired from the Planetary Data System (<http://anserver1.eprsl.wustl.edu>). Here we concentrate on the spectra obtained on relatively un-weathered rocks at Gusev crater, obtained before the rover found more weathered/oxidized rocks at Columbia Hills.

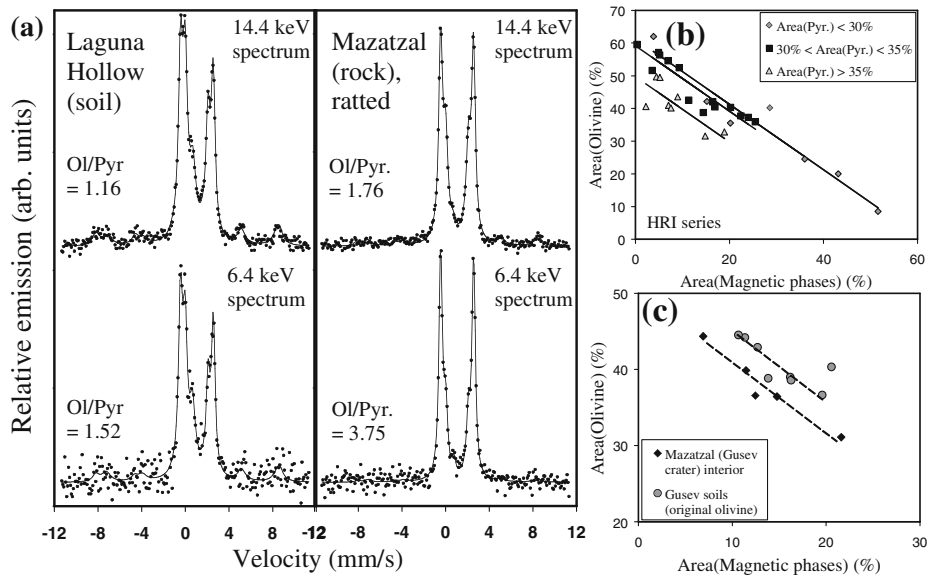
## 3 Results

Figure 1 shows representative spectra from Iceland. All the spectra were analysed in terms of eight spectral components, although no single spectrum contains more than seven components.

Symmetric quadrupole doublets were assigned to paramagnetic Fe(II) in olivine,  $(\text{Mg,Fe})_2[\text{SiO}_4]$ , pyroxene,  $(\text{Mg,Fe,Ca} \dots)[\text{SiO}_3]$ , ilmenite,  $(\text{FeTiO}_3)$  and unspecific



**Figure 1** Room temperature Mössbauer spectra of olivine basalt samples from Iceland. The *solid lines* show the sum of the fitting components indicated with *bar diagrams* together with their assignments. The inserted figure in the HRI29 spectra shows the hyperfine distribution for titanomagnetite with  $0.5 < x < 0.7$ .



**Figure 2** **a** Backscattering Mössbauer spectra from Mars of the targets and energy indicated. The spectral area ratio between olivine and pyroxene is indicated. **b** Correlation between the relative area of Fe in olivine and magnetic phases in spectra of the HRI series, binned after the pyroxene ratio. The *solid lines* are to guide the eye within each binning. **c** Correlation between the relative area of Fe in olivine and iron oxides for the Mars data following the procedures given in the text.

Fe(III). Simple magnetic hyperfine split sextets were assigned to hematite ( $\alpha\text{-Fe}_2\text{O}_3$ ) or maghemite ( $\gamma\text{-Fe}_2\text{O}_3$ ) and stoichiometric magnetite,  $\text{Fe}_3\text{O}_4$ . Some spectra showed very broad features (cf. the spectrum of HRI29 in Figure 1). A magnetic hyperfine field distribution was applied in these cases, assigned to titanomagnetite ( $\text{Fe}_{3-x}\text{Ti}_x\text{O}_4$ ) with  $0.5 < x < 0.7$ .

The spectra obtained from one sample (bulk, magnetic separates, CEMS measurements) were analysed simultaneously assuming the same hyperfine parameters of

components in different amounts. The fitting procedure is described in more detail in [7].

Figure 2 shows representative Mössbauer spectra from Mars.

Mössbauer spectra from Mars (Figure 2a) have been analysed in terms of the same components as the spectra from Iceland, with the exceptions that ilmenite was not detected in significant amounts on Mars; hematite and maghemite were not differentiated and a single sextet was assigned to ferric iron oxide, probably a mixture of maghemite and hematite. The magnetic hyperfine field distribution for titanomagnetite was not applied, though misfits at  $v \sim -4$  mm/s indicate the presence of this component in small amounts. The spectra from Mars are recorded at different temperatures, and were analysed simultaneously restricting the isomer shift of the components to follow the second order Doppler shift, and assuming that within the temperature range the quadrupole splitting could be described as linear in  $T$ . The fits obtained of the 14.4 keV spectra are in good agreement with the results presented in [4]. The spectra and analysis presented in Figure 2 are summed over all temperatures.

#### 4 Discussion and conclusions

The Mössbauer spectra of olivine basalt from Iceland, show a negative correlation between the proportion of Fe in olivine and the proportion of Fe in magnetic phases [7] (cf. Figure 2b). The correlation depends on the proportion of Fe in pyroxene, however, it is important to note that no significant correlation is found between the proportion of Fe in pyroxene and olivine nor pyroxene and magnetic phases. The correlation between olivine and magnetic phases is attributed to partial oxidation of olivine that can lead to the formation of magnetic iron oxides imbedded in the original olivine host. The process can take place at both high (600–1,100°C) and low (<600°C) [8, 9] temperatures. In the former case, the magnetic iron oxides can form in a single domain state (<1  $\mu\text{m}$  particles) above the Curie temperature giving rise to high magnetic remanence [10].

The correlation between the proportion of Fe in olivine and magnetic phases is not observed directly in the data from Mars (see e.g. the data from [4] based on the analysis of the 14.4 keV b-MS). The Mössbauer data from Mars shows a pronounced difference between the 14.4 keV spectra and the 6.4 keV spectra (cf. Figure 2a). The effect must be caused by variations in the mineralogy in the surface layer on the scale of tenths of micrometer. Generally, all rock targets, untreated surfaces, brushed or abraded, show the same characteristics. The difference can be characterised by the area ratio between olivine and pyroxene, showing enhancement of olivine in the surface layer of the rocks. For soils, the difference is less pronounced.

This characteristic difference is of importance for the conclusions that can be drawn from this work. First of all, the true bulk Mössbauer spectrum of the rock can be extrapolated from the measurements by subtracting the results of the analysis of the 6.4 keV spectra from the analysis of the 14.4 keV spectra, obtaining for the component labelled  $c$ :  $A_{\text{int}}(c) = (A_{14.4 \text{ keV}}(c) - k \cdot A_{6.4 \text{ keV}}(c)) / (A_{14.4 \text{ keV}}(\text{tot}) - k \cdot A_{6.4 \text{ keV}}(\text{tot}))$ , where  $A$  is the area of the respective spectra. With  $k=0.48$  the results shown in Figure 2c have been obtained for the rock target Mazatzal, where

five measurements were performed. Also shown in the figure are results obtained from 14.4 keV spectra of soil samples where we have assumed that part of the Fe(III) component originates from olivine. These findings support the assignments of components and are at variance with suggestions that the spectra are dominated by hydrous iron sulphates [11].

The surface olivine enhancement observed in the Mars spectra resembles that observed in terrestrial samples when comparing CEMS (sensitive to  $\sim 0.25 \mu\text{m}$ ) and transmission Mössbauer spectra of olivine basalt oxidised at high temperatures [7, 12]. In the latter the altered olivine crystals have lost their mechanical strength, and during sample grinding, they get overexposed in the surface layers [7]. In the Mars spectra the most probable explanation is that the rattling of the samples cuts through the weaker olivine crystals, while the more robust pyroxene crystals are removed as whole. The resulting surface layer will have higher olivine/pyroxene ratio than the rock as a whole. This observation indicates that the olivine crystals have been altered at high temperatures, a process known to lead to formation of highly magnetic rocks on Earth.

The fact that even untreated surfaces show the same effect, indicates that the weathering of these rocks is of mechanical nature.

The oxidation of the olivine in the rocks from Iceland is probably of low temperature origin. This is seen in the morphology of the olivine crystals [12] which shows more similarities with low temperature experiments [9] than high temperature experiments [8] and in the ratio of the olivine/pyroxene ratio between CEMS and transmission Mössbauer measurements (on the average 1.4 in spectra of the HRI series but up to 3 in highly magnetic olivine basalt [12]). The resulting remanence pr. weight percentage of highly magnetic phases of the HRI samples is likewise of the order of 1–4 A/m compared to  $\sim 20$  A/m for highly magnetic olivine basalt [7]. If the rocks at Gusev crater had solidified in an external magnetic field of terrestrial magnitude ( $\sim 50 \mu\text{T}$ ) they would have acquired magnetic remanence of the order of  $\sim 40$  A/m. Such rocks can easily explain the magnetic anomalies on Mars.

It has been shown, that olivine basalt can become an order of magnitude more magnetic than olivine poor basalt [7] due to high temperature oxidation of olivine during the solidification of the lava. The results from this work suggest that a major part of the magnetite found in the rocks at Gusev crater has formed in this way. For this to be true, the basalt must have had a high volatile content to drive the oxidation and this is corroborated by microscope images that show abundant vesicles and vugs, suggesting eruptive flows with high volatile content [13]. The rocks at the Gusev landing site have been reported to be considerably weaker physically than typical fine grained basalt [14] based on the grinding energy needed for the rattling. One possibility to explain this is that the weakening of the material as a whole is caused by weakening of the olivine component due to high temperature oxidation.

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