

## ANALYSIS OF 6.4 KEV MÖSSBAUER SPECTRA OBTAINED WITH MIMOS II ON MER ON COBBLES AT MERIDIANI PLANUM, MARS AND CONSIDERATIONS ON PENETRATION DEPTHS.

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**Introduction:** The miniaturized Mössbauer (MB) spectrometers MIMOS II [1] on board of the two Mars Exploration Rovers Spirit and Opportunity have obtained more than 600 spectra of more than 300 different rock and soil targets [2-7]. Both instruments have simultaneously collected 6.4 keV X-ray and 14.4 keV  $\gamma$ -ray spectra in backscattering geometry [1]. With Spirit's MB spectrometer, 6.4 keV and 14.4 keV spectra have been obtained for all targets through sol 461. After this date, only 14.4 keV spectra were collected. With Opportunity's spectrometer, 6.4 keV and 14.4 keV spectra have been collected for all targets to date. The Fe-mineralogy of rock and soil targets at both landing sites reported to date has been exclusively extracted from 14.4 keV spectra [2-5]. The comparison of 6.4 keV and 14.4 keV spectra provides depth selective information about a sample, but interpretation is not always straightforward [8].

**Penetration depths of MB radiation:** For the interpretation of depth selective MB spectra, knowledge about the penetration depth of 6.4 keV and 14.4 keV MB radiation is very important. Of special interest is the maximum thickness of a surface layer which allows the detection of a substrate at the detection limit of 2%. If a  $\gamma$ -ray with incident intensity  $I_0$  penetrates a sample with thickness  $x$ , the intensity  $I(x)$  is given by: 
$$I(x) = I_0 \cdot e^{-\mu \cdot x} \quad (1)$$

The absorption coefficient  $\mu$  can be calculated for different photon interaction processes (here: photoelectric effect, Compton- and Rayleigh scattering, and resonant absorption through the Mössbauer effect). For Fe, non resonant 6.4 keV and 14.4 keV absorption coefficients are rather similar, but can be an order of magnitude larger for 6.4 keV for other elements (e.g. Si).

Measurements on a layered sample composed of 50  $\mu\text{m}$  Fe foil on top of a hematite substrate yield subspectral areas of hematite of 1% in the 6.4 keV and 3% in the 14.4 keV spectrum. A pure Fe layer with a thickness of 50  $\mu\text{m}$  can therefore be regarded as having the maximum thickness which allows the substrate to be resolved in MB spectra. The maximum thickness increases with decreasing Fe-content. Equation 1 can be used to calculate the  $\gamma$ -ray intensity after passing through a layer. MIMOS II measures spectra in backscattering geometry, so that photons pass the surface layer twice before reaching the detectors. Attenuation processes on the way in and out of the sample must be

taken into account. With  $I_0$  set as 100%, the calculated intensity after passing through 50  $\mu\text{m}$  Fe foil is 0.78% for 14.4 keV  $\gamma$ -rays and 0.60% for 6.4 keV X-rays. These values can be used to estimate the maximum thickness of surface layers with other compositions.

We calculated maximum thicknesses for two different surface layers. For a surface layer composed of hematite ( $\text{Fe}_2\text{O}_3$ ) with a density of 5.3  $\text{g}/\text{cm}^3$ , we obtained a maximum thickness of  $\sim 100$   $\mu\text{m}$  for 14.4 keV  $\gamma$ -rays, and a maximum thickness of  $\sim 90$   $\mu\text{m}$  for 6.4 keV X-rays. For a surface layer of basaltic composition, a simplified model of 20 wt% FeO and 80 wt%  $\text{SiO}_2$  with a density of 3  $\text{g}/\text{cm}^3$  was used. We calculated a maximum thickness of  $\sim 530$   $\mu\text{m}$  for 14.4 keV  $\gamma$ -rays, and a maximum thickness of  $\sim 130$   $\mu\text{m}$  for 6.4 keV X-rays. These values are consistent with earlier results [1, 9], where a layer with maximum sampling depth is defined as a layer absorbing 95% of the incident radiation, taking into account an experimental setup in backscattering geometry as described above. With this approach, Morris et al. calculate a maximum sampling depth of  $\sim 200$   $\mu\text{m}$  (14.4 keV  $\gamma$ -rays) for a sample of basaltic composition [9].

The calculations discussed above are in agreement with results obtained from laboratory measurements: Figure 1 shows spectra obtained on a sample composed of 500  $\mu\text{m}$  Ortenberg basalt [10] on top of 50  $\mu\text{m}$  Fe foil. The 14.4 keV spectrum shows a clear signature of the Fe sextet, the area percentage is 4%. While the penetration depth in a certain surface layer does of course not change, the visibility of the substrate depends on the Fe content: if the substrate is not pure Fe, it is harder to detect or not visible at all. 6.4 keV spectra obtained on either 300  $\mu\text{m}$  or 500  $\mu\text{m}$  basalt on top of Fe foil do not show a definite Fe signature (area percentage less than 1%).

**Spectra obtained on cobbles at Meridiani Planum:** In this section, 6.4 keV and 14.4 keV spectra obtained on seven cobbles along Opportunity's traverse will be discussed. Cobbles at Meridiani Planum appear to have a variety of different origins [11].

*BounceRock (Sols 66-70):* Spectra obtained on the abraded surface of BounceRock reveal two pyroxene phases in both the 6.4 keV and the 14.4 keV spectrum without any nanophase ferric oxide (npOx) present. Spectra obtained on the undisturbed surface reveal an enrichment of npOx in 6.4 keV spectra. Additionally, a

magnetic phase is present in the 6.4 keV spectrum obtained on the spot “Fips2” (sol 68) (Fig. 1). This points to the existence of a surface layer on BounceRock, in which npOx and the magnetic phase are enriched.

*Barberton (Sol 121), and SantaCatarina (Sol 1047)*: Barberton was classified as a stony meteorite [12]. The 14.4 keV spectrum reveals a composition of 46% olivine, 35% pyroxene, 5% npOx, and 15% kamacite pointing to its meteoritic origin. In comparison, the 6.4 keV spectrum shows a slight depletion of kamacite (10%) along with an enhancement of olivine (48%) and npOx (7%). Barberton was too small to be brushed, so these differences probably result from soil contamination on its surface.

On SantaCatarina, spectra were obtained on the undisturbed, but relatively dust free surface [12]. This brecciated cobble is chemically similar to Barberton with 52% olivine, 26% pyroxene and 14% npOx from the 14.4 keV spectrum. Instead of kamacite, troilite (7%) is present in this rock. The 6.4 keV spectrum shows a slight enhancement of olivine (57%) and a slight depletion of pyroxene (22%), similar to what has been observed in 6.4 keV spectra obtained on Adirondack-class rocks [8]. These differences might result from the brecciated nature of SantaCatarina.

*HeatShieldRock (Sols 348-351)*: HeatShieldRock was classified as an iron meteorite. A coating, probably a remnant of a fusion crust, is visible in Pancam spectra [12]. MB spectra obtained on the undisturbed as well as on the brushed surface show mostly kamacite with very little npOx. The 6.4 keV spectrum obtained on the brushed spot shows less npOx (2%) than the corresponding 14.4 keV spectrum (4%). As the instrument’s field of view contained both coated and uncoated portions of the surface [12], this suggests that

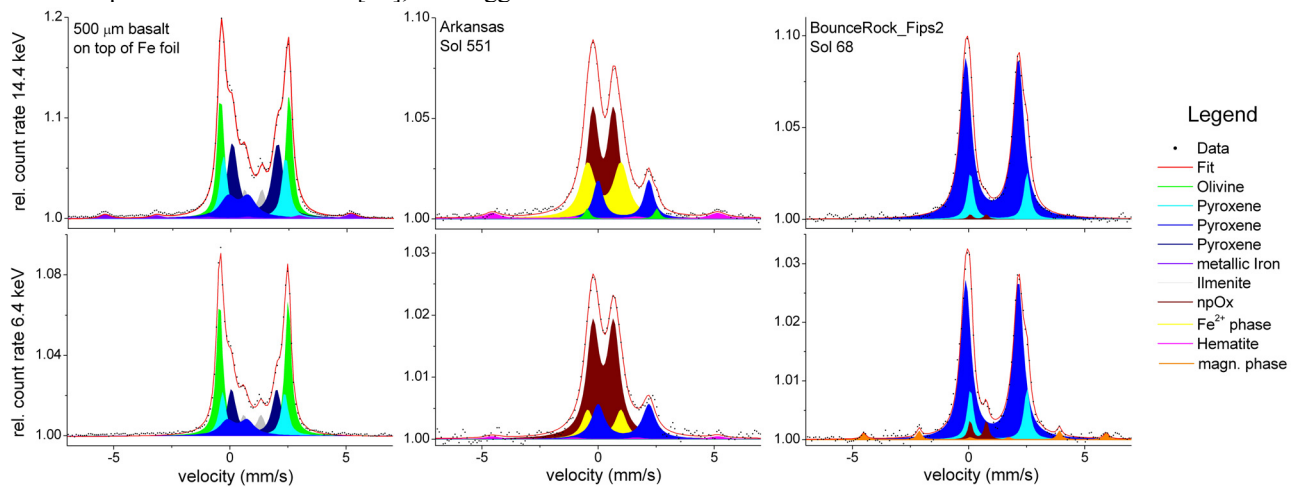
npOx does not stem from the coating, but rather from the rock itself.

*Arkansas (Sol 551) and Antistasi (Sol 641)*: The 14.4 keV spectrum obtained on Arkansas shows 3% olivine, 16% pyroxene, 41% npOx, 7% hematite and 34% of an additional  $\text{Fe}^{2+}$  phase (Figure 1). The 6.4 keV spectrum shows a significant enhancement of npOx (56%) and depletion of the  $\text{Fe}^{2+}$  phase (16%). The  $\text{Fe}^{2+}$  phase is probably a primary phase in the rock which is altered to npOx at the surface. Antistasi is composed of 19% olivine, 54% pyroxene and 12% npOx according to the 14.4 keV spectrum. An additional  $\text{Fe}^{2+}$  phase (12%) and a magnetic phase (3%) are also present. The 6.4 keV spectrum shows a slight enrichment of olivine (22%) and npOx (16%), and a depletion of the  $\text{Fe}^{2+}$  phase (6%). Because the target was not brushed, either soil contamination or minor alteration may account for these differences.

*JosephMcCoy (Sol 887)*: The 14.4 keV spectrum obtained on JosephMcCoy reveals 39% olivine, 38% pyroxene, and 23% npOx. The 6.4 keV spectrum is very similar with 36% olivine, 39% pyroxene and 25% npOx, consistent with only minor alteration.

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**References:** [1] Klingelhöfer, G., et al. (2003) *JGR* 108, 8067. [2] Klingelhöfer, G., et al. (2004), *Science*, 306, 1740-1745. [3] Morris, R.V., et al. (2006a), *JGR*, 111, E02S13. [4] Morris, R.V., et al. (2006b), *JGR*, 111, E12S15. [5] Morris, R.V., et al. (2008), *JGR*, to be submitted. [6] Squyres, S. W., et al. (2004), *Science*, 305, 842. [7] Squyres, S.W., et al. (2006), *JGR* 111, E02S11. [8] Fleischer, I., et al. (2007) *JGR*, submitted. [9] Morris, R.V. et al. (2000), *JGR* 105, E1, 1757-1817. [10] Fegley, B., et al. (1995), *Icarus* 118, 373-383. [11] Jolliff B. et al. (2006) *LPS XXXVII*, 2401. [12] Schröder, C. et al. (2007), *JGR*, in press.



**Figure 1:** left: Backscatter MB spectra obtained on a sample composed of 500  $\mu\text{m}$  basalt on top of Fe foil. Only the 14.4 keV spectrum shows a definite Fe signature. Center: comparison of 14.4 keV and 6.4 keV spectra obtained on the cobble “Arkansas” with a clear enrichment of npOx in the 6.4 keV spectrum. Right: comparison of 14.4 keV and 6.4 keV spectra obtained on “BounceRock”, with a magnetic phase present in the 6.4 keV spectrum.