MAGNETIC ANOMALIES IN ICELAND: IMPLICATIONS FOR THE MAGNETIC ANOMALIES ON MARS. H. P. Gunnlaugsson[1], L. S. Bendtsen[2], P. Bertelsen[2], C. S. Binau[2], J. Gaarsmand[2], W. Goetz[2], Ö. Helgason[3], L. Kristjánsson[3], J. M. Knudsen[1], K. Leer[2], M. B. Madsen[2], P. Nørnberg[4], S. Steinþórsson[3], G. Weyer[1], [1]Department of Physics and Astronomy, Aarhus University, Ny Munkegade, DK–8000 Århus C (hpg@phys.au.dk), [2]Center for Planetary Science, University of Copenhagen, Juliane Maries Vej 30, DK–2100 Copenhagen Ø, Denmark, [3]Science Institute, University of Iceland, Dunhagi 3, IS–107 Reykjavík, Iceland, [4]Department of Earth Sciences, Aarhus University, Ny Munkegade, DK–8000 Århus C, Denmark.

Introduction: Among the major discoveries of the Mars Global Surveyor mission is the finding of strong magnetic anomalies due to crustal remanence [1]. Models suggest magnetic rocks of tenths of km thickness with remanence magnetization up to $M_r \sim 20$ A/m [2], considerably higher than average values for terrestrial mid–ocean ridge basalt (MORB). Although Fe–Ti oxide phases, as in MORBs, are the obvious candidates for explaining the remanence, other mineralogical explanations have been suggested to account for the high remanence in comparison with MORBs. These include hemo–ilmenite [3], multidomain (MD) hematite [4], and pyrrhotite [5], none of which are common explanations for the magnetic properties of igneous rocks.

Aeromagnetic surveys over Iceland have revealed a large number of distinctly localized magnetic anomalies [6,7]. They are less extensive than their Martian counterparts and usually associated with volcanic centers or subglacial volcanism. In some cases, access to the magnetic rocks has been obtained, either through erosion or by drilling.

Given the assumption that the Icelandic anomalies may give hints regarding the origin of magnetism in the Martian anomalies, we have conducted a detailed investigation of the iron mineralogy of samples from two magnetic anomalies in Iceland and one site containing highly magnetic rocks. In this contribution emphasis will be given to the results obtained by means of Mössbauer spectroscopy. The Mössbauer spectra presented here were measured at room temperature in transmission geometry using conventional constant acceleration drive systems. Velocities and isomer–shifts are given relative to the center of the spectrum of α–Fe at room temperature.

Mössbauer spectroscopy is an ideal method to characterize the iron mineralogy of natural samples, giving simultaneously information on the valence state of iron, site symmetry, and magnetic interactions. The shift of resonance lines (relative to a standard) is characteristic for the valence state of iron atoms. Iron atoms in magnetic minerals give rise to a characteristic sextet–type spectrum where the splitting is proportional to the magnetic hyperfine field. Iron in paramagnetic minerals gives rise to a doublet–type spectrum due to quadrupole interactions. The splitting of lines is proportional to the electric field gradient at the iron site. The analysis of a Mössbauer spectrum may be a complicated task. If the iron atoms are situated in an environment characterized by statistical variations of the hyperfine parameters (e.g. in titanomagnetite or titanomaghemite, where the iron atoms have different numbers of Ti or vacancy neighbors), a successful description of the spectrum in terms of assignment of spectral features to specific minerals may be hampered. In basaltic rocks, the magnetic minerals may constitute only a few percent of the spectra, precluding an accurate determination. For this reason, spectra of both bulk samples and magnetic separates are obtained and analyzed simultaneously assuming the presence of the same spectral components, only in different amounts.

Included in the payload of NASA's 2003 Mars Exploration Rover missions (launched in May/June 2003, landing early 2004) [8] are magnets [9] that will accumulate dust for investigations by Mössbauer spectroscopy [10] and APX spectroscopy (elemental analysis) [11]. The results presented here may show how these techniques can work together to determine the mineralogy of the surface material on Mars.

To form a magnetic anomaly ($M_r > 20$ A/m) with rocks of igneous composition (i.e. concentration of Fe ~ 10 wt.%), three criteria must be fulfilled. (1) The rocks must contain single–domain (SD) magnetic particles, or particles with pseudo single–domain (PSD) magnetic properties. (2) The mineral responsible has to be substantially magnetic – titanomagnetite ($Fe_{3-x}Ti_xO_4$) with $x = 0.6$ is usually not magnetic enough to explain the high remanence magnetization of anomalously magnetic rocks. (3) The amount of the magnetic phase in the rocks has to be at least of the order of one wt.%. If only one of these criteria is not fulfilled, the more common situation will be obtained, i.e. $M_r \sim 1–5$ A/m.

The Stardalur Anomaly: The farm Stardalur is located 20 km Northeast of Reykjavík. Aeromagnetic surveys revealed a positive magnetic anomaly, roughly 2×2 km in dimension with surface residual magnetic fields as high as 28 μT. A drilling project was under-

taken in the 70s to get access to the magnetic rocks and seek answers regarding the source of the anomaly [12,13]. The top 41 meters consist of olivine tholeiite lava and breccia of low magnetization. Below are highly magnetic early Quaternary lavas, extending to depths of at least 140 m. The remanence magnetization of these rocks was found to be M_r = 61 A/m on the average. The remanence direction from specimens from over 100 m of drill core was found to vary with a standard deviation of 4°, which is much lower than in other NW–Iceland basalts [13,14]. The magnetic mineral was in all cases determined to be pure magnetite (Fe_3O_4) [15], in submicron solvus–exsolution lamellae together with ilmenite ($FeTiO_3$), originating from solvus–exsolution of the original titanomagnetite [12]. The rocks were found to contain a rather large amount of iron (~12 wt.% Fe), still not anomalous, but the Mössbauer spectra (see fig. 1) show an unusually high fraction of the iron in the magnetite phase, of the order of 30%, while 2–5% is a more usual finding.

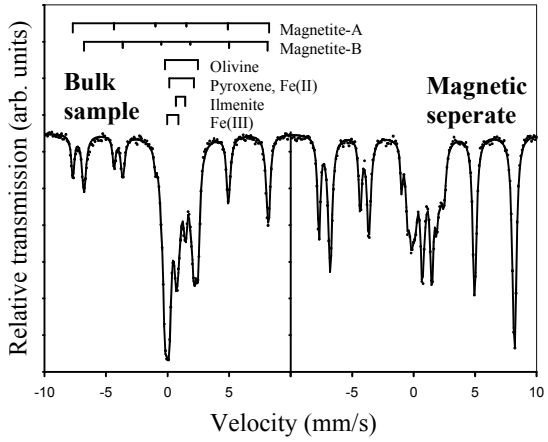

Fig. 1. Mössbauer spectra of a bulk sample and magnetic separate of a sample from the Stardalur anomaly (sample STI–60). The solid line shows the sum of the fitting components indicated with a bar diagram on top together with the spectral assignments.

The spectral line at ~ -6.7 mm/s is characteristic for the B sextet of magnetite (Mt–B), originating from Fe(II) and Fe(III) on octahedral sites, rapidly exchanging an electron resulting in one sextet component. The presence of this sextet–component implies the presence of the A–line of magnetite (Mt–A) originating from Fe(III) atoms on tetrahedral sites in magnetite. This component is seen in Fig. 1 with slightly higher magnetic hyperfine field than the B–component. For pure magnetite, the area ratio between the Mt–A sextet and the Mt–B sextets is close to ½. The center part of the spectrum is fitted with lines assigned to paramagnetic minerals, such as Fe(II) in pyroxene $(Fe,Mg)Si_2O_6$, olivine $(Fe,Mg)_2SiO_4$ and ilmenite. Additionally, the spectrum is fitted with a component assigned to paramagnetic Fe(III) mineral(s). Most likely, this is Fe(III) in pyroxene, but the hyperfine parameters are consistent with numerous mineral forms of Fe(III)–containing oxidation products, such as chlorite and illite. The hyperfine parameters and relative spectral areas are given in Table 1.

Table 1: Hyperfine parameters obtained from simultaneous analysis of the spectra of the Stardalur sample STI–60. Columns 2–4 show the values of the magnetic hyperfine field, isomer–shift and quadrupole splitting/shift, and the last two columns show the area fractions in the spectra of the bulk and magnetic separates, respectively.

Spectral Comp.	B_{hf} (T)	δ (mm/s)	ΔE_Q (mm/s)	A_b (%)	A_m (%)
Mt–A	49.4(2)	0.28(2)	<0.02	31(2)[a]	64(2)[a]
Mt–B	46.2(2)	0.68(2)	<0.02		
Olivine		1.13(3)	2.69(6)	16(1)	7(1)
Pyrox.		1.15(4)	2.02(7)	22(1)	7(1)
Ilmenite		1.06(3)	0.74(6)	8(1)	13(1)
Fe(III)		0.42(6)	0.9(2)	23(2)	9(2)

[a]Total spectral area of magnetite

The hyperfine parameters are in good agreement with their assignments (see e.g. [16]). The ilmenite fraction increases in the magnetic separate, indicating that it is found in close intergrowths with the magnetic phase. Combining the results from Mössbauer spectroscopy with the results from magnetization measurements ($\sigma_{S,rock}$ = 5.2(2) Am^2/kg, M_r ~ 60 A/m) and elemental analysis (11.9(4) wt.% Fe), we find the saturation magnetization of the magnetite to be 100(4) Am^2/kg, in rough agreement with theoretical values, and the remanence magnetization of the magnetite to be 1164(70) A/m (STI–60). It is assumed in these calculations that the iron in the different minerals has the same recoil–free fraction or Debye–Waller factors. For iron containing rock–forming minerals the recoil–free fractions are similar, and measurements at low temperatures (not shown) ensure that there are no missing fractions in the room temperature measurements.

The Stardalur rocks contain unusually high amount of magnetite. However, this alone does not explain the remanence found. Most likely, the rocks at Stardalur have been exposed to geothermal annealing at temperatures above the Curie temperature. This has led to solvus–exsolution of the original titanomagnetite resulting in the highly magnetic mineral magnetite with PSD magnetic properties. How the solvus–exsolution has led to the pure form of the magnetite and absence

of other oxidation products is a very interesting question, which we will not attempt to answer here.

The Bolungarvík rocks: The site called Bolungarvík is situated in the Tertiary part of Iceland, mainly built up of flood basalts representing the oldest exposed rocks in Iceland (14–16 M.y.).

During field work at the mountain Traðarhyrna close to the village Bolungarvík, samples were taken from 26 lavas (no. 26 on top) and investigated for their magnetic properties and remanence direction (L. Kristjánsson, private communication). Samples from three of these lavas were found to be unusually highly magnetic (M_r up to ~60 A/m). Fig. 2 shows representative Mössbauer spectra of samples from one of the lavas.

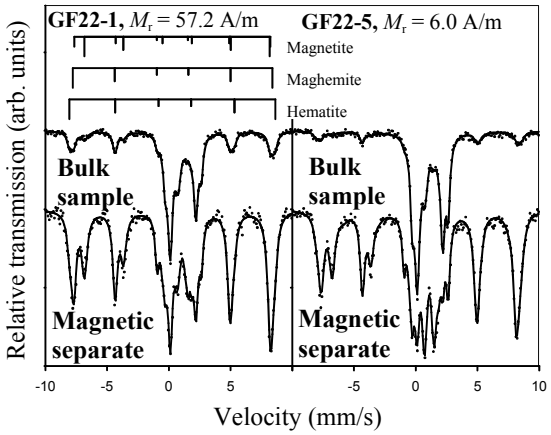

Fig. 2: Mössbauer spectra of two samples from Bolungarvík. The solid line shows the sum of the fitting components. The bar diagram shows line positions for the sextet components.

The main difference of the spectra in comparison to the spectra of samples from Stardalur is seen at negative velocities as a difference in the area ratio between the A and B sextets. This is caused by the presence of both hematite (α–Fe_2O_3) and fully oxidized titanomaghemite (γ–$Fe_{8/3-4x/3}Ti_xO_4$) [18]. Fully oxidized titanomaghemite in Icelandic basalts has been shown to form as an oxidation product of titanomagnetite $Fe_{3-x}Ti_xO_4$ with $x > 0.2$ while the oxidation of pure magnetite favors the formation of hematite [17]. The Mössbauer spectra of the two additional minerals are rather similar, but hematite shows a quadrupole shift (ΔE_Q = -0.2 mm/s) while titanomaghemite may be assumed to have only a small quadruple shift ($|\Delta E_Q| <$ 0.05 mm/s) due to the cubic structure of the Fe sites. Inserting these values as constraints in the simultaneous analysis of the spectra, meaningful results are obtained. The same paramagnetic minerals are found in the spectrum as in the case of the STI–60 sample.

Apart from few samples containing titanomagnetite ($x > 0.2$) and of low remanence, the samples from Bolungarvík can be roughly subdivided into two groups depending on their Mössbauer spectra and magnetic properties. (A) Samples containing fully oxidized titanomaghemite, almost pure magnetite ($x <$ 0.05) and hematite, but with low remanence intensities (<10 A/m). (B) Samples like (A), but with high remanence (>20 A/m). The Mössbauer spectra of the latter samples show generally larger peaks for the magnetic sextets, and less ilmenite than in the spectra of samples (A). This is easily seen, when comparing the spectra of the magnetic separates in Fig. 2, where the quadrupole split lines of ilmenite dominate the center part of the spectrum of the sample with low remanence.

This may suggest the following hypothesis for the origin of the magnetism in the samples. Storage at temperatures below 200°C for millions of years, leads to the solvus–exsolution of titanomagnetite to ilmenite/magnetite structures. If, however, the rocks are exposed to a high temperature event, the formation of fully oxidized titanomaghemite and magnetite takes place, as has been demonstrated in annealing experiments [17]. Both processes are known to lead to PSD magnetic properties, but the latter one has taken place at temperatures above the Curie temperature of the original titanomagnetite, leading to a realignment of the magnetic moment. There are no signs of hydrothermal activity in the area, and possibly lightning strikes could be an explanation for the annealing event.

It is not possible to state here with confidence, which of the magnetic minerals is responsible for the high remanence magnetization. However, combining the results from Mössbauer spectroscopy with measurements of magnetic properties and elemental analysis, an average over the magnetic oxides in the strongly magnetic samples gives a value of M_r ~ 1270(80) A/m (GF22–1).

The Kjalarnes anomaly: About 15 km north of Reykjavík, just outside the Kjalarnes peninsula, an aeromagnetic survey has revealed a strong negative magnetic anomaly [19]. The residual magnetic field 900 m above the surface is as strong as -3.8 μT. Onshore, highly magnetic intrusive rocks are found (M_r as high as 50 A/m).

The Mössbauer spectra of samples from Kjalarnes are very different from the spectra of the samples from both Stardalur and Bolungarvík (see Fig. 3). The sextet component shows broad lines with reduced magnetic hyperfine field indicating a distribution in Fe environments, hampering a detailed analysis of the Mössbauer spectra. Still, the average valence state of iron in the magnetic phase can be estimated to be $Fe(III)_{sextet}/Fe(tot)_{sextet}$ = 0.67(5), and the area fraction, or the relative concentration of Fe in the magnetic phase can be estimated (here 33(2) %).

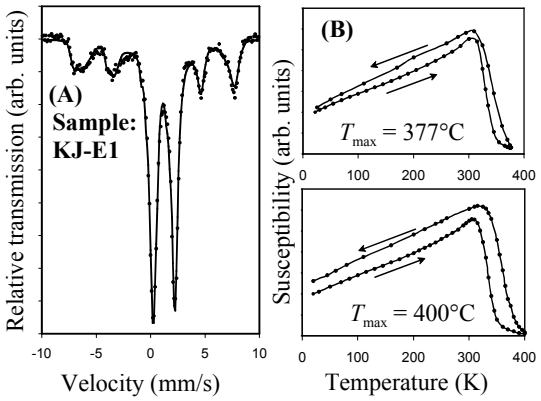

Fig. 3: (A) Mössbauer spectrum of a sample from Kjalarnes (KJ–E1). The solid line shows the sum of the fitting components. (B) Curie temperature determination.

A possible explanation for the spectral shape could be that the magnetic phase is titanomaghemite (not fully oxidized), and this is supported by X–ray diffraction results, which show the presence of a spinel phase and the absence of a rhombohedral phase (hematite). Attempts to obtain a magnetic separate by crushing the samples down to an average particle size ~ 50 μm and applying a hand magnet proved only moderately successful (increase in the spectral fraction of sextets by ~10%). This suggests small (micrometer–sized) particles of the titanomaghemite, as confirmed by inspection with an optical microscope. The Curie temperature (see Fig. 3) is found to be 350(50)°C, giving the Ti/Fe ratio of 0.25(5) using lattice parameter/Curie temperature diagrams (see e.g. [20]). Combining these findings with the results of the elemental analysis and the magnetic properties measurements, it is possible to estimate the saturation magnetization of the magnetic phase to be σ_S = 33(4) Am^2kg^{-1} and the remanence magnetization of the spinel phase to be M_r = 1035(90) A/m (KJ–3). The samples from Kjalarnes show rather poor thermal stability, and this is readily seen in the Curie temperature determination, where the Curie temperature increases upon annealing. Therefore, it seems rather unlikely that the rocks have been subjected to an annealing event, and more likely that the rocks solidified under oxidizing conditions. All these results suggest that the magnetism of the samples is due to SD titanomaghemite.

Discussion: The features common to the anomalous rocks in the present study are: Unusually high concentration of spinel phases in the rocks, and remanence magnetizations of the magnetic phases of the order of 1000 A/m. Only 2 wt.% of such material is needed to explain the remanence properties of the Martian crust, a value not too different from the findings in the SNC meteorites [21]. At least two different processes seem to lead to the formation of highly magnetic rocks. High–temperature oxidation of the magma prior to or during quenching, leading to the formation of SD titanomaghemite (Kjalarnes) or annealing of the lava above the Curie temperature (Stardalur, Bolungarvík). Which of these processes is a better candidate for the interpretation of events on Mars cannot be answered here. Kjalarnes seems to offer the simpler explanation, where the formation of the anomaly has taken place in a single process. However, the annealing hypothesis is not an unlikely scenario. The thickness of the crustal rocks that give rise to the anomalies on Mars may offer the necessary clue. The rocks have probably solidified deep below the surface, at temperatures above the Curie temperature. The slow cooling has then led to the annealing situation that may have given the rocks their PSD magnetic properties.

Conclusions: Three magnetic anomalies in Iceland have been studied. The carrier of the remanence magnetization is in all cases Fe–Ti oxide phases. Only 2 wt.% of the magnetic material is needed to explain the magnetic properties of the Martian crust.

Acknowledgement: Support from the Danish Natural Science Research Council is gratefully acknowledged. T. Anhøj at the Technical University of Denmark is acknowledged for experimental help.

References: [1] Acuña M. H. et al. (1999) *Science*, 284, 790–793. [2] Purucker M. et al. (2000) *Geophys. Res. Lett.*, 27, 2449–2452. [3] Robinson P. et al. (2002) *Nature*, 418, 517–520. [4] Kletetschka, G. et al. (2000) *Phys. Earth Planet. Int.*, 119, 259–267. [5] Rochette P. et al. (2001) *Earth Planet. Sci. Lett.*, 190, 1–12. [6] Sigurgeirsson Th. (1970) *Science in Iceland*, 2, 13–20. [7] Jónsson G. et al. (1991) *Tectonophysics*, 189, 229–247. [8] Squyres S. et al. (2003) *JGR* (Submitted). [9] Madsen M. B. et al. (2003) *JGR* (Submitted). [10] Klingelhöfer G. et al. (2003) *JGR* (Submitted). [11] Rieder R. et al. (2003) *JGR* (Submitted). [12] Steinþórsson S. and Sigvaldason G. E. (1971) Report, Science Inst., Univ. Iceland. [13] Friðleifsson I. B. and Kristjánsson L. (1972) *Jökull*, 22, 69–78. [14] Kristjánsson L. (1970) *Earth Planet. Sci. Lett.*, 8, 101–108. [15] Helgason Ö. et al. (1990) *Hyp. Int.*, 57, 2209–2214. [16] Greenwood N. N. and Gibb T. C. (1971) *Mössbauer spectroscopy*, Chapmann and Hall Ltd, London. [17] Gunnlaugsson H. P. et al. (2000) *Planet. Space Sci.*, 50, 157–161. [18] Steinþórsson S. et al. (1992) *Mineral Mag.* 56, 185–199. [19] Kristjánsson L. et al. (2003) *Náttúrufræðingurinn,* 71*,* (in press). [20] Weixin X. et al. (1996) *Geophys. Res. Lett.*, 23, 2811–2814. [21] Dodd R. T. (1981) *Meteorites*, Cambridge Univ. Press.