Hyperfine Interact (2012) 208:91–94
DOI 10.1007/s10751-011-0417-2

Mössbauer study of the Ordinary-Chondrite meteorite Thylacine Hole–001

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Published online: 26 October 2011

Abstract The Thylacine Hole–001 meteorite was recovered from the Nullarbor Desert (Australia) in 1977 and is an Ordinary Chondrite, Group H4/5br, which has undergone moderate to severe (B/C) weathering. We have characterised the Fe-bearing phases in Thylacine Hole–001 by ^{57}Fe Mössbauer Spectroscopy at 300 K, 100 K, 50 K and 4 K. The spectrum at 300 K is dominated by the paramagnetic doublets of Olivine, Pyroxene and a Ferric component which is most likely nanoparticulate Goethite. Magnetically split sextets due to Maghemite or Magnetite are also present, consistent with the relatively advanced terrrestrial age of 28,500 yrs The nanoparticulate Goethite component shows a blocked, magnetically split sextet at low temperatures. We also observe the effects of magnetic ordering of the Olivine and Pyroxene below 50 K.

Keywords Meteorite · Mössbauer spectroscopy

1 Introduction

The Ordinary Chondrites account for about 87% of all known meteorites recovered on Earth and are well suited to study by ^{57}Fe Mössbauer Spectroscopy as they contain significant amounts of Fe (as Fe^0 and Fe^{2+}), bound up mainly in silicates (Olivine, Pyroxene), Fe(Ni) metal (Kamacite, Taenite) and sulphides (FeS Troilite). In this paper, we use ^{57}Fe Mössbauer spectroscopy carried out over the temperature range

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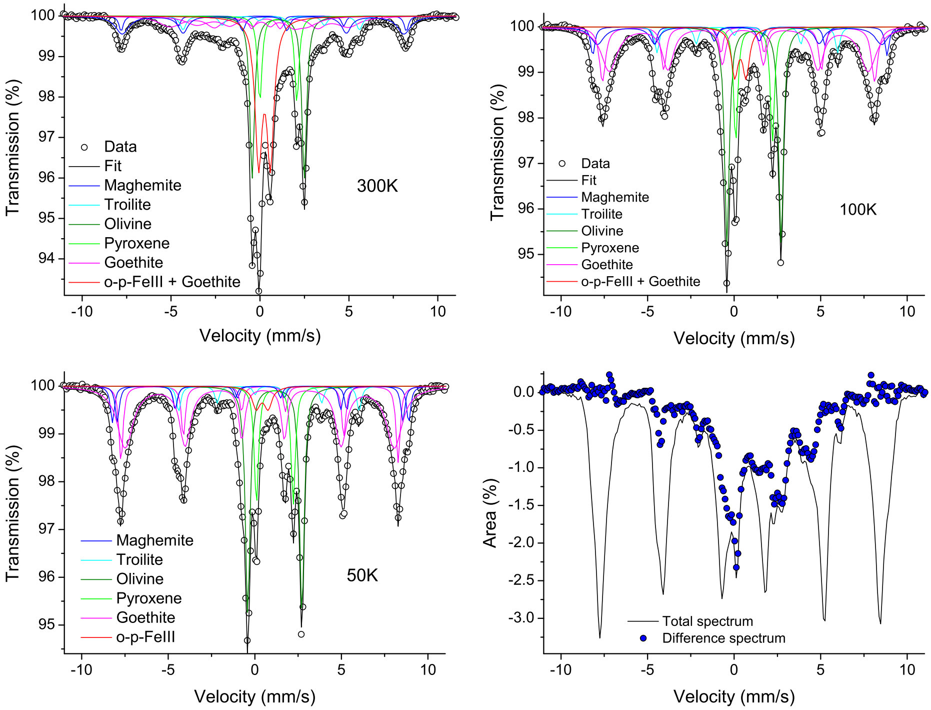

Fig. 1 The ^{57}Fe Mössbauer spectra of Thylacine Hole–001, collected at 300 K, 100 K, 50 K and 4 K. In the case of the 4 K spectrum, we show the full experimental spectrum as a *black*, *continuous line*, and the residual spectrum, after stripping the well-split magnetic components due to Maghemite and Goethite, as *blue dots*

4–300 K to study the Thylacine Hole–001 meteorite which was found in 1977 in the Nullarbor Desert region of Australia at the coordinates 31° 35′ S, 127° 36′ E [1]. Thylacine Hole–001 is classified as a brecciated H4/5 ordinary chondrite 'find' with medium to severe weathering (weathering grade B/C). Chemical analysis gave a Fayalite ($[Mg,Fe]_2SiO_4$) content of 19.7 mol.% and a Ferrosilite ($[Mg,Fe]_2(SiO_3)_2$) content of 17.6 mol.% [2]. Its 'terrestrial age' has been estimated at greater than 28,500 yrs [3]. The aim of this study is to quantify the relative amounts of Fe^{2+}/Fe^0 and Fe^{3+} present in this weathered meteorite to provide data crucial to the investigation of terrestrial weathering processes.

2 Experimental Methods

A small sample of the Thylacine Hole–001 meteorite was provided by Prof. A. Bevan of the Western Australia Museum and is representative of the bulk of the meteorite. Its catalogue number is WAM13428. The Mössbauer sample was prepared by grinding a portion of the meteorite and the absorber had an area density of about 300 mg cm^{-2}. ^{57}Fe Mössbauer spectroscopy was carried out at 300 K, 100 K, 50 K and 4.2 K in transmission mode with a ^{57}Co**Rh** source. All Mössbauer spectra were least-

Table 1 ^{57}Fe Mössbauer parameters for Thylacine Hole–001 (at 300 K)

Component	I.S. (mm/s)	Q.S. (mm/s)	B_{hf} (T)	Area (%)	Assignment
Doublet 1	1.13(2)	2.94(3)	0	20(2)	Olivine $(Mg,Fe)_2SiO_4$
Doublet 2	1.14(2)	2.08(3)	0	10(2)	Pyroxene $(Mg,Fe)SiO_3$
Doublet 3	0.36(2)	0.66(3)	0	26(2)	o-p-Fe^{3+}
Sextet 1	0.80(2)	−0.12(4)	30.9(3)	4(2)	Troilite (FeS)
Sextet 2	0.33(2)	−0.10(3)	49.4(2)	13(2)	Maghemite (γ-Fe_2O_3)
Sextet 3	0.24(2)	0.16(3)	50.0(2)	3(2)	Maghemite (γ-Fe_2O_3)
Sextet 4	0.26(2)	−0.38(3)	31.2(3)	13(2)	Goethite (α-FeOOH)
Sextet 5	0.36(2)	−0.54(3)	19.4(3)	10(2)	n-Goethite (α-FeOOH)

squares fitted using the WMOSS program and all isomer shifts are quoted relative to the α-Fe calibration spectrum.

3 Results and Discussion

The Mössbauer spectra of Thylacine Hole–001 are shown in Fig. 1 and in Table 1 we give the hyperfine parameters for the various spectral components determined at 300 K. The spectrum is dominated by the quadrupole doublets of Olivine (20(2)% area), Pyroxene (10(2)%) and paramagnetic Fe^{3+} (26(2)%), most likely in an octahedral coordination (denoted here as o-p-Fe^{3+}). The Olivine quadrupole splitting of 2.94(3) mm/s allows us to estimate the Olivine composition to be around 30(10) mol%Fa., using the data of Menzies et al. [4]. The rather large o-p-Fe^{3+} content is consistent with the advanced terrestrial age of this meteorite.

The presence of antiferromagnetic Troilite is readily distinguished from other possible magnetic phases with hyperfine fields in the range 30–33 T, such as Kamacite and Taenite, by its large positive isomer shift, indicative of the Fe^{2+} in Troilite. The identification of the magnetic components with hyperfine fields around 49–51 T is not straightforward and we have ascribed them to Maghemite, although one cannot completely rule out the possibility of some form of substituted Magnetite.

The most significant change observed upon cooling to 100 K is the decrease in the sub-spectral area associated with the o-p-Fe^{3+} doublet, from 26(2)% to 7(2)%. This reduction is accompanied by an increase in the area of the magnetically split component with a hyperfine field of 46.6(2) T, which we have ascribed to nanoparticulate Goethite. These data place the blocking temperature of the n-Goethite between 300 K and 100 K. Some Goethite particles are blocked at 300 K. In Tables 2 and 3 we give the hyperfine parameters for the various spectral components, determined at 100 K and 50 K, respectively.

A comparison of the spectra acquired at 50 K and 4 K shows the disappearance of the sharp paramagnetic doublets associated with Olivine and Pyroxene, indicating that these two components order magnetically below 50 K. The magnetic ordering of both Olivine and Pyroxene has been reported in [5, 6] and a ^{57}Fe Mössbauer study of ordering in Olivine has been published by de Oliveira et al. [5]. The magnetically split spectra are quite complex and to illustrate this effect we show in Fig. 1 the residual absorption in the 4 K spectrum, after stripping the well-split components due to Maghemite and Goethite.

Table 2 ^{57}Fe Mössbauer parameters for Thylacine Hole–001 (at 100 K)

Component	I.S. (mm/s)	Q.S. (mm/s)	B_{hf} (T)	Area (%)	Assignment
Doublet 1	1.25(2)	3.12(3)	0	21(2)	Olivine $(Mg,Fe)_2SiO_4$
Doublet 2	1.26(2)	2.12(3)	0	10(2)	Pyroxene $(Mg,Fe)SiO_3$
Doublet 3	0.46(2)	0.66(3)	0	7(2)	o-p-Fe^{3+}
Sextet 1	0.90(2)	−0.06(4)	32.5(3)	5(2)	Troilite (FeS)
Sextet 2	0.34(2)	0.14(3)	51.2(3)	9(2)	Maghemite (γ-Fe_2O_3)
Sextet 3	0.44(2)	0.00(3)	53.0(2)	5(2)	Maghemite (γ-Fe_2O_3)
Sextet 4	0.48(2)	−0.22(3)	49.0(2)	14(2)	Goethite (α-FeOOH)
Sextet 5	0.49(2)	−0.24(3)	46.6(2)	29(2)	n-Goethite (α-FeOOH)

Table 3 ^{57}Fe Mössbauer parameters for Thylacine Hole–001 (at 50 K)

Component	I.S. (mm/s)	Q.S. (mm/s)	B_{hf} (T)	Area (%)	Assignment
Doublet 1	1.26(2)	3.12(3)	0	21(2)	Olivine $(Mg,Fe)_2SiO_4$
Doublet 2	1.26(2)	2.12(3)	0	10(2)	Pyroxene $(Mg,Fe)SiO_3$
Doublet 3	0.53(2)	0.68(3)	0	3(2)	o-p-Fe^{3+}
Sextet 1	0.93(2)	−0.02(4)	32.5(3)	4(2)	Troilite (FeS)
Sextet 2	0.35(2)	0.12(3)	51.4(3)	6(2)	Maghemite (γ-Fe_2O_3)
Sextet 3	0.45(2)	0.02(3)	53.3(2)	6(2)	Maghemite (γ-Fe_2O_3)
Sextet 4	0.50(2)	−0.24(3)	49.9(2)	12(2)	Goethite (α-FeOOH)
Sextet 5	0.49(2)	−0.20(3)	48.5(2)	38(2)	n-Goethite (α-FeOOH)

4 Conclusions

We have identified the Fe-bearing phases in the ordinary chondrite meteorite Thylacine Hole–001 by ^{57}Fe Mössbauer spectroscopy. The principal components are Olivine, Pyroxene, Maghemite, n-Goethite and Troilite. We have also observed the effects of magnetic ordering of the Olivine and Pyroxene phases below 50 K.

Acknowledgements JMC is grateful for support from the Canada Research Chairs programme. Financial support for parts of this work was provided by NSERC (Canada). We are grateful to the Western Australia Museum for providing the Thylacine Hole–001 sample. Finally, JMC acknowledges many useful discussions with P.A. Bland.

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