

# Mössbauer Study of Weathered H-meteorite from the Desert of Oman

Ahmed D. Al-Rawas<sup>1,5,\*</sup>, Abbasher M. Gismelseed<sup>1</sup>, Subhi Nasir<sup>2</sup>, Ali A. Yousif<sup>1</sup>, Mohamed E. Elzain<sup>1</sup>, Hisham Widatallah<sup>1</sup>, Ali Al-Kathiri<sup>3</sup>, Susan Al-Riyami<sup>4</sup>

<sup>1</sup>Department of Physics, College of Science, P.O. Box 36, PC 123, Al-Khoud, Muscat, Sultanate of Oman; <sup>2</sup>Department of Earth Sciences, College of Science, SQU Box 36, PC 123, Sultanate of Oman; <sup>3</sup>Directorate General of Commerce and Industry, Ministry of Commerce and Industry, Salalah, Oman; <sup>4</sup>The Research Council, P.O. Box 92, Muscat 123, Sultanate of Oman; <sup>5</sup>Present Address: Dhofar University, P.O. Box 2509, PC 211, Salalah, Sultanate of Oman. \*Email: arawas@squ.edu.om.

**ABSTRACT:** A number of meteorites from the desert of Oman, classified as H-chondrites, with known and unknown ages, were studied by using <sup>57</sup>Fe Mössbauer spectroscopy to determine their Fe<sup>3+</sup>-bearing compositions. Mössbauer spectra measured at 78 K were composed of paramagnetic doublets superimposed on magnetic sextets. The doublets are assigned to the silicate minerals olivine and pyroxene and Fe<sup>3+</sup> phases. The magnetic sextets in most samples showed the presence of at least three magnetic phases, namely troilite, magnetite and kamacite, which commonly exist in most ordinary chondrites. The relative amounts (area %) of Fe<sup>3+</sup> in the known-age meteorites, determined from the Mössbauer spectra, were plotted against their terrestrial ages. The plot was used to estimate the terrestrial ages of meteorites with unknown terrestrial age.

**Keywords:** Oman meteorites; Mössbauer spectroscopy; Terrestrial age; Meteorites weathering.

دراسة موسباور لنيازك كوندريتية H ذات تجوية تم العثور عليها في صحراء عمان

أحمد الرواس، أبشر قسم السيد، صبحي ناصر، علي يوسف، محمد الزين، هشام وداعة الله، علي الكثيري و سوسن الريامي

**المخلص:** تمت دراسة عدد من النيازك المصنفة كوندريتية H ذات الأعمار المعلوم وغير المعلوم والتي عثر عليها في صحراء عمان باستخدام مطياف موسباور (Fe 57) لتحديد التركيبات الحاملة ل Fe +3. أطياف موسباور المقاسة عند درجة حرارة 78 كلفن تتكون من ثنائيات منطبقة على سداسيات مغناطيسية. تم تعيين الثنائيات على أنها سيليكات الأوليفين و البيروكسين و أحد 3 +Fe. وأظهرت السداسيات المغناطيسية في معظم العينات وجود ثلاث مكونات مغناطيسية على الأقل، وهي التروليت، الكاماسيت والتي توجد عادة في معظم الصخور الكوندريتية العادية إضافة لسداسيات المغنيتيت الناتجة من التجوية. تم تحديد الكميات النسبية (المساحة%) من 3 +Fe في النيازك معلومة العمر، والتي تم تحديدها من أطياف موسباور، ضد أعمارها الأرضية. تم استخدام المنحنى لتقدير الأعمار الأرضية للنيازك.

**الكلمات المفتاحية:** العمانيّة، مطياف موسباور، العمر.



## 1. Introduction

In recent years, Oman has become one of the world centers of meteorite discovery. The Omani meteorite recovery areas are mainly restricted to the flat carbonate plains and therefore meteorites have had a chance to accumulate over prolonged periods of time. The terrestrial ages of Omani meteorites range from less than 1000 years to more than 50,000 years [1]. The majority of finds are ordinary chondrites (OC) [2]. The ordinary chondrites are divided into three groups, which have different amounts of metal and different amounts of total iron. The groups are named H (high iron), L (low iron), and LL (very low iron), with reference to the meteorite's oxidation state and the amount of total iron they contain [3].

Iron-bearing minerals (kamacite (Fe-Ni), troilite (FeS), olivine (Fe, Mg)<sub>2</sub>SiO<sub>4</sub> and pyroxene (Fe,Mg)SiO<sub>3</sub>) are important constituents of meteorites and can give important information about their type and origin and are important

# MÖSSBAUER STUDY OF WEATHERED H-METEORITE

indicators of the environmental change of the local area since the date of impact. Mössbauer spectroscopy has played an important role in the study and identification of these mineral phases through their Mössbauer parameters derived from the best computer fit [4-6]. Due to its sensitivity to  $\text{Fe}^{3+}$  and  $\text{Fe}^{2+}$  ions, Mössbauer spectroscopy has been particularly useful to study weathering patterns of meteorites [7, 8]. Weathering bearing concentrations have been used to estimate the terrestrial age of L-Chondrite from arid Australian deserts [9], and reveals an initial rapid weathering followed by much slower oxidation. The origin of magnetite is usually due to the length of time a meteorite has spent on the earth's surface. A detailed study of the weathering of ordinary chondrites in Oman [1] demonstrated the correlation of weathering parameters with terrestrial age.

Mineral analysis, classification and age determination of DHO787, DHO802 and UaH02 were carried out by the Swiss-Omani team at Bern University, Switzerland [1, 10]. Mineral analyses for DHO1670 and DHO1895 were carried out at Stuttgart University using the wavelength-dispersive system of a CAMECA SX100 electron microprobe. X-Ray analysis was carried at Sultan Qaboos University [11, 12] (Table 1).

**Table 1.** Data information of classification, petrographic weathering grades and carbon terrestrial ages of the studied meteorites.

Name	Classification	Weathering Grade	Age (kyrs)
DHO787	H4	W4	19.6
DHO802	H6	W2	17.8
UaH2	H3	W1	9.4
DHO1670	H4	W3	unknown
DHO1895	H5	W2	unknown

In this paper, we aim to find the degree of weathering by using Mössbauer spectroscopy on ordinary H-chondrites found in the desert of Oman. The Fe-weathering products formed were used to estimate the unknown terrestrial ages of DHO1670 and DHO1895 meteorites.

## 2. Experimental

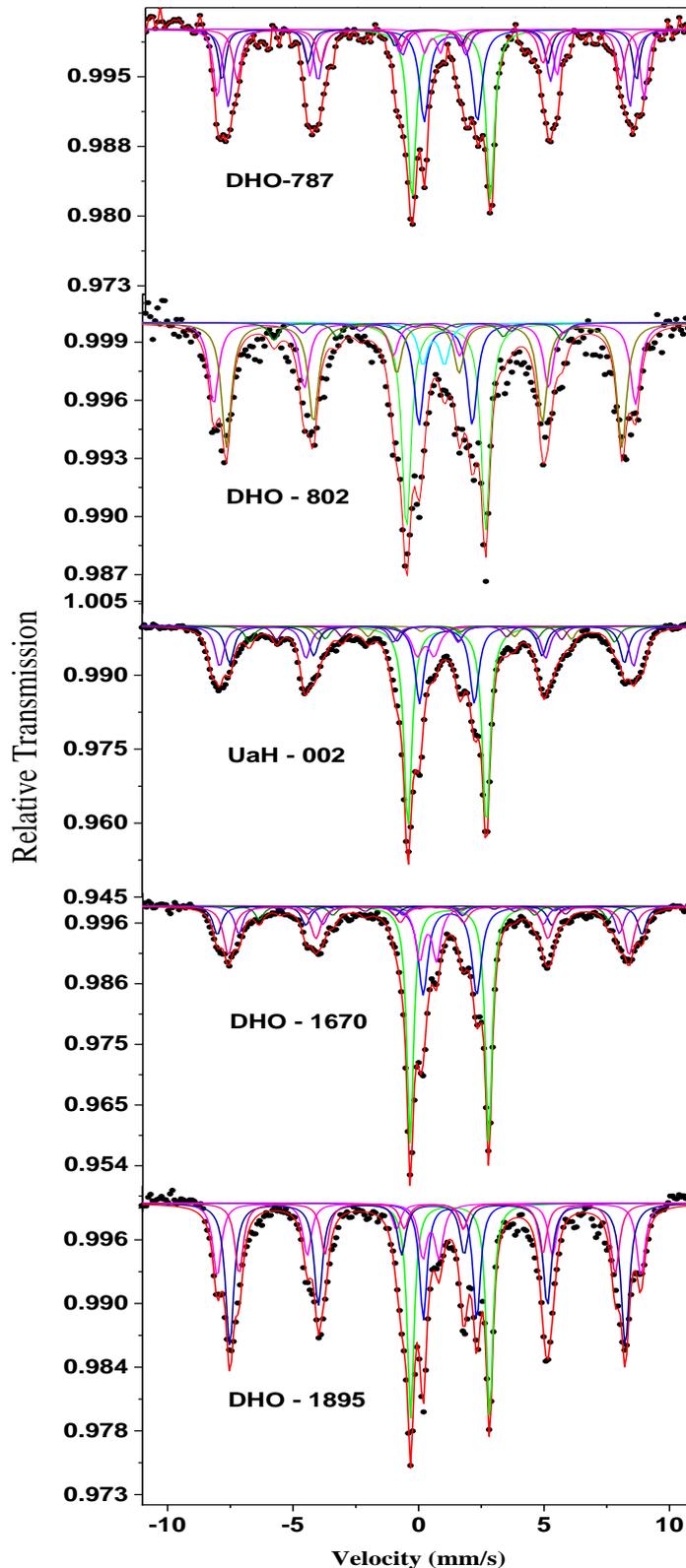
Samples of five meteorites were prepared for Mössbauer analysis in such a way that the fusion crust and the inner core were well mixed. Mössbauer spectra were taken at 78 K for all five samples employing transmission geometry using a 50 mCi,  $^{57}\text{Co}/\text{Rh}$  source at Sultan Qaboos University. A spectrometer interfaced to a PC was used for collecting the data. The data were fitted by selecting the positions and intensities of the Lorentzian lines; all other parameters were kept fixed. The center shifts of the doublets were then fitted assuming no coupling to the splitting. Finally, the width of the Lorentzian components was fitted. All parameters were allowed to vary during the final fits. Isomer shifts (IS) are referred to  $\alpha\text{-Fe}$  at 300 K.

## 3. Petrography

The studied meteorites consist of 50-60 vol% chondrules, 20-30 vol% matrix, and 5-10 vol% metals/opaque minerals. Chondrules display porphyritic olivine or pyroxene, barred olivine and cryptocrystalline texture. The chondrule mineralogy is mainly olivine and orthopyroxene; however, the cryptocrystalline chondrules contain inclusions of pigeonite, augite, and metal. The matrix is recrystallized, transparent, and some grain sizes are visible. The diameter of the chondrules range between 0.7-0.8 mm. Cracks, or veins, with altered material occur throughout the whole thin sections. Many of the silicate grains have acquired a reddish, yellowish colour. Small cracks go through both chondrules and individual grains. Only a few olivine grains appear to show undulose extinction. Some chondrules have a thin rim while others have a thick rim. The weathering has not influenced the silicates to any significant degree. Heavy oxidation of metals and sulfides, abundant Fe-oxide veinlets, and dominant rusty-staining of the specimens indicate moderate weathering (W2 to W3). The sample contains abundant irregular and planar fractures, a few undulatory extinction, opaque shock veins and some weakly mosaic olivine, indicating shock stage S3 to S4.

## 4. Results and Discussion

The Mössbauer spectra collected from the five meteorite samples viz. DHO787, DHO802, UaH02, DHO1670 and DHO1895, at 78 K are presented in Figure 1. All spectra depict the existence of central doublets flanked by magnetic sextets. The best fits to all Mössbauer spectra were obtained using three doublets and several magnetic components. A summary of the Mössbauer hyperfine parameters of the different spectral components and the minerals assigned to them are given in Table 2.



**Figure 1.** Mössbauer spectra of ordinary Chondrites DHO787, DHO802, UaH02, DHO1670 and DHO1895 measured at 78 K.

The Mössbauer parameters of the central doublets are consistent with those reported in the literature for olivine pyroxene and superparamagnetic ultrafine particles containing  $\text{Fe}^{3+}$  with blocking temperature below 78 K [4-10]. Accordingly, the isomer shifts in the range of 1.26-1.29 mm/s and the quadrupole splitting of the first doublet in the range of 3.11-3.16 mm/s are attributed to olivine [9]. The isomer shifts and quadrupole splittings of the second doublet in the ranges of 1.23-1.29 mm/s and 2.13-2.20 mm/s, respectively, are consistent with those reported for pyroxene [9]. The third doublet with isomer shifts and quadrupole splittings in the ranges of 0.40-0.76 mm/s and

## MÖSSBAUER STUDY OF WEATHERED H-METEORITE

0.40-0.86 mm/s, respectively, are consistent with those reported for superparamagnetic particles such as  $\alpha$ -FeOOH(Goethite)  $\beta$ -FeOOH (Akaganite)  $\gamma$ -FeOOH (Lapidocrocite) [13]. The spectral area percentages show variations spanning between 18-32 % for olivine, 10-15 % for pyroxene and 3-9 % for ultrafine particles containing Fe<sup>3+</sup>.

**Table 2.** The Mössbauer parameters for DHO787, DHO802, UaH02, DHO1670 and DHO1895 measured at 78 K.

Name	$\delta$ ( $\pm 0.05$ ) mms <sup>-1</sup>	QS ( $\pm 0.01$ ) mms <sup>-1</sup>	B ( $\pm 1$ ) (T)	A ( $\pm 1$ ) (%)	Components
DHO787 [1]	1.28	3.16	-	23	Olivine
	1.26	2.13	-	14	Pyroxene
	0.53	0.63	-	02	Fe <sup>3+</sup>
	0.44	-0.06	48	14	$\alpha$ -FeOOH
	0.51	-0.06	53	16	$\gamma$ -Fe <sub>2</sub> O <sub>3</sub>
	0.53	-0.11	50	20	Magnetite (B)
	0.37	0.03	52	11	Magnetite (A)
DHO802 [1]	1.26	3.16	-	22	Olivine
	1.24	2.13	-	12	Pyroxene
	0.80	-0.10	29.9	03	Troilite
	0.18	-0.10	32.7	05	Kamacite
	0.76	0.86	-	05	Fe <sup>3+</sup>
	0.46	-0.15	49.0	32	$\alpha$ -FeOOH
	0.44	-0.08	52.3	21	$\gamma$ -Fe <sub>2</sub> O <sub>3</sub>
UaH002 [10]	1.29	3.11	-	29	Olivine
	1.29	2.14	-	15	Pyroxene
	0.95	0.02	31.8	09	Troilite
	0.18	0.00	33.3	07	Kamacite
	0.45	0.69	-	05	Fe <sup>3+</sup>
	0.50	-0.04	50.6	16	$\alpha$ -FeOOH
	0.52	0.04	52.7	07	$\gamma$ -Fe <sub>2</sub> O <sub>3</sub>
	0.68	-0.04	46.8	08	Magnetite (B)
0.34	0.04	48.2	04	Magnetite (A)	
DHO1670 [11]	1.26	3.13	-	32	Olivine
	1.23	2.19	-	12	Pyroxene
	0.78	-0.07	33.4	06	Troilite
	0.03	-0.10	34.5	05	Kamacite
	0.50	0.47	-	08	Fe <sup>3+</sup>
	0.48	-0.07	49.4	15	$\alpha$ -FeOOH
	0.46	-0.02	52.3	10	$\gamma$ -Fe <sub>2</sub> O <sub>3</sub>
	0.52	-0.09	46.5	11	Maghemite
DHO1895 [12]	1.26	3.15	-	18	Olivine
	1.26	2.13	-	11	Pyroxene
	0.49	0.65	-	06	Fe <sup>3+</sup>
	0.43	-0.02	52	16	$\gamma$ -Fe <sub>2</sub> O <sub>3</sub>
	0.57	-0.13	47	33	Magnetite [B]
	0.36	-0.11	49	16	Magnetite (A)

The parameters are:  $\delta$ : the isomer shift, QS: the quadrupole splitting, B: the magnetic field and A: area percentage

On the other hand, the magnetic components of the spectra (Table 1) have hyperfine parameters comparable to those reported for troilite, kamacite and weathering products magnetite, maghemite,  $\alpha$ -FeOOH, and  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> [7-10]. The magnetic spectral components of the DHO802, UaH02, DHO1670 meteorites show the existence of iron sulfide (Troilite FeS) and iron nickel (Kamacite FeNi) phases whose isomer shifts and quadrupole splitting are in good

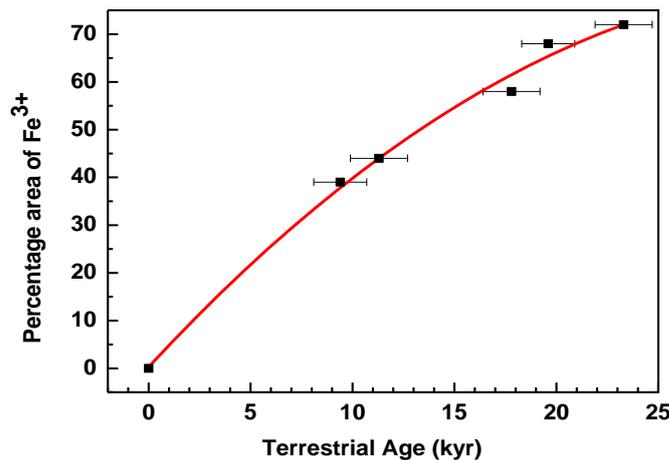
agreement with corresponding literature values [5-10]. The troilite is identified by its hyperfine field and its large isomer shift of  $\sim 0.8$  mm/s while kamacite is distinguished by its isomer shift of  $\sim -0.1$  mm/s. The percent ranges of the troilite and kamacite in the different meteorites' compositions were (3-9%) and (5-7%) respectively. The non-existence of these two minerals in the DHO787 and DHO1895 meteorites could indicate high terrestrial weathering.

As seen from the percentages of the weathering products (Table 2), there exists a good correlation with the weathering grades determined by petrographic and probe analysis given in Table 1 for all samples except that of DHO1895. This particular sample shows a high weathering component (73%) which is not consistent with W2 grade of weathering. The reason could be associated with the sample preparation methods used in the two techniques. While in petrographic analysis only the inner core is probed, for the Mössbauer measurements both the crust and core were mixed. So the DHO1895 apparently has a higher weathering product on the surface relative to the other samples.

The terrestrial age of DHO787, DHO802, UaH02 (Table 1) was plotted against the  $\text{Fe}^{3+}$  percentages in the weathering products determined from the fits of the Mössbauer spectra (Table 2) assuming there was no  $\text{Fe}^{3+}$  (due to weathering) at the time of the impact on earth. The plotted graph shows an almost linear correlation. The fitting curve was used to estimate the terrestrial ages of DHO1670 and DHO1895 that correspond to their  $\text{Fe}^{3+}$  percentages. These were found to be  $11 \pm 2$  kyr and  $23 \pm 2$  kyr, respectively. The almost linear variation of the  $\text{Fe}^{3+}$  percentage with terrestrial age (Figure 2) found for these H-chondrites reflects an almost constant weathering rate. This is to be contrasted with that of L-chondrite [9] where the weathering at the initial stages is faster than later ones. Further studies are required to elucidate this point.

## Conclusion

Mössbauer spectroscopy was used to determine the weathering products of ordinary H-chondrites from the desert of Oman. The terrestrial weathering products were identified. The terrestrial ages of DHO1670 and DHO1895 were estimated using Figure 2 by considering the  $\text{Fe}^{3+}$  area percentages determined from the Mössbauer spectra of DHO787, DHO802 and UaH02, whose ages are known. The ages of DHO1670 and DHO1895 were found to be  $11 \pm 2$  kyr and  $23 \pm 2$  kyr respectively. The rather linear variation of  $\text{Fe}^{3+}$  spectral area with terrestrial age (Figure 2) relative to that of an L-Chondrite [9] reveals their weathering at the initial stages following their fall to the earth. H-Chondrites have higher total Fe concentrations and amounts of metals, which make them more susceptible to faster alteration following their fall.



**Figure 2.** Terrestrial age of DHO787, DHO802, UaH02 against the total percentage area of  $\text{Fe}^{3+}$  weathering products.

## Conflict of interest

The authors declare no conflict of interest.

## Acknowledgment

Many thanks are due to Drs. Beda A. Hofmann and Edwin Gnos, Swiss-Omani Joint project for meteorite research in Oman, for providing DHO787 and DHO802 samples. A.D. Al-Rawas thanks the College of Arts and Applied Sciences at Dhofar University for hosting him for a sabbatical year (September 2018-August 2019) during which the draft of this paper was prepared for publication.

## MÖSSBAUER STUDY OF WEATHERED H-METEORITE

### References

1. Al-Kathiri, A., Hofmann, B.A., Jull, A.J.T., and Gnos, E., *Meteoritics and Planetary Science*, 2005, **40**, 1215.
  2. Norton, O.R., 2002: *The Cambridge encyclopedia of meteorites*. Cambridge University Press UK. 352pp.
  3. Al-Kathiri, A., Studies on Oman Meteorites, *PhD Thesis*, University of Bern (2006).
  4. Knudsen, J.M., *Hyperfine Interactions*, 1989, **47**, 3-31.
  5. Rubin, A.E., *Meteoritics and Planetary Science*. 1997, **32**, 231-247.
  6. Gismelseed, A.M., Bashir, S., Worthing, M.A., Yousif, A.A., Elzain, M.E., Al Rawas, A.D., *Meteoritics and Planetary Science*, 2005, **40**, 255-259.
  7. Bland, P.A., Sexton, A.S., Jull, A.J.T., Bevan, A.W.R., Berry, F.J., Thornley, D.M., Astin, T.R., Britt, D.T., and Pillinger, C.T., *Geochimica et Cosmochimica Acta*, 1998, **62**, 3169-3184.
  8. Bland, P.A., Berry, F.J., Jull, A.J.T., Smith, T.B., Bevan, A.W.R., Cadogan, J.M., Sexton, A.S., Franchi, L.A., and Pillinger, C.T., *Hyperfine Interactions*, 2002, **142**, 481-494.
  9. Cadogan, J.M., Rebbouh, L., Mills, J.V.J. and Bland, P.A. Devlin EJ, *Hyperfine Interactions*, **222**, (Suppl 2):S91-S98, 2013.
  10. Al-Rawas, A.D., Gismelseed, A.M., Yousif, A.A., Elzain, M.E., Worthing, M.A., Al-Kathiri, A., Gnos, E., Hofmann, B.A., and Steele, D.A., *Planetary and Space Science*, 2007, **55**, 859-863.
  11. Meteoritical Bulletin, no. **101**, MAPS 50, 1661, September (2015).
  12. Meteoritical Bulletin, no. **103**, MAPS 52, 1014, May (2017).
  13. Buchwald, V.F. and Clarke, R.S., *American Mineralogist*, 1989, **74**, 657-667.
- 

Received 17 April 2019

Accepted 30 October 2019