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North West Africa stony meteorite: a case study

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Abstract
The present study focusses on a stony meteorite found in the 90's in North West Africa, that has not yet been classified. It was studied by optical microscopy, X-ray fluorescence, X-ray diffraction and Mössbauer spectroscopy. The Fe-bearing phases found by Mössbauer spectroscopy are consistent with the elements found by XRF measurements as well as with phases determined by XRD patterns. The RT spectrum is complex mainly due to the large linewidths of the lorentzians or to the distribution of sites that can obscure the presence of sextets or doublets. From the results obtained the classification of the NWAXX meteorite can be made to an achondrite Winonaite.

Keywords Stony meteorite · Achondrites · Mössbauer spectroscopy

1 Introduction

A stony meteorite was found in North West Africa in the 1990's in the form of many small rock fragments. With the aim of identifying this meteorite, we carried out some physical and

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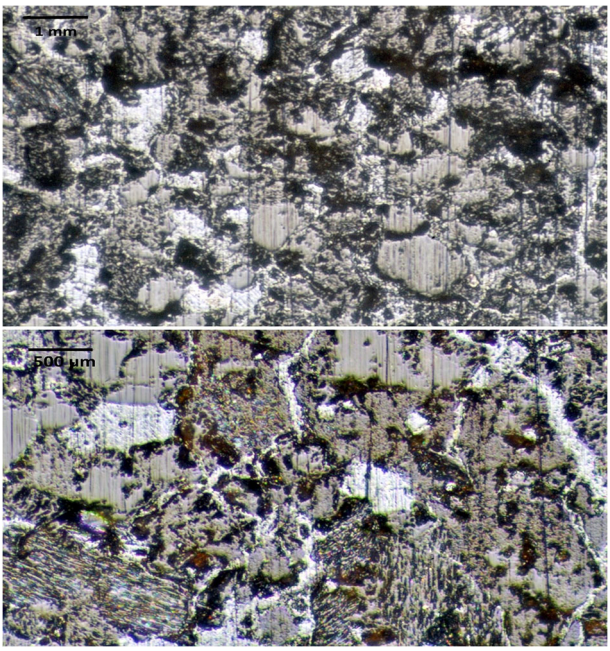

Fig. 1 Optical micrographs of the NWAXX meteorite

chemical characterizations on it. We named the meteorite as NWAXX because it has not been classified yet. The "XX" represents an unknown-as-yet number. Stony meteorites are mainly composed of silicate materials. Additionally, they often contain iron-nickel alloys. They are the most common type of meteorite fall and are divided in two groups, chondrites and achondrites, depending on whether they contain chondrules that are silicate millimetre sized spherules.

We chose several experimental techniques to study the NWAXX meteorite including 57-Fe Mössbauer spectroscopy as it had the potential to contribute a lot in the understanding the meteorite iron mineralogy.

2 Experimental

2.1 Analysis by optical microscopy

Optical microscopy was done with reflected visible light using a *Nikon Optiphot* varying the light source, position of the sample and magnification.

2.2 X-ray fluorescence analysis (XRF)

The sample powder was pressed into a pellet and was analyzed by X-ray fluorescence. The measurements were undertaken in air at atmospheric pressure on a *Hitachi SEA6000VX* bench top high-sensitivity XRF analyzer, with an X-ray tube with a tungsten target, operating at potentials of 15 and 50 kV and a current of 1000 mA, and a 3 mm wide primary-beam collimator. The *SEA6000VX* measurement geometry is fixed, with its energy-dispersive Vortex Si semiconductor

Table 1 Elemental composition of the NWAXX meteorite obtained by XRF analysis. The composition, in wt%, is given relatively to oxygen

Element	Concentration (wt%)	Element	Concentration (wt%)
Mg	22.8(4)	Cr	0.572(7)
Al	5.4(1)	Mn	0.275(8)
Si	24.3(2)	Fe	30.72(6)
P	0.42(4)	Co	0.23(2)
S	1.12(13)	Ni	9.22(1)
Cl	0.023(48)	Cu	0.016(3)
K	0.37(3)	Ga	0.0017(7)
Ca	4.36(5)	Ge	0.0044(6)
Ti	0.171(1)		

detector positioned at a scattering angle of 135° and a distance of 19 mm from the specimen, with no additional slits to restrict its acceptance angle.

2.3 X-ray diffraction (XRD)

XRD was used to identify the crystalline phases of the synthesized nanocomplexes. X-ray diffraction patterns of the samples were obtained by a *Bruker 8D Advance* diffractometer, operating in Bragg-Brentano geometry (θ-2θ), using Cu Kα radiation (λ = 0.154184 nm) and an applied voltage and current of 40 kV and 40 mA, respectively. The data were collected over the range of 5°-120° (2θ), with the step of 0.03° and the recording time of 7 s per step. The phases identification was done using the database ICDD-JCPDS installed on software *DIFFRAC.SUITE EVA*, and analysis of diffractograms was performed with the Pawley method and the software *DIFFRAC.SUITE TOPAS*.

2.4 Mössbauer spectroscopy (MS)

Mössbauer spectra were recorded at room temperature in a *WissEL* spectrometer, using ^{57}Fe as isotope and a source of ^{57}Co (energy of 14.4 keV) in a matrix of Rh with an activity of 25 mCi. The spectra were fitted by a set of Lorentzian lines determined by the least squares method, applying the *NORMOS* program distributed by *Wissel GmbH*. Isomer shifts are given, as usually, relatively to α–Fe measured at room temperature.

3 Results and discussion

The NWAXX fragments have a dark crust but after being crushed the powder reveals a brown-reddish colour. After microscopic investigations, chondrules appear to be absent, so it was tentatively grouped in achondrites meteorites. Figure 1 shows representative micrographs.

The chemical composition, as obtained by XRF, is presented in Table 1. Iron has the highest concentration (30.72(6) wt%) followed by Si and Mg (24.3(2) and 22.8(4) respectively). Ni has a concentration of 9.22(1) wt% which is relatively high for stony meteorites. Al, Ca and S also exist in small amounts. The other elements have much lower concentrations. Weathering can account for the presence of K and Cl.

XRD measurements were done in a qualitative way and from the analysis a sort of more abundant phases can be done. The analysis of XRD patterns shows the presence

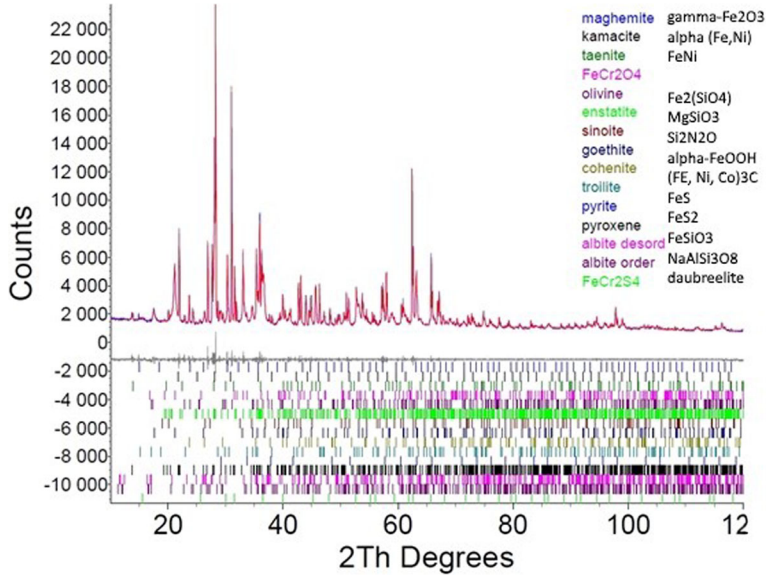

Fig. 2 XRD pattern obtained at RT of the NWAXX meteorite

of several silicates and oxides as well as alloys bearing elements that are in accordance with the XRF elemental analysis. Figure 2 depicts the XRD pattern obtained for the NWAXX meteorite, as well as the analysis performed on it. The phases that exist in largest amounts are kamacite (α-(Fe,Ni)), orthopyroxene ($(Mg,Fe)SiO_3$), troilite (FeS) and pyrite (FeS_2), which bear the elements with highest concentrations. Albite ordered and disordered ($(Na,Ca)AlSi_3O_8$), chromite ($FeCr_2O_4$) and daubréelite ($FeCr_2S_{4)}$ are present in small amounts.

Figure 3 shows the Mössbauer spectrum obtained at RT for the NWAXX meteorite, as well as the fitting done to the spectrum. The obtained hyperfine parameters are presented in Table 2. The spectrum is complicated and the lorentzians that fit it have very large linewidths, revealing a distribution of sites or a certain degree of superparamagnetism.

The fit to the spectrum was done taking into account the mineral phases found by XRD.

After the fitting procedure we found that the magnetic part of the spectrum consists of 7 components and the paramagnetic one of 4 components.

The sextet with the larger B = 47.4 T can be assigned to maghemite. This iron oxide can be found in various stony meteorites [1, 2].

Kamacite that is the bcc phase of Fe-Ni with less than about 8 at% of Ni, exist in large quantity. This metallic phase is a typical component of stony meteorites [1, 2]. Taenite is the Fe-Ni phase with more than 8 at% of Ni, is also present.

Other metallic inclusions as cohenite $(Fe, Ni, Co)_3C$ with B = 20.0 T can be found.

The silicate component of enstatite found by XRD has a small amount of Fe, or none, and is not observed in the Mössbauer spectrum.

Magnetic phases containing sulfur have been identified, as pyrrhotite, $Fe_{0.98}S$, chromium sulfide, $FeCr_2S_4$ and troilite, FeS. Their existence has been identified in several stony meteorites that contain sulfur [3, 4].

In the group of paramagnetic subspectra there are 3 doublets and 1 singlet.

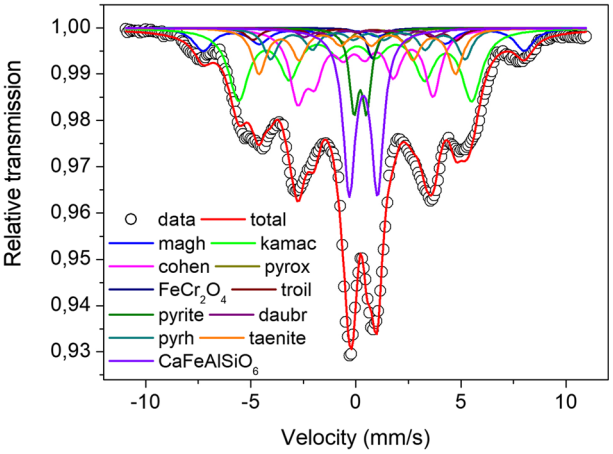

Fig. 3 RT Mössbauer spectrum of the NWAXX meteorite

Table 2 Hyperfine parameters resulted from the fitting procedure of the spectrum showed in Fig. 2. Isomer shifts are given relatively to α-Fe. Literature references [3, 5, 6]

	IS (mm/s)	QS (mm/s)	B (T)	W (mm/s)	%
Kamacite	0.07(1)	0.09(1)	34.4(2)	[1.10]	25
Cohenite	0.28(2)	0.53(2)	20.0(2)	[0.90]	17
$Ca(Mg,Fe,Al)SiO_6$	0.79(1)	1.50(1)		0.70(1)	13
Taenite-ordered	0.05(1)	0.06(1)	29.0(2)	0.80(1)	11
Maghemite	0.20(1)	0.54(1)	47.4(2)	[1.10]	8
Pyrrhotite	0.69(1)	−0.04(1)	28.7(1)	[0.80]	7
Pyroxene	1.01(1)	2.90(1)		0.86(1)	6
Pyrite	0.31(1)	0.61(1)		[0.50]	6
Troilite	0.48(1)	−0.88(1)	30.0(2)	[0.80]	3
$FeCr_2O_4$	0.90(1)			[0.60]	2
Daubreelite	0.71(1)	0.14(1)	19.4(1)	[0.80]	2

IS isomer shift, *QS* quadrupole splitting, *B* hyperfine magnetic field, *W* full width at Lorentzian half maximum, *%* percentage of site

When W was fixed in the fitting procedure its value is represented inside brackets

The main paramagnetic phase is $Ca(Mg,Fe,Al)SiO_6$ with pyroxene structure [3], with about 13% abundance. Other important phase with hyperfine parameters close to the Fe^{3+} silicate is pyroxene Another phase observed in a small amount (6%) is pyrite, FeS_2.

Metallic oxide chromite, $FeCr_2O_4$, is also determined from the fitting procedure, which is common to find in many meteorites.

With the minerals obtained in the XRF, XRD and MS analysis, the group of Winonaites can be assigned to the NWAXX meteorite. Furthermore, the relation of molar Fe/Mn ratio to molar Fe/Mg ratio stay in the range belonging to the Winonaite group in the plot given by Goodrich et al. [6].

4 Conclusions

The present study, of a not yet classified stony meteorite, NWAXX, found in the 90's in North West Africa is the first report on it. The Fe-bearing phases found by Mössbauer spectroscopy

are consistent with the elements found by XRF measurements as well as with phases determined by XRD patterns. The RT spectrum is complex mainly due to the large linewidths of the lorentzians or to the distribution of sites that can obscure the presence of sextets or doublets. To confirm the presence of superparamagnetism a measurement at low temperature is necessary. From the microscopy, XRF, XRD and MS results the classification of the NWAXX meteorite can be made to an achondrite Winonaite. Some more studies need to be conducted in order to completely assign the meteorite to a group.

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