



Magnetic Properties of the Tuxtuac Meteorite via ^{57}Fe Mössbauer Spectroscopy

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Abstract

It has been studied a sample of the Tuxtuac meteorite, which was classified as an ordinary chondrite. It was applied three analytical techniques. Thus, energy dispersive X-ray fluorescence allowed us to identify iron, nickel and cobalt, which form the structure of the kamacite and taenite minerals. Likewise, X-rays diffractometry allowed us to recognize the presence of the structural phases of the silicates olivine, pyroxene and orthopyroxene. Furthermore, ^{57}Fe transmission Mössbauer spectroscopy indicated the presence of two magnetic sextets. One was assigned to troilite and the other, to goethite. After the magnetic separation process, this same technique was used to determine more detailed information about the magnetic minerals present in the sample. This resulted in other two magnetic sextets, which were assigned to kamacite and taenite, respectively. Besides, the presence of goethite in the sample may be the result of chemical weathering.

Keywords: Tuxtuac meteorite, energy dispersive X-ray fluorescence, X-ray diffractometry, ^{57}Fe transmission Mössbauer spectroscopy.

Propiedades Magnéticas del Meteorito de Tuxtuac por Espectroscopia Mössbauer de ^{57}Fe

Resumen

Se ha estudiado una muestra del meteorito de Tuxtuac, clasificada como una condrita ordinaria. Se aplicaron tres técnicas analíticas. Así, la fluorescencia de rayos X por dispersión de energía nos permitió identificar hierro, níquel y cobalto, que forman la estructura de los minerales kamacita y taenita. Asimismo, la difracción de rayos X nos permitió reconocer la presencia de las fases estructurales de los silicatos olivino, piroxeno y ortopiroxeno. Además, la espectroscopia Mössbauer de transmisión con ^{57}Fe indicó la presencia de dos sextetos magnéticos. Uno fue asignado a troilita y el otro, a goethita. Después del proceso de separación magnética, esta misma técnica se utilizó para determinar información más detallada sobre los minerales magnéticos presentes en la muestra. Como resultado, en los respectivos espectros Mössbauer se obtuvieron otros dos sextetos magnéticos, asignados a kamacita y taenita, respectivamente. Además, la presencia de goethita en la muestra puede ser el resultado de la meteorización química.

Palabras clave: Meteorito de Tuxtuac, fluorescencia de rayos X por dispersión de energía, difracción de rayos X, espectroscopia Mössbauer de transmisión con ^{57}Fe .

Introduction

On October 16, 1975, the Tuxtuac meteorite hit the state of Zacatecas, Mexico. The meteorite impact site is approximately located at 21°40' N and 103°22' W [1-3]. As a consequence of the impact, two crusted fragments of 1924 g and 2340 g formed [1]. So far an official abbreviation for Tuxtuac meteorite has not been assigned. Likewise, we must also indicate that the Tuxtuac meteorite is 1 out of 13 reported from Zacatecas and 1 out of

109 reported from the United Mexican States [4-6].

Nowadays, in the Universidad Nacional Mayor de San Marcos, we are consolidating a research group specialized in mineralogical analysis of meteorites. We also intend to attract a good number of undergraduate students interested in researching about meteorites. Consequently, being interested in this space material, we have acquired by donation a sample of this meteorite. Also, we must point out that we have already studied other meteorites specimens. Specifically, we have researched two meteorites.

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One impacted in the surroundings of a Peruvian town called Carancas (in the Chucuito province, the Puno region) on September 15, 2007 [7,8]. The other is a meteorite that impacted in the Peruvian Amazonia; the meteorite owner did not provide us with additional information because we lost touch with him [9].

The driving force to research meteorites is they can be useful or lethal. On the one hand, they are useful because meteorites are solid objects, keeping evidence of past events occurred in our solar system [10]. Meteorites are composed of dust, rock and other space materials, which allowed the origin of the earth and other planets. Consequently, meteorites could have contributed to the origin of life. On the other hand, meteorites can be lethal because geologic studies indicate the happening of events creating enormous craters and, consequently, provoking often biological damages in an irreversible way.

Besides, specifically, the Tuxtuc meteorite is catalogued as a chondrite LL5 [11]. Chondrites were formed by the accumulation of dust particles and sand present in the primitive Solar System. They gave rise to asteroids more than 4 550 Ma ago. Many chondritic asteroids are affected by impact processes due to collisions with other asteroids. These events cause a variety of effects, ranging from simple compaction to brecciation as well as the formation of high pressure minerals [12-14].

Furthermore, from our results of transmission Mössbauer spectroscopy, we could state that there was a transformation from kamacite with cobalt impurities to taenite, i.e., from (γ -FeNi) to (α -FeNi,Co). Kamacite and taenite appear in a typical diagram of temperature vs Ni content. In that diagram it is shown the transformation and nucleation experimented by the nickel grains [15].

The mineralogical characterization of meteorites is very important because it provides us with useful information about the primitive matter of our solar system, the formation processes of asteroids and planets. Likewise, the mineralogical characterization also helps us in the search of our origins.

Materials and Methods

The meteorite sample was donated by a foreigner researcher to the Laboratory of Soils of the Faculty of Physical Sciences at the Universidad Nacional Mayor de San Marcos, which has the Spanish acronym UNMSM. It weighed approximately 1.65 g and was gray in color; besides, it had a fine texture inside and it was compacted on the surface.

Thus, part of the sample was ground in an agate mortar to obtain a fine powder, and then by using magnets it was possible to obtain its magnetic part; consequently, two sub-samples were obtained. We named them Met-Tuxtac and Met-Tuxtac-Mag, respectively.

The used physical techniques were energy dispersive X-ray fluorescence (EDXRF), X-ray diffractometry (XRD) and transmission Mössbauer spectroscopy (TMS) [15-20].

Analysis by energy dispersive X-ray fluorescence (EDXRF)

A portable EDXRF AMPTEK instrument was used to perform the elemental composition analysis. A piece of this instrument is an X-ray tube having a silver cathode, which operated at 30 kV and 30 μ A, approximately. An EDXRF AMPTEK instrument allowed identifying the elements having atomic number Z greater than 12 (that is, greater than magnesium). Table 1 shows the elemental composition. This one was obtained after fitting the experimental EDXRF spectrum with a simulated EDXRF spectrum, which was based on a fundamental parameters model. In Figure 2, in a logarithmic scale, it is shown the experimental spectrum of the Met-Tuxtuc sample.

Table 0: Quantitative elemental analysis of the Met-Tuxtuc sample. We have the chemical elements and the respective concentrations (%).

Al	Si	S	Cl	K	Ca	Ti	Cr
0.00	11.14	0.66	0.00	0.01	0.97	0.00	0.30
Mn	Fe	Co	Ni	Cu	Zn	Ba	
0.33	13.12	0.19	0.57	0.07	0.01	0.15	

Analysis by X-Ray Diffractometry (XRD)

This technique was used to carry out a structural analysis of the minerals present in the Met-Tuxtuc sample. Specifically, it was manipulated a RIGAKU diffractometer, model Miniflex, which used Cu-K α radiation ($\lambda = 1.54178 \text{ \AA}$) as well as a vertical goniometer. The scanned angles were within $4^\circ < \theta < 70^\circ$, being the 2θ advance 0.02° per step with a time interval of 3 seconds per step.

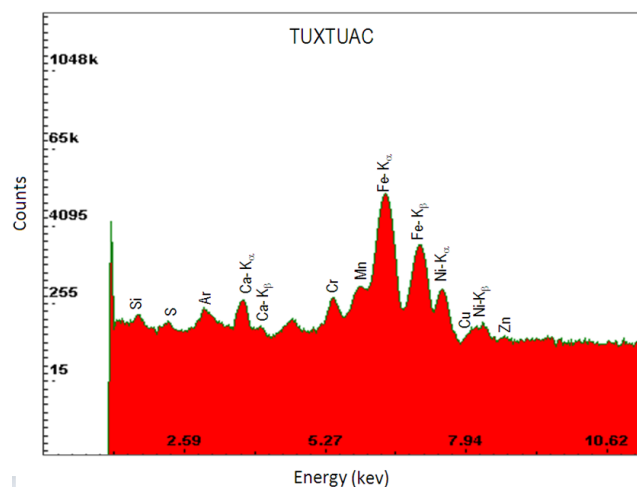


Figure 1: EDXRF experimental spectrum of the Met-Tuxtucac sample. It is a semilogarithmic plot.

Analysis by ^{57}Fe transmission Mössbauer spectroscopy (TMS)

After the aforementioned magnetic separation, ^{57}Fe TMS was used. This isotopically selective technique allowed obtaining more detailed information about the minerals containing iron. It was used a conventional Mössbauer spectrometer having a sinusoidal velocity modulation signal and 1 024 channels. Likewise, the aforementioned spectrometer used a ^{57}Co source in a rhodium matrix; the corresponding spectra were analyzed by using the Normos program in its crystalline sites version (Normos Site) [21]. The Mössbauer spectra of the sample were collected at room temperature (RT) in the Soils Analysis Laboratory, Faculty of Physical Sciences, UNMSM.

Discussion and results

After an analysis by EDXRF of the Met-Tuxtucac sample (Table 1), we have found the presence of the following

elements: Si, S, K, Ca, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn and Ba. The highest concentrations of these elements were as follows: Si (11.14%) and Fe (13.12%); in less quantity, in the following order, we have $\text{Ca} > \text{S} > \text{Ni} > \text{Mn} > \text{Cr}$. The presence of cobalt was found in high percentages and would be present as an impurity in the kamacite mineral. The analysis by XRD revealed several mineral phases such as orthopyroxene ($\text{Mg,Fe}_2\text{Si}_2\text{O}_6$), olivine ($\text{Mg,Fe}_2\text{SiO}_4$), pyroxene ($\text{Mg,Ca,Mn,Fe}_2\text{Si}_2\text{O}_6$), troilite (FeS) and goethite ($\alpha\text{-FeOOH}$) [22-24]. In accordance with Whitney and Evans (2010), the names of these phases were abbreviated Opx, Ol, Px, Tro and Gth, respectively [25]. Thus, in Figure 2, it is observed the presence of the main peaks of olivine and other superimposed peaks between Ol + Opx. At $2\theta = 35.46^\circ$ and from $2\theta = 51.93^\circ$ to $2\theta = 52.22^\circ$, there are wide peaks, with overlapping between the structural phases of Ol + Px + Opx, and only olivine with very wide peaks in $2\theta = 56.47^\circ$. The presence of the goethite phase did not occur with its main characteristic peaks, except in $2\theta = 33.67^\circ$ and $2\theta = 33.77^\circ$, where it appeared superimposed with troilite and olivine, respectively; troilite appeared with its main characteristic peak at $2\theta = 43.19^\circ$.

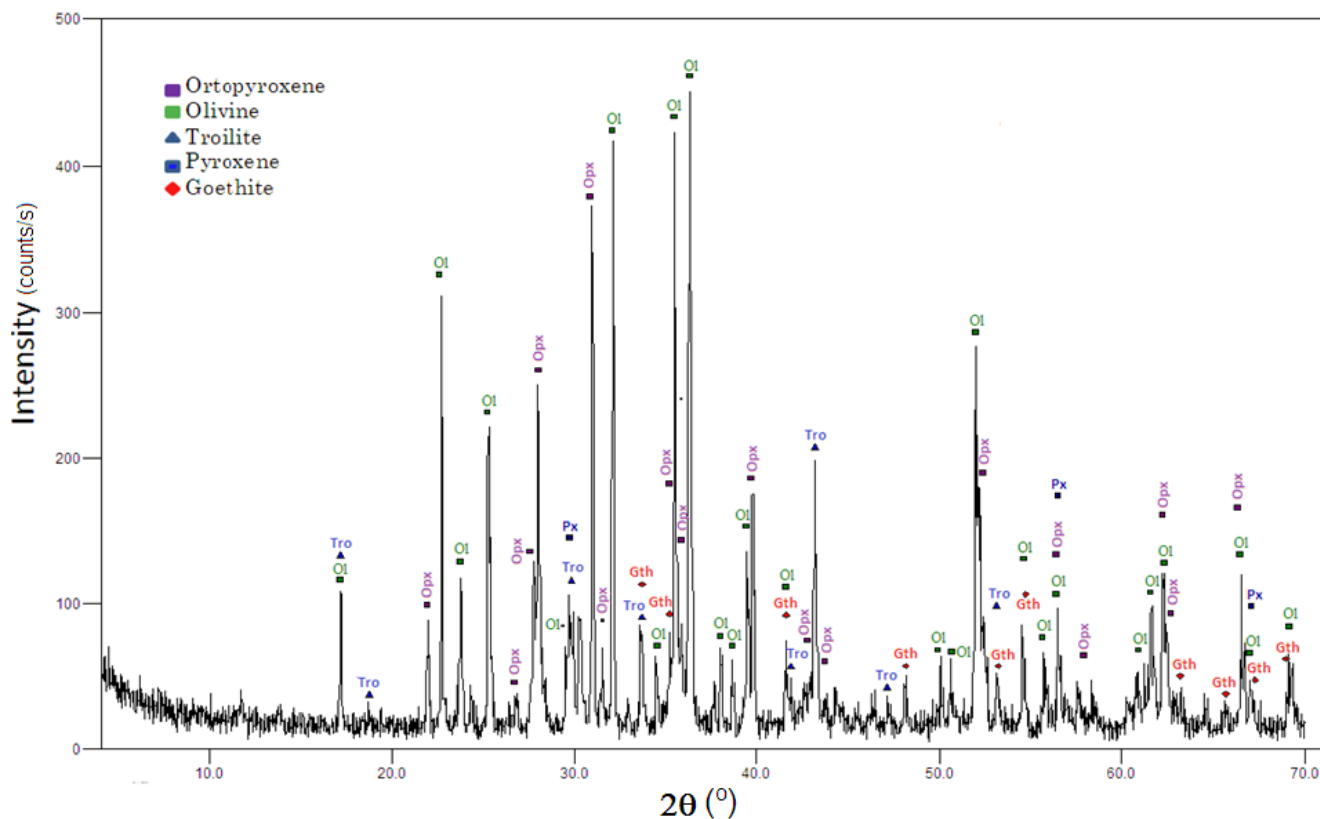


Figure 2: X-ray pattern for the Met-Tuxtucac sample showing reflections of orthopyroxene (Opx), olivine (Ol), troilite (Tro), pyroxene (Px) and goethite (Gth).

Besides, for the Met-Tuxtucac and Met-TuxtucacMag samples, the spectra obtained from TMS can be observed Fig. 3. Meanwhile, for the aforementioned samples, Table 2, shows the hyperfine parameters of the different sub-spectra taken at room temperature.

In the Met-Tuxtucac sample, it was observed the presence of two magnetic sextets (S1 and S2) and three paramagnetic doublets (D1, D2 and D3) [24]. Sextet S1 was assigned to goethite ($B_{hf} = 30.31$ T) and sextet S2, to troilite ($B_{hf} = 31.40$ T). Two out of the three doublets were assigned to Fe^{2+} sites: doublet D1 was assigned to olivine ($(Mg,Fe)_2SiO_4$) and doublet D2, to pyroxene ($(Mg,Ca,Mn,Fe)Si_2O_6$); the third doublet was assigned to Fe^{3+} sites. The presence of goethite could be due to chemical weathering because it is 42 years old and its cations are not inserted in the structure of the sample. Therefore, in order to certify the existence of the magnetic part, it was also carried out the magnetic separation by using ^{57}Fe TMS, which allowed us to determine additional information about the magnetic components. Namely, the found result was only two magnetic sextets we named S3 and S4. Sextet S3 was assigned to kamacite (α -FeNi,Co) with $B_{hf} = 29.84$ T; sextet S4 was assigned to taenite (γ -FeNi) with $B_{hf} = 32.04$ T. Furthermore, concerning kamacite and taenite, the former is a mineral found majorly in meteorites containing nickel-iron metal and the latter is a mineral appearing in the crystallization and structure of iron meteorites [26].

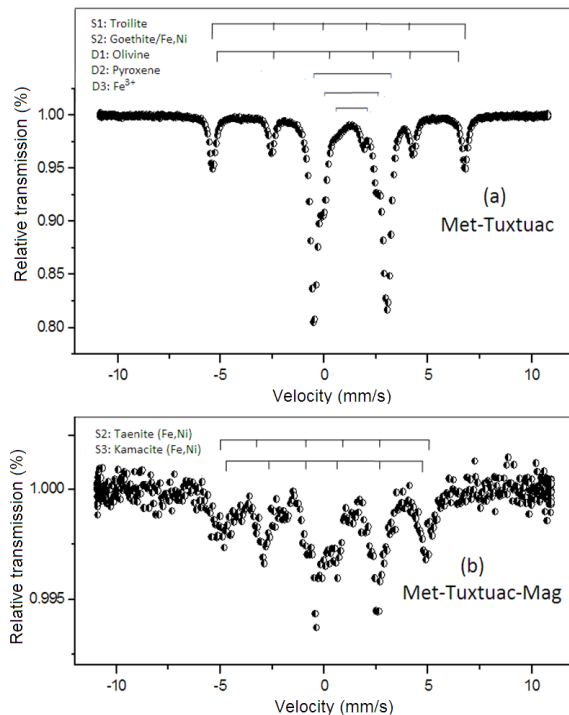


Figure 3: Mössbauer spectrum showing the mineralogical phases for sub-samples Met-Tuxtucac (a) and Met-Tuxtucac-Mag (b).

Table 2: Hyperfine parameters of the two meteorite sub-samples. ISO means isomer shift; QUA, quadrupole splitting; B_{hf} , hyperfine field; and A, relative area.

Mineral Phases	ISO (mm/s)	QUA (mm/s)	B_{hf} (T)	A (%)
Met-Tuxtucac				
Troilite	0.69	-0.18	31.40	18.071
Goethite/FeNi	0.52	-0.43	30.31	7.735
Olivine	1.079	2.93	-	57.353
Pyroxene	1.076	2.10	-	14.825
Fe^{3+}	0.353	0.53	-	2.015
Met-Tuxtucac-Mag				
FeNi/Taenite	-0.144	0.1370	32.024	39.986
FeNi/Kamacite	-0.0546	0.1011	29.840	60.124

Conclusions

The applied analytical techniques allowed obtaining very useful information concerning the Tuxtucac meteorite sample. Concretely, EDRXF allowed identifying iron, nickel and cobalt in different concentrations; these elements are part of the mineralogical structure of kamacite and taenite. Besides, the X-rays diffractometry allowed recognizing the presence of the structural phases of the following silicates: olivine, pyroxene and orthopyroxene, all of them having their main characteristic peaks and their corresponding base width. Thus, it is probable that there was a transformation between $Ol + Opx + Px$; troilite with its main peaks was also observed. However, goethite was observed with superimposed peaks of troilite, $Gth + Tro$.

Finally, the application of the TMS of the Met-TuxtucacMag sample, at room temperature, indicated the existence of two magnetic phases: kamacite with impurities of cobalt (α -FeNi,Co) and taenite (γ -FeNi). This existence was possible because it was a consequence of a transformation of phases occurred inside the meteorite sample cooled after the impact on the Earth' crust.

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