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Characterization of the Carancas–Puno meteorite by energy dispersive X-ray fluorescence, X-ray diffractometry and transmission Mössbauer spectroscopy

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Abstract We report the results of the study of a meteorite that impacted an inhabited zone on 15 September 2007 in the neighborhood of the town of Carancas, Puno Region, about 1,300 km south of Lima. The analysis carried out by energy dispersive X-ray fluorescence, X-ray diffractometry and transmission Mössbauer spectroscopy (at room temperature and at 4.2 K), reveal the presence in the meteorite sample of magnetic sites assigned to taenite (Fe,Ni) and troilite (Fe,S) phases, and of two paramagnetic doublets assigned to Fe^{2+}, one associated with olivine and the other to pyroxene. In accord with these results, this meteorite is classified as a type IV chondrite meteorite.

1 Introduction

On 15 September of 2007 it was reported the impact of a meteorite in the neighborhood of the town of Carancas, Desaguadero, Chucuito Province, Puno Region, near the Bolivian border. One of the authors traveled to this site 4 days later to gather in situ samples of the meteorite and soil inside and outside the crater. The purpose of this work was to characterize the structural properties of these samples applying the analytical techniques available in our Faculty of Physical Sciences-UNMSM such as energy dispersive X-ray fluorescence (EDXRF), X-ray diffractometry (XRD) and particularly transmission Mössbauer spectroscopy (TMS) for being an isotopically selective technique. This impact caused a great explosion and the formation of a crater with approximate dimensions of 20 m in diameter and 3 m in depth. It was also reported the emission of sulfurous gases that irritated the eyes and respiratory organs of the people in the area. Newspapers announced that the fallen object contained radioactive material. To confirm the news a Geiger counter model Radalert 50

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was carried to the site and gave very low readings of 0.030 μS. At the site, the underground water table lies at a depth of about 3 m; therefore, the crater lies partially filled with water.

2 Materials and methods

The collection of the sample used in this study was undertaken 5 days after the meteorite impact. The meteorite sample is grayish and of fine texture, with small surface striates probably related to the impact with the ground. About 180 mg of loose material that separated from the sample was used to prepare the analyte for analysis. This material was grinded in an Agata mortar to a fine 160 μm mesh powder for analysis by XRD and TMS at RT; a pellet was prepared for EDXRF analysis. The TMS spectrum at 4.2 K was taken at CBPF in Brasil using an analyte with a mass of 100 mg from another section of the sample.

2.1 Analysis by energy dispersive X-ray fluorescence (EDXRF)

The elemental composition analysis was performed using a portable EDXRF AMPTEK instrument. This instrument uses an X-ray tube with an Ag anode, that operated at 30 kV and about 30 μA. This instrument allows the identification of elements with $Z > 12$ (magnesium). Figure 1a shows the experimental spectrum and the results of the quantitative analysis are given in Table 1. This was done by fitting the experimental EDXRF spectrum with a simulated XRF spectrum based on the fundamental parameters model. The simulation of the spectra is done by using a program written in FORTRAN It simulates all the physical processes that affect X-rays; production, scattering, absorption and photoelectric production, that take place in an XRF measurement with the used experimental geometry. It uses X-ray cross sections data provided by NIST and atomic characteristic X-ray parameters provided by IAEA. The X-ray distribution function, which includes continuous and discrete components, has been calibrated performing scattering of these X-rays by known samples. The performance of the program has been checked using reference samples. The estimated uncertainty in these measurements of the elemental concentrations is about 10%. Figure 1b shows the fitting of this spectrum of the meteorite sample together with its simulated version in semi logarithm scale (Dr. J.A. Bravo C., private communication) [1].

2.2 Analysis by X-ray diffractometry (XRD)

For the structural analysis of the minerals present in the sample, the XRD technique was applied using a RIGAKU diffractometer, model Miniflex, using Cu–Kα radiation with $\lambda = 1.54178$ Å and a vertical goniometer. The scanned angle interval was $4^\circ < 2\theta < 70^\circ$ and the 2θ advance was of 0.02°/step with a time interval of 3 s per step.

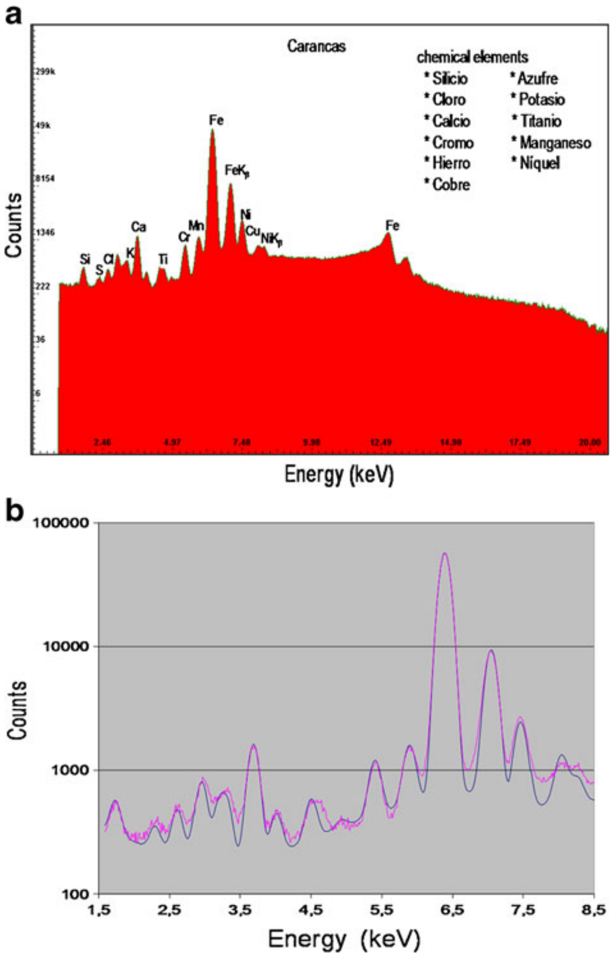

Fig. 1 **a** EDXRF experimental spectrum of the meteorite sample from Carancas- Puno, shown in semi-logarithmic scale. **b** EDXRF experimental spectrum of the meteorite sample shown together with its simulated version in semi-logarithmic scale (Bravo C., J.A., private communication)

Table 1 Quantitative elemental analysis of a meteorite sample from Carancas, Puno

Element	Al	Si	S	Cl	K	Ca	Ti	Cr	Mn	Fe	Ni	Zn	La
Concentration (% weight)	7.5	13.0	0.90	0.90	0.35	0.66	0.04	0.11	0.12	6.00	0.22	0.01	0.10

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

TMS was used to obtain more detailed information about iron containing minerals. A conventional spectrometer was used with a sinusoidal velocity modulation signal and 1024 channels. The Mössbauer spectrum at room temperature (RT) of the sample was collected at the Laboratory of Archaeometry, Facultad de Ciencias Físicas, UNMSM. TMS measurements at liquid helium temperature (LHT) were collected at the Centro Brasileiro de Pesquisas Fisicas (CBPF). A ^{57}Co source in a Rh matrix was used to collect the spectra, which were analyzed using the Normos program by Brand in its crystalline sites version (Normos Site) [2].

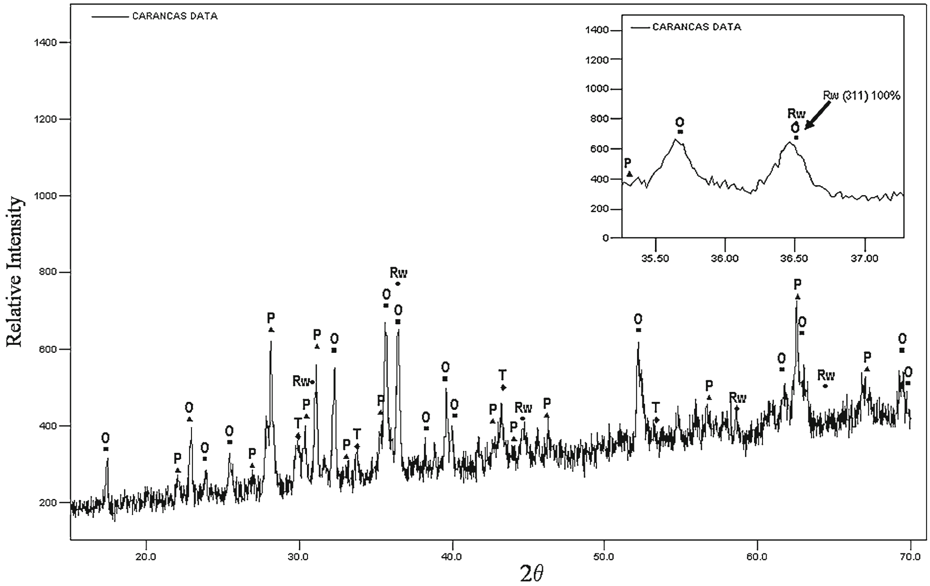

Fig. 2 Diffractogram of the Carancas meteorite sample showing: olivine (*O*), piroxene (*P*), troilite (*T*), and ringwoodite (*Rw*)

Table 2 Hyperfine parameters of the Carancas meteorite sample

MineralPhases	δ (mm/s)	2ε (mm/s)	B (T)	A (%)
	CARANCAS(RT) Total area: 0.33mm/s			
Taenite	−0.10	0.03	33.8	19
Troilite	0.65	−0.16	31.4	17
Olivine	1.04	2.95		43
Pyroxene	1.03	2.09		21
	CARANCAS (LHT) Total area: 0.28 mm/s			
Troilite I	0.73	−0.17	35.7	10
Troilite II	0.60	−1.14	38.6	9
Taenite	0.14	0.16	39.6	4
Tetrataenite	0.00	0.65	34.4	9
Antitaenite S1	−0.06			2
Olivine D1 / Fe^{+2}	1.08	2.44		5
Olivine D2	1.21	3.03		55
Pyroxene D3	1.09	3.40		6

Estimated errors are of about 0.01 mm/s for the isomer, δ, and quadrupole shifts, 2ε, of about 0.1 T for the magnetic hyperfine field, B, and of about 2 % for area values, A

3 Results and discussion

The results of the analysis by EDXRF of the meteorite sample (see Table 1) show the presence of the following elements: Si, Cl, S, K, Fe, Cr, Cu, Ca, Ti, Mn and Ni; with relatively high concentrations of Fe, as well as of S, Cl, Cr and Ni compared to a regular terrestrial soil sample (see Fig. 1a). The XRD results show the presence of

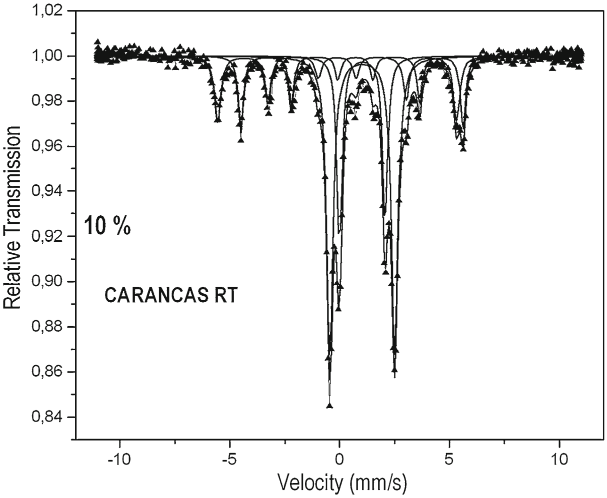

Fig. 3 Mössbauer spectrum of the Carancas meteorite sample taken at room temperature (RT)

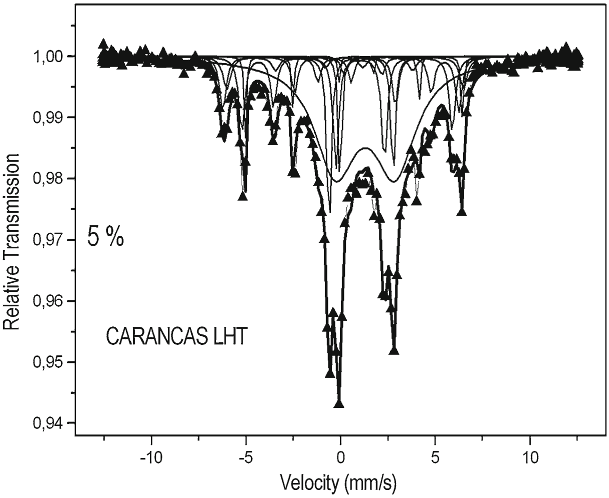

Fig. 4 Mössbauer spectrum of the Carancas meteorite sample taken at liquid helium temperature (LTH)

mineral phases such as troilite (FeS), ringwoodite (Rw, $(Mg, Fe)_2SiO_4$), olivine, and pyroxene as the main mineralogical phases (see Fig. 2).

The origin of Rw (a polymorph of olivine) may be related to the extremely high pressures generated during the impact of a meteorite moving at high speed [3]. Fused materials may be also generated by meteoritic impacts at high speed [4]. The presence of a metastable high pressure mineral, such as Rw, indicates crystallization at pressures between 13 and 23 GPa (maximum pressure generated by the shock wave) [5]. These extremely high pressures are impossible in the crust of the Earth except in the case of meteoritic impacts. Under this hypothesis, it is supposed that the mineral rich in magnesium, precursor of Rw (probably olivine), had previously been part of the meteorite. Since olivine in meteorites is present with three different crystalline structures, it is possible that rhombic olivine transformed into Rw which takes place at pressures between 6 and 16 GPa (depending on Fe content) [6]. The primary mineral quartz (SiO_2) and the Fe oxides and hydroxides are not observed.

Table 2 lists the hyperfine parameters of the different subspectra of the meteorite sample taken at RT and LHT. As shown in Fig. 3 the spectrum taken at RT was fitted by two magnetic sextets, assigned to troilite (FeS) and the Fe–Ni phase (taenite) respectively, and two paramagnetic Fe^{2+}doublets, one associated to olivine $(Fe, Mg)_2SiO_4$ and the other to pyroxene (Mg, Ca, Mn, Fe) Si_2O_6 [7]. In the results of the spectrum taken at LHT (see Fig. 4), it is observed the presence of two ordered magnetic components of Fe^{3+} associated with troilite I and troilite II, and two magnetic sextets attributed to Fe–Ni phases, which may be associated to crystalographically ordered taenite (tetrataenite [8]), with $Bhf = 34.54$ T, and to taenite in a disordered phase, $Bhf = 38.83$ T [8]. A singlet, S1, is assigned to antitaenite. It is known that tetrataenite is believed to be formed when meteorites cool very slowly below 320°C. Antitaenite, as evident from Mossbauer spectroscopy, has never been observed alone in meteorites [9]. In meteorites olivine may appear in three different crystalline structures. From the obtained results, it is probable that due to this fact olivine is observed to be associated to two paramagnetic doublets, D1 and D2 (with large line width). Pyroxene is associated with an Fe^{2+} site and continues appearing as a paramagnetic doublet D3.

4 Conclusions

1. The results obtained from analytical techniques show the merits of these techniques to obtain basic information about the studied sample. This information allowed to classify this meteorite as a type IV chondrite.
2. The analysis by EDXRF allowed to identify the presence of S in relatively high concentration, which was probably the source of reported toxic gases that affected the population of Carancas.
3. The analysis by XRD allowed to identify the presence of the structural phases of olivine and Rw - with a spinel structure with its main peak at (311). The presence of these two phases, olivine and Rw, would indicate that part of the olivine transformed into Rw and that the meteoritic impact generated pressures between 6 and 16 GPa. The presence of Rw is an evidence of the high pressures generated by the meteoritic impact in Carancas-Puno.
4. The analysis by TMS at RT allowed the observation of superposed magnetic and paramagnetic phases. The presence of the magnetic phases of troilite are evident. The Fe–Ni phases may be related to taenite (crystalline and disordered); the singlet S1 may be also related to antitaenite. With these results we have shown the presence of the Fe–Ni phase in the Carancas meteorite. At low temperature it is observed that olivine, which is present as a paramagnetic phase, is associated with two doublets. With the help of XRD it can be shown that one of them is associated to ringwoodite (cubic) and the second doublet may correspond to wadleysite o forsterite. Additional Mössbauer measurements in an applied external magnetic field are required to better resolve the structural phases of taenite.

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