NORMATIVE AND MODAL MINERALOGY IN ORDINARY CHONDRITES: A COMPARATIVE STUDY BETWEEN CHEMICAL ANALYSIS, EPMA, XRD, MÖSSBAUER, FTIR, AND RAMAN SPECTROSCOPY.

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Introduction: Most of the new geochemical data obtained by space missions for planetary bodies are limited to major elements that can be measured remotely, and major rock-forming minerals that can be studied by means of spectroscopic techniques. For this reason, there is renewed interest in bulk major element compositions and mineralogy of meteorites [1], as they serve as reference, well-known planetary materials that can be characterized in detail in the laboratory. Here we use a fresh meteorite fall to compare its normative mineralogy obtained by wet chemical analysis and electron microprobe (EPMA) data, with band areas obtained by a variety of techniques: X-ray diffraction (XRD), Mössbauer spectroscopy, infrared spectroscopy (FTIR), and Raman spectroscopy. It is well known that the diffraction or spectral intensity for a particular phase is proportional to the total amount of that phase present in the sample, but the area ratio corresponding to various phases need not be the same as the ratio of their present amounts. Then, it is not possible to compare directly band areas with mineral abundance. From this work, modal mineralogy correction factors from band areas obtained by different instrumental techniques over strictly the same meteorite samples with respect to normative mineralogy values can be obtained. They may represent a valuable tool for predicting mineral abundances in unsampled asteroids.

Experimental methods: Several fragments of the Villalbeto de la Peña L6 (S4) ordinary chondrite that were collected shortly after their fall on January 4, 2004 in Spain were used for this study [2]. Studies were carried out over gram-sized powdered fractions taken from the interior of the meteorite specimens. Electron microprobe analysis were taken from [2], and bulk chemical analysis, Mössbauer and Raman spectroscopy data from [3]. XRD was performed with a Philips MRD instrument by counting 15 s at a step size of 0.03°. FTIR was carried out with a Nicolet Magna 520 spectrometer at a resolution of 2 cm^{-1}.

Results and discussion: Abundances of 36 chemical elements were determined by means of ICP-MS and ICP-OES [3]. For most elements, the measured abundances were within the range observed for L6 chondrites [4-5] and values within 20% of the average were found. Using the electron microprobe analyses of olivine, pyroxene, plagioclase, chromite, troilite, kamacite, and taenite reported in [2] and the bulk content of Si,

Mg, Fe, Al, Ca, Na, S, Ni, and Cr obtained by wet chemical analysis it is possible to perform mass balance calculations and derive normative mineralogy (Table 1).

Bulk magnetic properties of Villalbeto de la Peña were also studied in detail [3], and it was found that the only metal phases present in the meteorite were kamacite and taenite. Then, in the absence of other metal phases, it is possible to calculate the total metal content of the meteorite from its specific magnetic susceptibility and the corresponding theoretical value for kamacite-taenite spheres [6]. The calculated wt % of metal in the Villabeto de la Peña meteorite from magnetic measurements is 6.6, which is in full agreement with the amount of metal calculated from chemical analysis of 6.8 wt %. An additional supporting evidence that the normative calculation of metal vs. silicate and sulfide phases in the meteorite is well accurate comes from metal separation by magnetic methods and HF treatment of the residue. The wt % of metal obtained at the end of the separation process is 6.5, which is comparable to the amount of metal obtained by chemical analysis and magnetic measurements.

Figure 1 shows the X-ray diffractogram of the meteorite. Characteristic olivine, pyroxene, pagioclase, troilite, and metal phase peaks are identified. The relative peak areas of silicate phases after peak adjustment is reported in Table 1. Sulfide and metal phases are not included since it is known that XRD is not appropriate for their quantification in chondrites. Olivine, pyroxene, and plagioclase absorption bands due to vibrations of [Si-O] bonds are well recognized in the 450-1150 cm^{-1} portion of the infrared spectrum (Figure 2). Band fitting of the spectrum with these three components accounts for most bands at this wavenumbers (residual below 5%). The relative amount of each silicate on a band area basis is given in Table 1.

^{57}Fe Mössbauer spectroscopy is particularly useful for characterization of iron-bearing minerals in planetary materials because it probes the local environment of iron nuclei quite sensitively. Two well-defined, strong paramagnetic doublets with quadrupole split absorptions of QS=2.92 and 2.10 mm s^{-1} were recorded for the Villalbeto de la Peña meteorite [3]. These signals are characteristic for ordinary chondrites and correspond to Fe^{2+} in the ferromagnesian silicates olivine and pyroxene, respectively. In addition to the strong paramagnetic doublets, weak absorptions due to mag-

netically ordered troilite and metal phases were also present. The relative areas of these phases are compiled in Table 1.

The Raman spectra in macro mode of three different specimens of Villalbeto de la Peña are shown in Figure 3. It is apparent that all spectra are quite similar. Raman peaks are located at the same wavelength and exhibit similar FWHM values, and the relative band areas are similar, too. Prominent bands at 820 and 850 cm^{-1} correspond to olivine and result from the fundamental vibrations of [SiO$_4$] tetrahedra. Weak olivine bands are also observed at 916 and 955 cm^{-1}. Bands at 231, 334, 393, 662, 678, and 1007 cm^{-1} correspond to pyroxene. No other bands are observed in the spectra, but the strong fluorescence at 400-520 cm^{-1} could hide the most intense feldspar Raman bands at about 500 cm^{-1}. FeNi metal has no active modes for Raman spectroscopy and troilite is a weak Raman scatterer. Deconvolution of the spectra yields the relative band areas for olivine and pyroxene (Table 1).

It is found that olivine vs. pyroxene ratios derived from XRD, FTIR, and Raman band calculations are consistently lower than those obtained from normative mineralogy and Mössbauer calculations. Troilite relative abundance obtained from Mössbauer band ratios appears overestimated, and plagioclase relative abundance derived from FTIR band ratios is underestimated with respect to normative mineralogy values. Finally, with these data, futher constrain into the origin of the progenitor body of the Villalbeto de la Peña meteorite [7] may be gained.

References: [1] McSween et al. (1991) *Icarus* 90, 107 [2] Llorca et al. (2005) *Meteorit. Planet. Sci.* 40, 795 [3] Llorca et al. (2007) *Meteorit. Planet. Sci.* in press. [4] Kallemeyn et al. (1989) *GCA* 53, 2747 [5] Friedrich et al. (2003) *GCA* 67, 2467 [6] Rochette et al. (2003) *Meteorit. Planet. Sci.* 38, 251. [7] Trigo-Rodríguez et al. (2006) *Meteorit. Planet. Sci.* 41, 505.

Table 1. Normative mineralogy (wt. %) derived from chemical analysis (CA) and electron microprobe (EPMA) data (1.2 % chromite not included) compared to relative band areas (area %) in XRD, FTIR, Mössbauer, and Raman spectra.

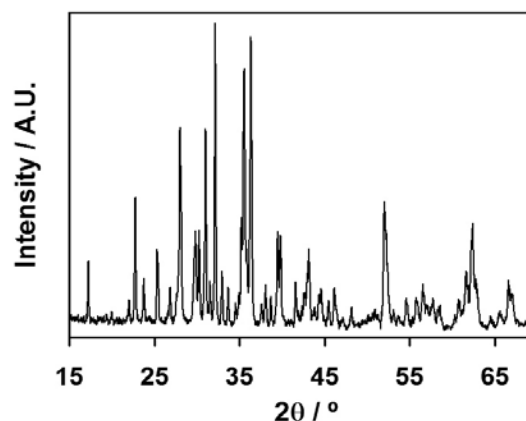| Mineral	CA+EPMA	XRD	FTIR	Raman	Mössb.
Olivine	51.4	57.8	59.5	65.3	60.0
Pyroxene	25.0	33.1	35.8	34.7	24.6
Plagioclase	8.8	9.1	4.7	-	-
Metal	6.8	-	-	-	4.3
Troilite	6.1	-	-	-	11.1

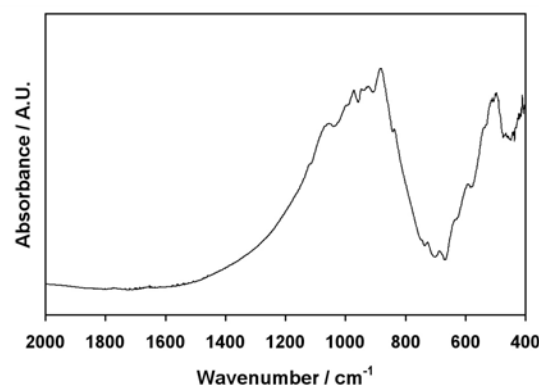Figure 1. X-ray diffractogram of a powdered sample of the Villalbeto de la Peña meteorite.

Figure 2. Infrared spectrum recorded in transmission mode of the Villalbeto de la Peña meteorite.
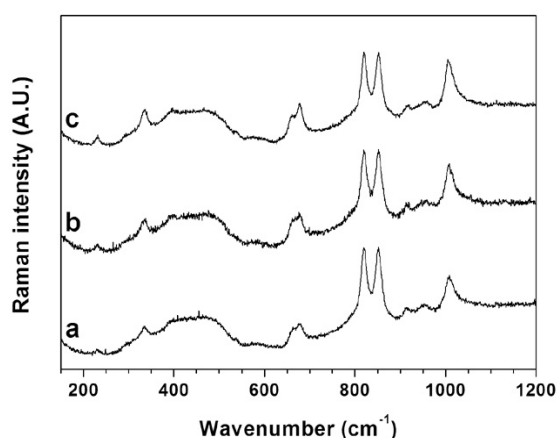

Figure 3. Raman spectra recorded in macro mode from three different specimens of the Villalbeto de la Peña meteorite (laser power at the sample 50 mW).