CO3 CHONDRITES: METAMORPHIC SEQUENCE AND INTERCLASSIFICATION WITH ORDINARY CHONDRITES.

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Introduction: Based on silicate and metal compositions and on contents of rare gases, McSween (1977) revealed a metamorphic sequence among the CO carbonaceous chondrites [1]. The 3 determined metamorphic subgroups were refined by the definition of a petrologic type (PT) by [2,3] (Table 1), who considered Induced Thermo-Luminescence (ITL) properties. This technique was also applied to type 3 ordinary chondrites (UOC). But, a same subtype number does not necessarily indicate equivalent conditions of metamorphism for the ordinary and CO chondrites [4]. On the contrary, a new technique, based on structural order of the Organic Matter (OM), has been applied on UOC [5] and CV3 [6] and appears as an interclassification tool.

The goal of this work is to propose an interclassification, with UOC, of 7 CO chondrites: Colony, Kainsaz, Felix, Ornans, Lancé, Isna and Warrenton. The method is based on the structural order of the Organic Matter (OM), attempted by Raman µ-spectrometry. The results are confronted with petrographic indicators: zonation of olivine phenocrysts and petrography of opaque minerals, both depending on metamorphic grade [6, 9].

Samples and experimental: Colony and Isna are both find CO chondrites. Kainsaz, Felix, Ornans, Lancé and Warrenton are fall CO. Raw samples and thin sections were all supplied by the Museum National d'Histoire Naturelle (Paris-France). The same procedure than in [6] was followed for the preparation of the samples.

Raman experiments were performed at Laboratoire de Sciences de la Terre (ENS-Lyon, France) by using a LABRAM spectrometer. In order to get consistent data allowing to compare ordinary and CO chondrites, experimental parameters were strictly the same than in [6]: a single wavelength excitation source at 514.5nm of a Spectra Physics Ar^+ laser; power at the sample surface of 515 ± 5µm and acquisition time of 2×30s. A minimum of 10 spectra was acquired for each meteorite in the spectral region 700-3700cm^{-1}.

The petrographic study was done by observations with an optical microscope and by acquisition of high-resolution images of polished sections with a Scanning Electron Microscope.

Results: All spectra exhibit the 1st (1000-1700cm^{-1}) and 2nd (2500-3200cm^{-1}) orders of carbon bands. The 1st order is characterized by 2 main bands: the D and the G-bands (around 1360cm^{-1} and 1580cm^{-1} respectively). A preliminary visual exam of the rough spectra (Fig. 1) reveals significant differences between the samples: Colony is the unique CO where the peak intensity of the D band is lower than that of the G band. Moreover, Kainsaz is distinguishable from Lancé, Ornans, Felix, Warrenton and Isna by a less structured 2nd order of the OM.

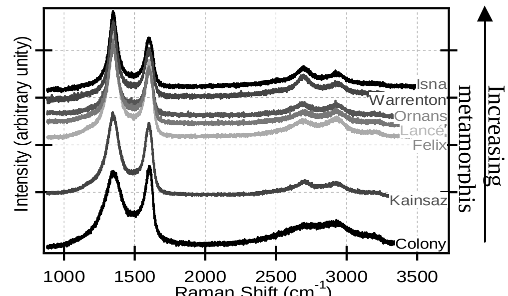

Figure 1: rough spectra of the chondrites CO. Differences are revealed in the structural state of the Organic Matter. $I_D/I_G < 1$ for Colony; the 2nd order is less structured for Kainsaz than for Lancé, Ornans, Félix, Isna and Warrenton.

Raman spectrum of OM is sensitive to changes in ordering degree of materials [5]. In particular, the full width at half maximum of the D band (FWHM-D) and the intensity ratio of the D and G bands (I_D/I_G) are the most sensitive and relevant parameters to study the range of maturity of our samples [5,6]. These parameters are obtained for each spectrum from a fitting method included 2 components: a Lorentzian for the D-band and a Breit-Wigner-Fano for the G-band [5, 6]. Afterwards, the name of parameter designs the average value. FWHM-D and I_D/I_G reveal differences between the 7 CO chondrites (Fig. 2). Colony is the unique CO chondrite with $I_D<I_G$. Kainsaz is characterized by FWHM-D ~ 120cm^{-1} and I_D/I_G ~ 1.05. Felix, Lancé, Ornans, Isna and Warrenton are such as 68 <FWHM-D (cm^{-1}) < 90 and $1.30 < I_D/I_G < 1.50$. Fitting of the 2nd order will be engaged in a 2nd step. But qualitatively it allows to distinct Warrenton and Isna from Lancé, Felix and Ornans, by a band at ~2700cm^{-1} with a higher intensity than the band at ~2900cm^{-1} (Fig. 1). With an increasing structural order of the OM, FWHM-D decreases and I_D/I_G increases [5, 6] and seeing the 2nd order [10], the following structural hierarchy is induced: Colony < Kainsaz < Felix < Lancé < Ornans < Isna ~ Warrenton.

Inferring metamorphic grade from Raman parameters of a line of objects is relevant only if the precursors are the same [7]. In a recent scenario on the origin and evolution of the chondritic OM, Alexander et al. (1998) supposed that all chondrites have accreted the same initial OM [8]. In a 1st step, we found on this hypothesis to compare UOC and CO parameters. In a 2nd step, the petrographic study allows to evaluate the pertinence of the results and to validate the starting hypothesis.

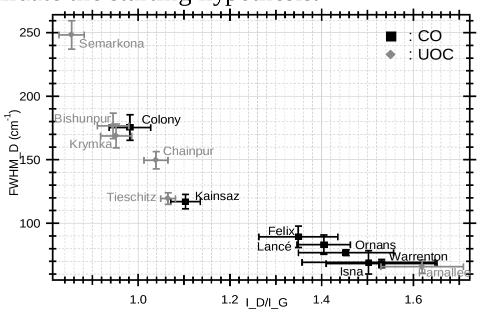

Figure 2: Spectral parameters of Raman bands of carbonaceous materials: FWHM-D vs I_D/I_G. Grey dots = UOC. Dark dots = CO. The error bars equal ± 1σ

Raman parameters (Fig. 2) of Colony are comparable with those of Bishunpur (LL3.1) and Krymka (LL3.1). Kainsaz is closed to Tieschitz (H/L 3.6) and Tieschitz (H/L3.6) < Felix < Lancé < Ornans < Isna ~ Warrenton< Parnallee (L3.7). Thus, Colony is the most primitive CO (3.1 type) among our samples, Kainsaz would be better described as a 3.6 type, and the following metamorphic sequence is suggested Warrenton ~ Isna > Ornans > Lancé > Felix >> 3.6.

Concurrently with the structural study a petrographic work was done. The petrography of opaque minerals (OP) is based on reflected light observations of large sulfide-metal nodules whose texture and mineralogy strongly depend on the metamorphic grade [9]. In UOC, up to 3.5 type, sulfides diffuses between the chondrules and appears in increasing quantities associated with metal beads inside chondrules. Contact metal-sulfide progressively change from contorted to straight. From 3.5 to 4, metal and sulfide start separating from one another and sulfides tend to connect together. The terrestrial alteration prevents to do any observations on Colony , which is found to be a CO chondrite. Although shock has disturbed the contact between the both phases in Isna and Lancé, where eutectic associations were observed, a petrographic study can be anyway achieved. In Ornans some accreted grains are visible, on the contrary to Felix and Kainsaz. In Warrenton, accreted grains are observed with a clear separation between metal and sulfide. Kainsaz has more metal than the others CO. These textures are observed in UOC of at least 3.6 type. Thus compiling the OP, the following hierarchy of metamorphism grade is observed: Kainsaz < Felix < Lancé < Ornans < Warrenton. < Isna

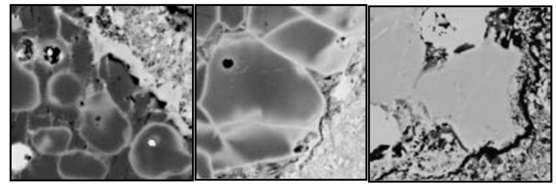

Figure 3: matrix/olivine contact (a: Félix, b: Lancé, c: Isna).

Thermal metamorphism induces interdiffusion of ferromagnesian cations between the unequilibrated minerals. It results in zonation of olivine phenocrysts in chondritic objects [6]. Only FeO poor chondrules with a size, a composition and environment quite constant were selected and matrix-olivine contacts considered. The zonation in Colony, Kainsaz and Felix (Fig. 3a) is fine but systematic. In Ornans and Lancé (Fig. 3b), the zonation is larger. The zonation is obvious in Warrenton and Isna (Fig. 3c), which seems more equilibrated. This implies the following hierarchy: Colony – Kainsaz – Felix < Lancé – Ornans < Warrenton < Isna.

Sample	[1]	[3]	[2]	This work
Colony	I	3.0	3.0	3.1
Kainsaz	II	3.1	3.2	3.6
Felix	II	3.2	3.4	>3.6
Ornans	II	3.3	3.4	>3.6
Lancé	II	3.4	3.4	>3.6
Warrenton	III	3.6	3.6	≥3.8
Isna	III	3.7	3.7	≥3.8

Table 1: comparison of PT assigned to the CO chondrites according to McSween (1977) [1] and to ITL [1, 2] and to our study. Raman spectrometry displays finer metamorphic sequence than allows the subtype classification.

Conclusion: Structural and petrographic studies leads to the same metamorphic sequence, than [1, 2, 3]. Nevertheless, the metamorphic grade seems to be under-evaluated by the ITL (Table 1), particularly for Kainsaz, Felix, Ornans and Lancé. The classical metamorphic scale does not allow to render an account of the differences between Felix, Lancé, Isna Ornans and Warrenton, revealed by the Raman spectrometry combined with our petrographic analysis.

References: [1] McSween (1977) *GCA*, *41*, 477. [2] Sears et al. (1991) *Proc. NIPR Symp. Antarct. Met.*, *4*, 319. [3] Scott and Jones (1990) *GCA*, *54*, 2485. [4] Brearley and Jones (1998) *Planet. Mat.*,$3.[5] Quirico et al. (2003) *MPS*, *38*, 795. [6] Bonal et al, GCA, *sub.* [7] Wopenka and Pasteris (1993) *Am. Mineral.* **78**, 533. [8] Alexander et al. (1998) *MPS* **33**, 603. [9] Bourot-Denise et al. (1997) PBNM workshop. [10] O. Beyssac (2002) *Contrib. Mineral. Petrol.* 143, 19.