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The Hautes Fagnes meteorite find: A new LL5 (S1) chondrite from Belgium

Veerle VANDEGINSTE[1], Herman GOETHALS[1], Walter DE VOS[1], Jan HERTOGEN[2] and David LAGROU[3]

[1]*Royal Belgian Institute of Natural Sciences – Geological Survey of Belgium, Jennerstraat 13, B-1000 Brussel, Belgium*
[2]*Afd. Geologie, Dept. AOW/EES, Katholieke Universiteit Leuven, Celestijnenlaan 200E, B-3001 Leuven-Heverlee, Belgium*
[3]*Vlaamse Instelling voor Technologisch Onderzoek, Boeretang 200, B-2400 Mol, Belgium*

ABSTRACT. Around 1965 a meteorite was found in the Hautes Fagnes region in eastern Belgium. It was made available for scientific investigation in 2007. The meteorite specimen has a mass of 185 g and a density of 3.56 g/cm³. It is light grey with darker angular fragments, and a thin fusion crust. It contains specks of metal of submillimetre size that show little weathering. Submillimetre sized chondrules with blurred outlines make up ca. 40 % of the specimen, and consist mainly of olivine and orthopyroxene. Troilite, kamacite and taenite were found in the chondrules and in the matrix. Native copper was identified at the contact of troilite and iron-nickel grains. Minor minerals in the matrix include albitic plagioclase, clinopyroxene, chromite, and chlorapatite. The average molar fayalite content of olivine was estimated at 29.37 % , and the ferrosilite content of orthopyroxene was estimated at 23.75 %. Bulk chemical analysis with ICP-OES was carried out (1) after fusion with $LiBO_2$ and (2) after microwave digestion in strong acids. The meteorite is distinctly magnetic, with a mass specific magnetic susceptibility logX of 3.83. This meteorite can be classified as a LL ordinary chondrite of petrologic type 5, and of shock classification stage S1 (unshocked).

KEYWORDS: ordinary chondrite, fayalite, ferrosilite, magnetic susceptibility, RBINS meteorite collection.

1. Introduction

Until recently, only four authentic meteorites have been recovered in Belgium. They are all ordinary chondrite falls. Sint-Denijs-Westrem (also spelled St. Denis Westrem) is a L6 chondrite that was observed to fall in 1855 (Duprez, 1855). The L6 chondrite Tourinnes-la-Grosse fell in 1863 (Van Beneden, 1863), and the L6 chondrite Lesves fell 1896 (Renard, 1896). Finally, the H3-6 brecciated chondrite Hainaut (also called Bettrechies) fell in 1934 (Lecompte, 1935).

The Hautes Fagnes meteorite is not an observed fall. It was found around 1965 during a school excursion through the Hautes Fagnes area (High Fens, a raised bog with sphagnum moss in Liège province, eastern Belgium). The approximate geographical coordinates of this area are 50°35’ ± 5’ N latitude and 6°10’ ± 5’ E longitude. The stone was kept by a teacher, who was intrigued by its peculiar characteristics. Only in 2007, after visiting an exposition on meteorites, the teacher guessed its true nature, and consulted Vincent Jacques, an experienced meteorite collector, who acquired the meteorite specimen and donated half of it to the Royal Belgian Institute of Natural Sciences for further investigation and curation.

The Hautes Fagnes meteorite was officially recognised by the Meteorite Nomenclature Committee in December 2010. The salient features of the specimen are summarized in the Meteoritical Bulletin N°99 (De Vos, 2011). The present paper supplements this short note and deals with a more comprehensive study of the mineralogy, and of the mineral and bulk chemical composition. A determination of chemical group, metamorphic/petrologic type and shock grade not only meets curatorial needs, but also provides useful information for studies of the frequency distribution of the various types and subtypes of chondrites.

2. Methodology

The original stone consisted of a single piece. It was cut in two halves, of which the major half (itself broken in two pieces) is in the possession of Vincent Jacques, whereas the other part and two smaller pieces that broke off during cutting, are held at the Royal Belgian Institute of Natural Sciences (RBINS). The macroscopic description is based on the original single piece as well as on the meteorite pieces (and their cut surfaces) that are present at the RBINS (Fig. 1A).

The mineralogical and petrographical analysis was performed on two thin sections and a polished section. XRD powder diffraction analysis with a Philips Analytical PW3830 spectrometer provided additional information on the mineralogy. The XRD spectrometer operated with FeKα radiation at 40 kV and 30 mA.

A SEM-EDXA (JEOL JSM-6340F) at VITO (Vlaamse Instelling voor Technologisch Onderzoek, Flemish Institut for Technological Research) was used to characterize small phases, difficult to determine by optical microscopy, on a polished section.

An Environmental Scanning Electron Microscope (ESEM Quanta 600 of FEI) equipped with an Energy Dispersive System (EDS of EDAX) was used at the Royal Belgian Institute of Natural Sciences, to realise point analyses of mineral grains and also to perform element mapping, in low-vacuum conditions, on two polished sections. This mapping was also used to estimate mineral abundances.

Electron microprobe analyses were performed at the Université Catholique de Louvain with a Cameca France SX50 microprobe. By this method, the concentrations of Si, Fe, Mg, Ca, Al, Ti, Mn, Cr, Na, K and Ni were determined in olivine and orthopyroxene.

Whole rock chemical analysis of aliquots of a ground, homogenised powder of a meteorite fragment was carried out at the Katholieke Universiteit Leuven with a Varian 720ES ICP-OES spectrometer, after (1) fusion with $LiBO_2$ and (2) microwave digestion in strong acids (HF, HNO_3 ,$HClO_4$, and aqua regia). Calibration was based on the analysis of reference rock powders USGS DTS-1 (dunite), USGS BCR-2 (basalt) and ANRT BR (basalt).

The first procedure is an adaptation and enhancement of the method of Bankston et al. (1979). 100 mg aliquots of two meteorite samples and of the three standards were fused with 500 mg $LiBO_2$ (Alfa Aesar/ Johnson Matthey Spectroflux 100A) in high purity graphite crucibles. The fusion bead was dissolved in 50 mL 0.4 M HNO_3 and diluted

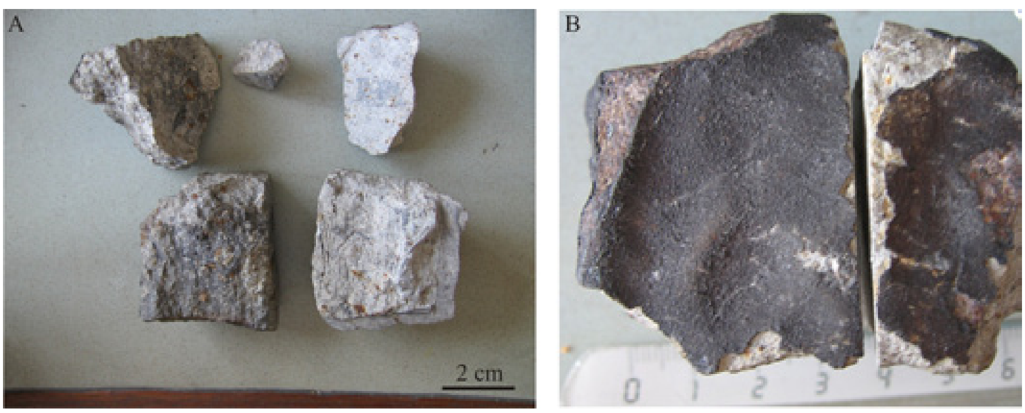

Figure 1. Macrophotographs of the Hautes Fagnes meteorite. A: The pieces of the cut and broken meteorite. The two larger pieces at the left of the photograph belong to V. Jacques, whereas the others are present at the Royal Belgian Institute of Natural Sciences. B: Rather wavy meteorite surface covered by a fusion crust, which displays a melting texture.

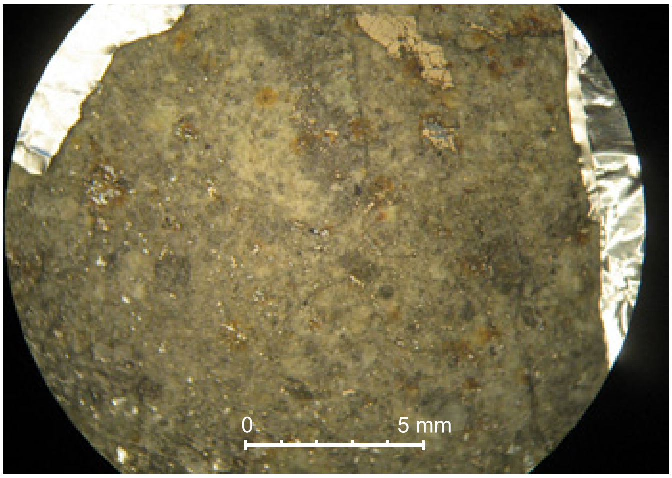

Figure 2. Photograph of polished section in normal incident light, showing chondrules, lighter and darker zones, and small inclusions of either metal or troilite, or both. In the upper section is a larger troilite inclusion (length 3 mm). The sample is wrapped in aluminum foil to enhance electron evacuation in ESEM.

10x prior to ICP-OES measurement. The elements Si, Ti, Al, Fe, Mn, Mg, Ca, Na, Cr and P were determined. Potassium data of the meteorite samples were of low quality due to significant background contribution of K from the Li-metaborate flux. Ni data were too low, because a small fraction of taenite grains did not dissolve in the fusion bead.

To remedy the latter problem, a second procedure was applied. 100 mg aliquots of the meteorite and standards were dissolved in a 'Milestone Ethos 900' microwave digestion unit in high-pressure, high temperature PTFE ('teflon') vessels (210°C, 8 bar). The procedure was adapted from Mareels (2004). Samples were first dissolved in mixtures of concentrated high-purity acids HF, HNO_3 and $HClO_4$. After the evaporation of HF and SiF_4, the samples were again attacked in aqua regia to ensure complete dissolution of FeNi metal grains. The elements Ti, Al, Fe, Mn, Ca, Na, K, P, Ni and Co were measured. Results for Cr had to be rejected because the refractory chromite grains from the dunite calibration standard DTS-1 failed to dissolve completely in the acid dissolution procedure.

The bulk composition of the meteorite has been derived from an average or combination of the results of the two procedures. None of the two procedures allows the content of sulphur to be determined, because the element is lost during fusion or acid attack, either as SO_2 or as H_2S.

3. Macroscopic description

The Hautes Fagnes meteorite was found as a single light-grey stone with a size of about 7 x 4 x 3.5 cm and a weight of 185 g. The volume is 52 cm^3; it was measured by the volume of water displaced by the immersed piece. Weight and volume correspond to a density of 3.56 g/cm^3. The specimen has a wavy surface and is largely covered by a fusion crust (Fig. 1B). The uncovered part indicates that the stone broke up late during entry in the atmosphere or during impact. The broken surface is rough and slightly stained by surface alteration. The dark brown to black fusion crust (about 0.3 mm thick) shows microscopic melt structures with a netted texture.

The meteorite contains dark grey rather angular lithic fragments of cm size embedded in the surrounding lighter grey material. Specks of a metallic phase and of sulphide are scattered throughout the rock. Few of these specks reach mm size (Fig. 2). The weathering of the metallic grains is rather weak. Chondrules are not readily recognised with the naked eye in the cut or broken surface.

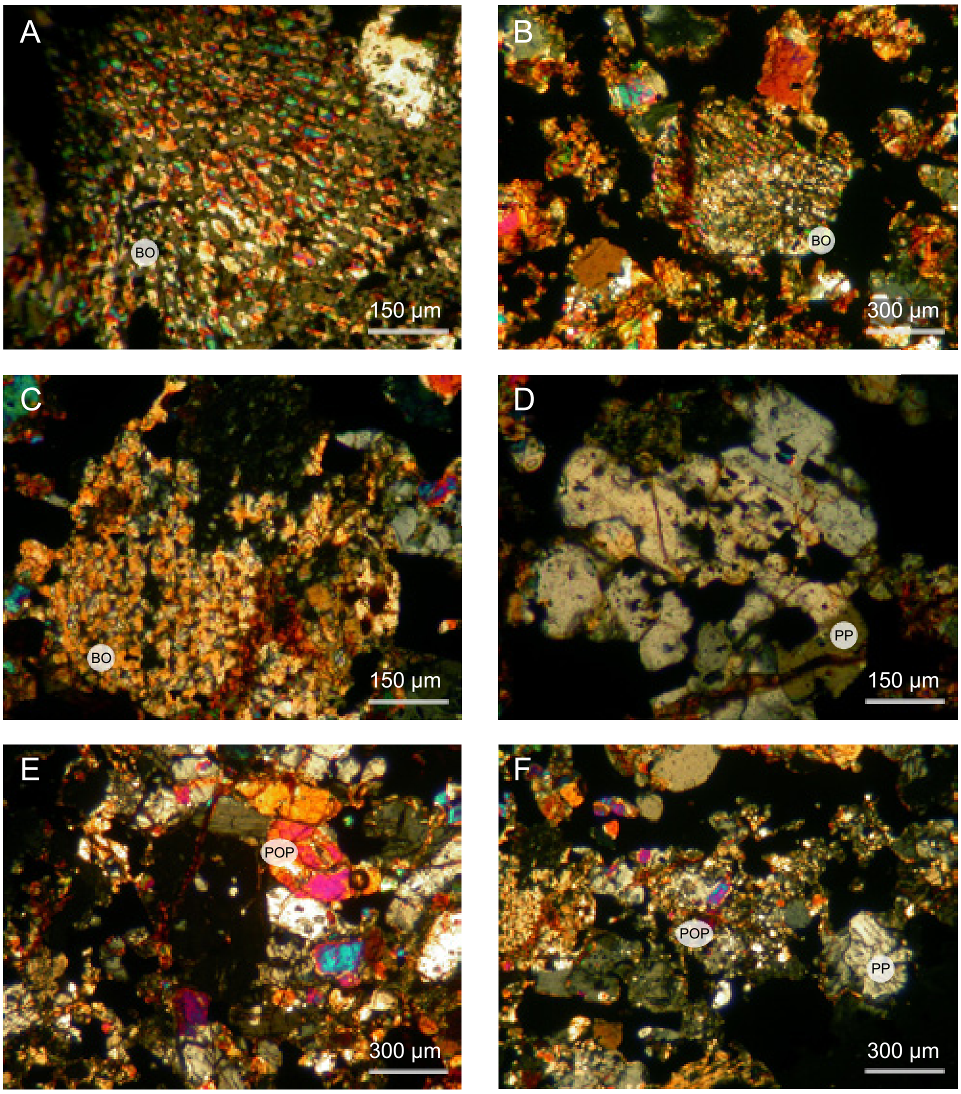

Figure 3. Microphotographs of chondrules in thin sections (transmitted light, crossed polars). A-C: Barred olivine chondrules (BO). Bars are not very well developed, especially in C. Bars are lineated in different directions in A, resembling a rather radial pattern. D: Porphyritic-pyroxene chondrule (PP). E: Porphyritic-olivine-pyroxene chondrule (POP). F: Porphyritic-olivine-pyroxene chondrule of the poikilitic type in the centre of the photograph (POP) and a porphyritic-pyroxene chondrule (PP) on the right.

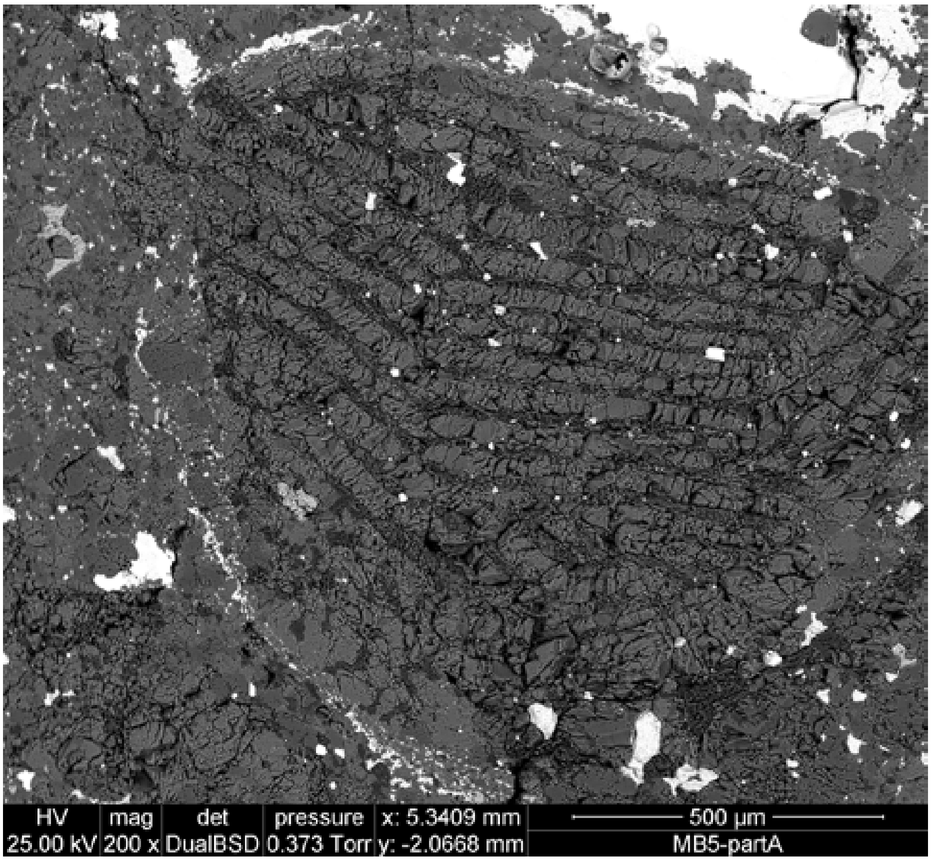

Figure 4. Barred olivine chondrule surrounded by small troilite and metal grains. ESEM backscatter electron image.

4. Mineralogy and petrography

4.1. Chondrules

The presence of chondrules was apparent in petrographic thin sections. About 40% of the rock consists of chondrules, which are generally 350 to 800 µm in diameter. The chondrules often lack distinct borders (Fig. 2). The clearly identified chondrules can be grouped according to the textural scheme of Gooding and Keil (1981). They consist of barred olivine (BO, fig. 3A-C, fig. 4), porphyritic pyroxene (PP, fig. 3D), and porphyritic-olivine-pyroxene (POP, fig. 3E) with a poikilitic variety (Fig. 3F). The barred-olivine chondrules consist of elongated fragments of olivine, all having the same optical orientation. The bars are lined up in one or several orientations, and often are abutting on a more continuous olivine rim. As is commonly observed in chondrites, the original quenched glass between the olivine bars has recrystallized to plagioclase. The bars are, however, not always very well developed. The porphyritic-pyroxene chondrules (PP) can consist of one large zone in optical continuity. The porphyritic-olivine-pyroxene chondrules (POP) consist of euhedral olivines and some pyroxenes, both having variable crystal sizes (100 to 750 µm). Metal and troilite are scattered throughout the rock, but also (partly) delineate many

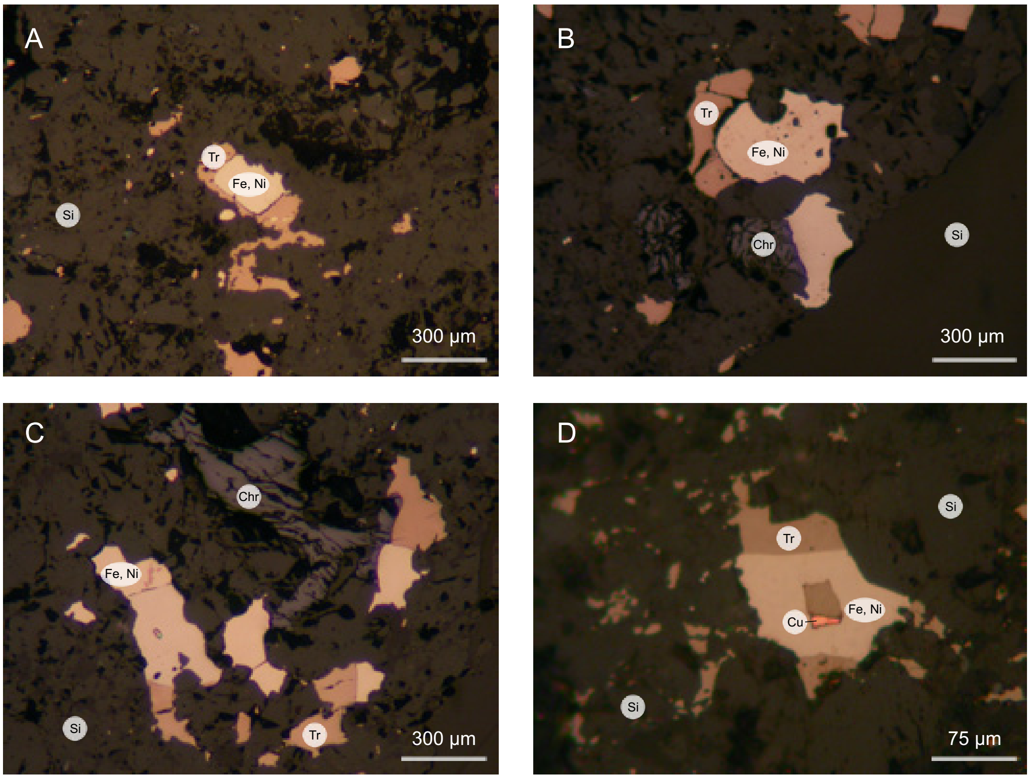

Figure 5. Microphotographs of opaque phases in polished sections (view with incident light). A: Subhedral cubic shape of light-yellowish iron-nickel (Fe,Ni) partially surrounded by light-brownish troilite (Tr) that is irregular in shape, in a dark-coloured silicate matrix (Si). B and C: Iron-nickel (Fe,Ni, light yellowish), troilite (Tr, light brownish) and chromite (Chr, dark grey) with irregular fissures, in a silicate matrix (Si, dark coloured). D: Native copper (Cu, orange) at contact between troilite (Tr, light brownish) and iron-nickel (Fe,Ni, light yellowish), also fine distribution of troilite in the silicate matrix (Si, dark coloured).

chondrule borders (Fig.4). Some small flecks of opaque minerals are also present inside the chondrules.

4.2. Matrix

Apart from the chondrules, the meteorite is composed of olivine, pyroxene, plagioclase, iron-nickel metal, troilite and a small percentage of chromite. The dark-coloured character of some dark grey blocky lithic fragments in the generally lighter grey rock is caused by the abundance of metal and troilite phases. These dark fragments typically show 5 to 8 % iron-nickel and 22 to 25 % troilite, whereas the lighter grey zones are characterized by about 3% iron-nickel and 7 % troilite (visual estimates in volume %). The metallic and sulphidic minerals often occur as irregular patches, but some rounded troilite grains and a few veinlets can be observed. Troilite sometimes occurs at the rim of an iron-nickel inclusion, but it is generally not associated with metal, occurring as discrete grains in the silicate matrix. The few troilite veinlets occur near the fusion crust. Chromite occurs as isolated grains or in association with troilite inclusions (Fig.5, B and C). Small grains (of about 20 µm) of plagioclase are scattered throughout the matrix. Small chlorapatite grains and one merrilite grain were detected with EDS (semi-quantitative analysis).

4.3. Olivine

Olivine occurs as grains of different sizes in both matrix and chondrules, from micrometric to about 500 µm. The olivine crystals are often euhedral. The olivines are pleochroic, varying in colour from light green to light pink. There are no petrographic indications that the olivine crystals experienced appreciable shock metamorphism (Stöffler et al., 1991). Some olivine crystals are cracked, but they lack planar features ('shock lamellae') and the extinction is sharp, not undulose.

Zone	anal. N°	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Total	Fa %
	7	37,59	0,00	0,00	25,46	0,35	35,74	0,10	99,24	28,56
	8	37,94	0,00	0,00	25,38	0,44	36,17	0,09	100,01	28,25
BO chondrule 1	9	38,03	0,00	0,00	25,46	0,44	35,54	0,07	99,55	28,67
	10	*38,41*	*0,03*	*0,00*	*24,56*	*0,45*	*35,14*	*0,19*	*98,78*	*28,17*
	11	*37,45*	*0,05*	*0,00*	*23,68*	*0,37*	*34,31*	*0,81*	*96,66*	*27,92*
BO chondrule 1	aver. 7-9	37,85	0,00	0,00	25,43	0,41	35,81	0,09	99,60	28,49
	13	38,18	0,03	0,00	25,56	0,50	35,66	0,04	99,97	28,68
	14	38,20	0,00	0,00	25,68	0,48	35,34	0,03	99,73	28,96
	15	37,76	0,00	0,00	26,10	0,43	35,83	0,00	100,11	29,01
matrix, dark zone	16	37,83	0,04	0,00	26,11	0,43	36,09	0,00	100,51	28,88
	17	37,79	0,00	0,00	26,57	0,35	36,11	0,00	100,83	29,22
	18	37,69	0,00	0,00	26,22	0,48	35,87	0,00	100,27	29,09
	21	37,73	0,00	0,00	26,52	0,43	36,03	0,00	100,70	29,23
matrix, dark zone	average	37,88	0,01	0,00	26,11	0,44	35,85	0,01	100,30	29,01
	32	37,17	0,00	0,00	26,46	0,43	35,23	0,00	99,30	29,65
	33	37,14	0,00	0,00	26,57	0,40	35,17	0,00	99,27	29,77
POP chondrule	34	37,08	0,00	0,00	26,31	0,52	35,34	0,00	99,25	29,47
	35	37,24	0,00	0,00	27,15	0,49	35,32	0,00	100,20	30,13
	36	37,19	0,00	0,00	26,70	0,46	35,02	0,00	99,37	29,96
	37	37,08	0,00	0,00	26,62	0,41	35,56	0,00	99,67	29,57
POP chondrule	average	37,15	0,00	0,00	26,63	0,45	35,27	0,00	99,51	29,76
	38	*37,23*	*0,00*	*0,23*	*25,88*	*0,42*	*34,69*	*0,00*	*98,44*	*29,51*
	39	36,96	0,00	0,10	26,57	0,46	35,52	0,00	99,61	29,56
	40	*36,58*	*0,00*	*0,00*	*26,28*	*0,39*	*35,03*	*0,00*	*98,28*	*29,63*
matrix, light zone	41	37,11	0,00	0,19	26,68	0,43	35,39	0,00	99,80	29,73
	42	37,00	0,00	0,11	26,58	0,38	35,73	0,00	99,79	29,45
	43	37,31	0,00	0,00	26,42	0,56	35,57	0,00	99,86	29,41
matrix, light zone	av. 39, 41-43	37,10	0,00	0,10	26,56	0,46	35,55	0,00	99,76	29,54
	51	37,23	0,00	0,00	26,64	0,51	35,24	0,04	99,65	29,79
	52	37,31	0,00	0,00	26,35	0,42	35,50	0,00	99,58	29,40
BO chondrule 2	53	37,39	0,00	0,00	27,04	0,40	35,46	0,00	100,30	29,96
	54	37,56	0,00	0,00	26,25	0,47	35,11	0,00	99,39	29,55
	55	37,49	0,03	0,00	26,76	0,46	35,32	0,00	100,05	29,83
	56	37,39	0,03	0,00	26,71	0,58	35,33	0,00	100,04	29,78
BO chondrule 2	average	37,39	0,01	0,00	26,63	0,47	35,33	0,01	99,84	29,72

Table 1a. Electron microprobe analyses of olivine, 30 analyses (wt %) in three chondrules and two matrix zones. The last column shows fayalite content calculated from Fe/(Fe+Mg) in mol %. Averages are calculated for each zone, ignoring four analyses that have a sum < 99% (in italic).

	BO chondrule 1	matrix, dark zone	POP chondrule	matrix, light zone	BO chondrule 2
anal. N°	9	17	35	39	52
wt%					
SiO_2	38,028	37,793	37,241	36,963	37,313
FeO	25,463	26,570	27,152	26,570	26,351
MnO	0,442	0,353	0,485	0,458	0,416
MgO	35,542	36,113	35,324	35,522	35,503
CaO	0,071	0,000	0,000	0,000	0,000
Total	99,546	100,829	100,202	99,513	99,583
Unit cell content (on the basis of 4 oxygens)					
Si	1,012	0,993	0,989	0,985	0,994
Fe	0,567	0,584	0,603	0,592	0,587
Mn	0,010	0,008	0,011	0,010	0,009
Mg	1,410	1,415	1,398	1,411	1,410
Ca	0,002	0,000	0,000	0,000	0,000
Total	3,001	3,000	3,001	2,998	3,000
fa %	28,67	29,22	30,13	29,56	29,40

Table 1b. Calculation of number of cations for olivine, based on 4 oxygen atoms. From the analyses in Table 1a, one analysis was selected from each zone, to cover the range of Fe content. The last row shows the corresponding fayalite content in mol%.

The chemical composition of the olivine was determined with the electron microprobe (Table 1a). Additional analyses with XRD and SEM-EDXA, on a larger number of grains, were focused especially on the Fe/Mg ratio of olivine grains, as this is a critical parameter for the classification of the meteorite (e.g. Keil & Fredriksson, 1964).

a) Electron microprobe analyses

Olivine was analysed with the electron microprobe in five different zones of the meteorite. A minimum of six measurements were performed in each zone in order to obtain a reliable average value and to evaluate the homogeneity. A total of 30 analyses were performed (table 1a), 26 of which are considered valid, with a sum between 99 and 101%. The different analysed zones consist of two barred-olivine chondrules (BO), a porphyritic olivine-pyroxene chondrule (POP), and two matrix zones in a dark clast, respectively a light zone. The fayalite content, calculated from the ratio FeO/(FeO+MgO), does not display distinct variations between the different zones. It varies overall between 28.25 and 30.13 mol% fayalite, with a mean of 29.37 mol% and a standard deviation of 0.48 %, a very low figure typical for equilibrated chondrites. The structural formula based on 4 oxygen atoms was calculated for one analysis from each of the zones, covering the range of Fe contents (table 1b).

b) XRD and SEM-EDXA

The sole purpose of these analyses is to have additional estimates of the fayalite content of the olivine. The XRD data of olivine (multiple grains) were processed using the d_{130} determinative curve of Yoder and Sahama (1957); the composition varies between 29 ± 6 mol% fayalite. The SEM-EDXA analyses at VITO covered the range 30 ± 5 mol% fayalite. These analyses confirm the average estimate of 29 mol% fayalite from the microprobe analyses.

4.4. Orthopyroxene (low-Ca pyroxene)

The low-Ca pyroxene in the Hautes Fagnes specimen is generally orthopyroxene, according to optical observations in thin section. The grains can be slightly elongated, but almost no euhedral prismatic crystals were observed. Some crystals show fine striations or cleavage in the elongated direction. Although pleochroism is not as clear as observed in olivine, orthopyroxene crystals show minor colour variations from light green to light pink. Under crossed polars they display a sharp, parallel extinction, which points to the absence of shock features.

The chemical composition of the pyroxene was determined with an electron microprobe. Some additional analyses, focused especially on the Fe/Mg ratio, were carried out on the SEM-EDXA. Together with the fayalite content of olivine, the ferrosilite content of low-Ca pyroxene is a critical parameter for the classification of the meteorite (Keil & Fredriksson, 1964; Brearley & Jones, 1998).

a) Electron microprobe analyses

Orthopyroxene in five different zones of the meteorite were analysed with the electron microprobe (Table 2a). A minimum of six measurements were performed in each zone in order to obtain a reliable average value and to evaluate the homogeneity. The different zones measured consist of barred-olivine (BO), porphyritic olivine-pyroxene (POP) and porphyritic pyroxene (PP) chondrules, and finally a dark clast and a light zone, both in matrix. In all, 28 analyses were carried out, 26 of which are considered valid, with a sum between 99% and 101% (table 2a). The analytical differences between the five zones are small, which again points to the equilibrated nature of the chondrite. The ferrosilite content, calculated from the FeO/(FeO+MgO+CaO) ratio, varies between 22.62 and 24.61 mol% ferrosilite, with a mean of 23.75 mol% and a standard deviation of 0.47%. The mean wollastonite content of the orthopyroxene is estimated at 1.69 mol%, calculated from the CaO/(FeO+MgO+CaO) ratio. Table 2b shows the calculation of the structural formula based on 6 oxygen atoms, for one analysis per zone, covering different Fe contents.

From tables 1a and 2a it can be deduced that the MnO content is very similar in olivine and low-Ca pyroxene, mostly in the range 0.35% to 0.50 %. The TiO_2, Al_2O_3 and Cr_2O_3 content is generally higher in pyroxene, between 0% and about 0.2%.

b) SEM-EDXA analyses of orthopyroxene gave a composition of 26 ± 5 mol% ferrosilite.

4.5. Feldspar

Plagioclase occurs in fine grains of about 10 to 20 µm in size. ESEM-EDS point analyses were performed (Table 3) on 18 grains. Structural analysis shows that the plagioclase is an albite-rich oligoclase with low K content : 8.32 to 11.33 mol% anorthite with a mean of 9.62%, and 3.02 to 7.36 mol% orthoclase with a mean of 4.50 % (table 3).

4.6. Opaque minerals (metals, sulphide and chromite)

The metallic and sulphide phases occur in different sizes, from only a few µ to 300 µ, and different shapes (Fig. 5A-D). They are slightly oxidized (visible with optical microscopy in polished sections, and by the occasional detection of oxygen with EDS). Under incident light, the Fe-Ni phases are light grey and have a high reflectivity, whereas troilite is more brownish with lower reflectivity (Fig. 5A-D). Chromite has the lowest reflectivity in incident light and is dark grey (Fig. 5B-C). Both troilite and iron-nickel were observed in the chondrules as well as in the matrix, whereas chromite grains have only been found in the matrix. Very small native copper grains have been detected,

Zone	anal. N°	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Total	fs %	wo %
	57	55,03	0,20	0,17	0,14	15,62	0,50	27,24	1,04	99,93	23,84	2,02
	58	54,81	0,20	0,14	0,13	16,07	0,36	27,39	0,89	99,99	24,34	1,73
PP chondrule	59	54,88	0,18	0,17	0,15	15,33	0,46	27,39	0,91	99,45	23,47	1,78
	60	54,95	0,15	0,16	0,13	15,96	0,44	27,14	0,73	99,66	24,46	1,43
	61	54,69	0,19	0,13	0,00	15,64	0,46	27,23	0,73	99,06	24,02	1,43
	62	55,00	0,17	0,15	0,16	15,69	0,48	27,32	0,86	99,83	23,96	1,68
PP chondrule	average	54,89	0,18	0,15	0,12	15,72	0,45	27,29	0,86	99,65	24,01	1,68
	1	55,52	0,19	0,16	0,00	15,98	0,47	27,60	0,73	100,65	24,17	1,41
	3	55,25	0,19	0,17	0,16	15,44	0,51	27,68	0,80	100,19	23,47	1,56
BO chondrule	4	55,10	0,17	0,16	0,14	15,50	0,46	27,60	0,77	99,89	23,60	1,51
	5	55,14	0,20	0,15	0,00	14,79	0,48	27,77	0,86	99,39	22,62	1,69
	6	55,11	0,16	0,13	0,12	15,18	0,47	27,58	0,82	99,57	23,21	1,61
BO chondrule	average	55,22	0,18	0,15	0,08	15,38	0,48	27,65	0,80	99,94	23,41	1,56
	19	55,35	0,08	0,14	0,00	15,59	0,44	27,83	0,91	100,34	23,50	1,75
	20	55,35	0,18	0,16	0,00	15,54	0,54	27,58	0,78	100,13	23,66	1,52
matrix, dark zone	22	55,25	0,22	0,15	0,53	15,46	0,48	27,98	0,84	100,89	23,28	1,61
	23	55,18	0,16	0,13	0,12	15,56	0,47	27,67	0,79	100,07	23,61	1,53
	24	*54,55*	*0,15*	*0,12*	*0,10*	*14,60*	*0,45*	*27,60*	*0,80*	*98,37*	*22,52*	*1,58*
	25	54,99	0,21	0,16	0,16	15,23	0,52	28,00	0,85	100,12	22,99	1,65
matrix, dark zone	av. 19-23, 25	55,22	0,17	0,15	0,16	15,48	0,49	27,81	0,83	100,31	23,41	1,61
	26	*54,31*	*0,15*	*0,15*	*0,00*	*15,54*	*0,51*	*27,10*	*0,97*	*98,73*	*23,87*	*1,92*
	27	54,78	0,17	0,16	0,18	15,61	0,39	27,31	0,97	99,57	23,82	1,90
POP chondrule	28	54,71	0,18	0,14	0,15	15,69	0,40	27,41	0,97	99,65	23,84	1,89
	29	55,21	0,16	0,13	0,18	15,75	0,40	27,34	0,99	100,15	23,95	1,92
	30	55,04	0,17	0,14	0,00	15,84	0,44	27,14	0,98	99,74	24,20	1,91
	31	54,63	0,21	0,17	0,18	16,01	0,37	27,53	0,95	100,05	24,14	1,83
POP chondrule	av. 27-31	54,87	0,18	0,15	0,14	15,78	0,40	27,35	0,97	99,83	23,99	1,89
	44	54,55	0,20	0,14	0,19	15,38	0,45	27,27	0,98	99,15	23,57	1,92
	45	55,21	0,15	0,15	0,00	15,67	0,44	27,18	0,86	99,66	24,03	1,68
matrix, light zone	46	55,39	0,19	0,16	0,12	15,20	0,63	27,76	0,89	100,33	23,10	1,73
	47	55,20	0,20	0,16	0,13	16,24	0,48	27,29	0,87	100,57	24,61	1,68
	48	55,41	0,15	0,16	0,00	15,60	0,37	27,14	0,85	99,68	23,97	1,67
matrix, light zone	average	55,15	0,18	0,15	0,09	15,62	0,48	27,33	0,89	99,88	23,86	1,74

Table 2a. Electron microprobe analyses of low-Ca pyroxene, 28 analyses (wt %) in three chondrules and two matrix zones. The last two columns show ferrosilite (fs %) and wollastonite content (wo %) calculated from Fe/(Fe+Mg+Ca) and Ca/(Fe+Mg+Ca) respectively, in mol %. Averages are calculated for each zone, ignoring two analyses that have a sum < 99% (in italic).

always occurring on the contact between troilite and Fe-Ni metal (Fig. 5D). Some chondrules are surrounded by a rim of fine troilite and metal grains (Fig. 4). The SEM-EDXA analyses and backscatter electron images facilitated the distinction between kamacite and taenite varieties of the Fe-Ni inclusions (Fig. 6). Backscatter electron images with the scanning electron microscope at high magnification locally show plessite-like intergrowths (Buchwald, 1975, pp.95-99) in the metal phase (Fig. 7).

The composition of the metal phase was determined with ESEM-EDS on 94 random points. The results are shown in Fig. 8, where analyses have been ranked according to increasing Fe content. There is clearly a bimodal population, with a mode of 37 wt % Ni for taenite, and 6 wt % Ni for kamacite. A few intermediate Ni-values may reflect analysis of the plessitic intergrowth within the depth of the excitation volume. Kamacite contains on average 2.9 wt % Co according to the EDS analyses, but this may not be very accurate because of partial overlapping Fe and Co peaks. Nevertheless, Co contents of 2% to 4% in kamacite are compatible with LL chondrites (Kallemeyn et al., 1989; Rubin, 1990).

4.7. Other minerals

Other minerals were found with the ESEM-EDS, in small quantities and mostly small grains. About 1 in 20 pyroxene grains is high-Ca clinopyroxene, showing 8 to 9 atom% Ca, pointing to a pigeonite composition. In the electron microscope with backscattered electron (BSE) detector , these grains look identical to low-Ca pyroxene; they also contain some Al, and have a molar ratio Fe/(Fe + Mg) between 16 and 18%. Chlorapatite is present as an accessory mineral in small grains, containing about 4 wt% Cl.

5. Whole rock chemical analysis of the chondrite

Two sets of two 100 mg sample aliquots have been analysed with ICP-OES using two different sample dissolution procedures (see section 2.Methodology). The results of the separate analyses and the

anal. N°	PP chondrule 60	BO chondrule 5	matrix, dark zone 22	POP chondrule 27	matrix, light zone 47
wt%					
SiO_2	54,95	55,14	55,25	54,78	55,20
TiO_2	0,15	0,20	0,22	0,17	0,20
Al_2O_3	0,16	0,15	0,15	0,16	0,16
Cr_2O_3	0,13	0,00	0,53	0,18	0,13
FeO	15,96	14,79	15,46	15,61	16,24
MnO	0,44	0,48	0,48	0,39	0,48
MgO	27,14	27,77	27,98	27,31	27,29
CaO	0,73	0,86	0,84	0,97	0,87
Total	99,66	99,39	100,89	99,57	100,57
Unit cell content (on the basis of 6 oxygens)					
Si	1,993	1,995	1,974	1,985	1,985
Ti	0,004	0,006	0,006	0,005	0,005
Al	0,007	0,006	0,006	0,007	0,007
Cr	0,004	0,000	0,015	0,005	0,004
Fe	0,484	0,447	0,462	0,473	0,488
Mn	0,013	0,015	0,014	0,012	0,015
Mg	1,467	1,498	1,490	1,476	1,463
Ca	0,028	0,033	0,032	0,038	0,033
Total	4,000	4,000	3,999	4,001	4,000
wo	1,41	1,67	1,61	1,91	1,66
en	74,13	75,73	75,10	74,28	73,74
fs	24,46	22,60	23,29	23,80	24,60

Table 2b. Calculation of number of cations for low-Ca pyroxene, based on 6 oxygen atoms. From the analyses in table 2a, one analysis was selected from each zone, to cover the range of Fe content. The lower rows show the end-member contents corresponding in mol%.

calculated average composition are listed in Table 4. Results of Si, Cr, Ni and K are only from one of the two analytical procedures; further details are found in the notes to Table 4. The elements Ti, Al, Fe, Mn, Co, Mg, Ca, Na and P were determined in the two procedures. Agreement between the two methods is very good, taking into account the relatively small sample sizes.

The column 'Average' lists the composition expressed as weight percent oxides, as is the convention in silicate rock analysis. The total amount of Fe is given as 'FeOTot', because the chemical analysis cannot distinguish between Fe^0, Fe^{2+} and Fe^{3+} . The Sum-total of

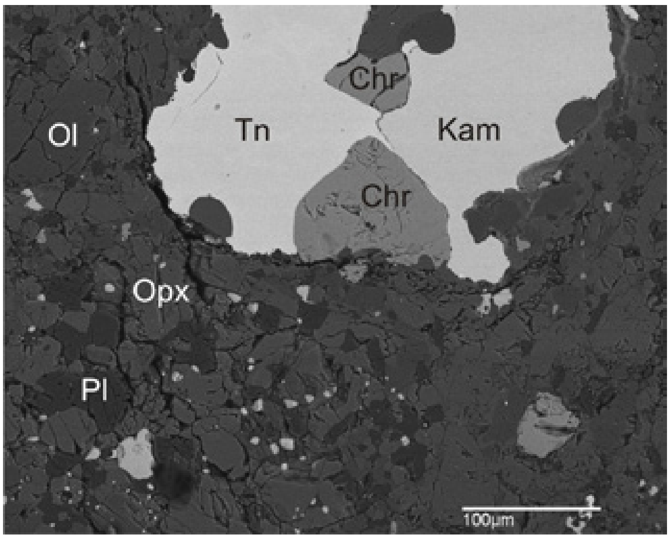

Figure 6. Backscattered electron image showing a kamacite (Kam) – taenite (Tn) grain with chromite (Chr) in an olivine (Ol) – orthopyroxene (Opx) matrix with plagioclase (Pl) grains.

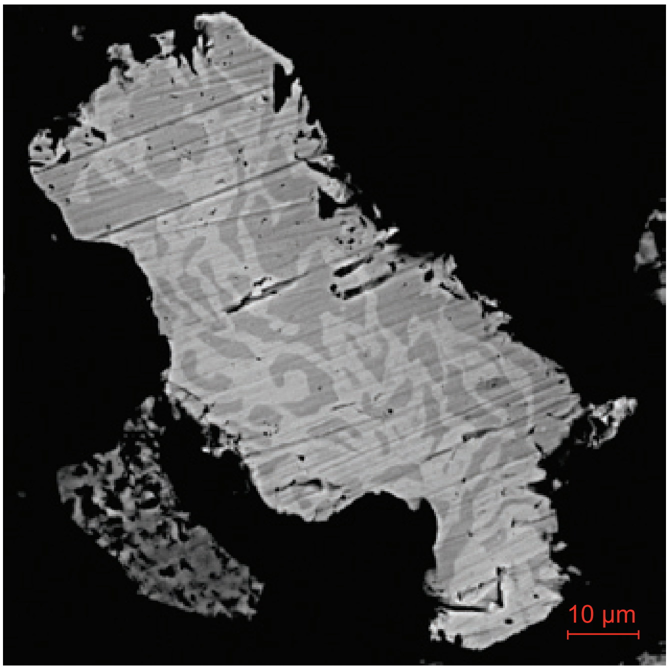

Figure 7. Plessitic intergrowth between kamacite (darker) and taenite (lighter). Backscattered electron image.

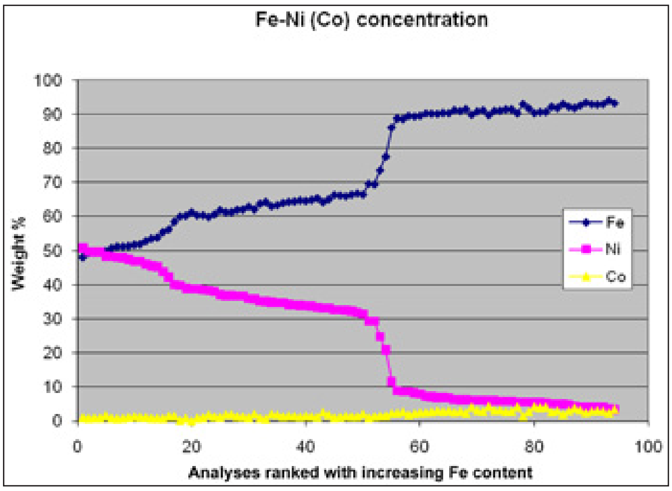

Figure 8. Composition of the metal phase, based on 94 random point analyses with ESEM-EDS, ranked according to increasing Fe content. There is clearly a bimodal population, with average modes of 37 wt % Ni for taenite (left side), and 6 wt % Ni for kamacite (right side). Kamacite contains on average 2.9 wt % Co.

the oxides amounts to 96.3 wt%. The remainder 3.7 wt.% is largely sulphur, and minor amounts of elementary carbon and ambient moisture absorbed after grinding the meteorite fragment. As explained in the 'Methodology' section, neither of the two analytical procedures allows the determination of the sulphur content.

In the two right-side columns the average composition of the Hautes Fagnes meteorite is recast as weight percent of the elements, and compared to the average values for L and LL chondrites calculated by Hutchison (2004; Tables 2.1 and 2.2). No standard deviation figures are published on these averages, and the difference between L and LL averages is well-marked for some elements only, Fe being one of them. The Hautes Fagnes meteorite samples appear to have a slightly higher Fe and P and slightly lower Mg and Si content than the average LL chondrites. The values for Si, Mg and P are somewhat closer to the average for L chondrites. The content of the other elements, including Fe, is closer to the LL average, however. Deviations of such an extent

	average of 18 analyses	lowest Na content	highest Na content	highest Ca content
wt%				
SiO_2	63.87	64.06	63.47	64.30
Al_2O_3	21.94	21.70	22.06	22.08
FeO	1.12	1.70	0.64	0.87
MgO	0.67	0.47	0.39	0.56
CaO	1.96	2.07	1.87	2.25
Na_2O	9.67	8.80	11.01	9.34
K_2O	0.77	1.20	0.57	0.60
Total	100.00	100.00	100.01	100.00
Unit cell content (on the basis of 5 cations)				
Si	2.814	2.845	2.768	2.841
Al	1.139	1.136	1.134	1.150
Fe	0.041	0.063	0.023	0.032
Mg	0.044	0.031	0.025	0.037
Ca	0.093	0.099	0.087	0.107
Na	0.826	0.758	0.931	0.800
K	0.043	0.068	0.032	0.034
# of oxygens	7.949	8.000	7.853	7.999
An	9.62	10.66	8.32	11.33
Ab	85.88	81.99	88.66	85.08
Or	4.50	7.36	3.02	3.60

Table 3. EDS semi-quantitative analyses of plagioclase, and calculation of structural formula based on 5 cations. First column: average of 18 analyses. Next columns: analysis with lowest Na content (and highest K content), with highest Na content, and with highest Ca content respectively. The bottom rows show the anorthite (An), albite (Ab) and orthoclase (Or) contents in mol.%.

are within the natural variation range of LL chondrites (Kallemeyn et al., 1989).

The chemical analysis confirms the conclusion drawn from the mineral analysis that the Hautes Fagnes meteorite belongs to the class of LL-chondrites. The tell-tale chemical characteristics are the low total Fe and Ni contents, the low Fe/Si and Ni/Si atomic ratio's, and Al/Si and Ca/Si atomic ratios in the low range of values observed for ordinary (H, L and LL) chondrites.

6. Magnetic susceptibility

Magnetic susceptibility measurements were made with a handheld SM-30 magnetic susceptibility meter of ZH Instruments (2006). The readings of four different orientations of the stone, which has a thickness of about 2 cm, were averaged. We applied the corrections for finite thickness recommended by ZH Instruments. These take into account the thickness of the sample and the air gap between sample and instrument.

Following the procedure of Rochette et al. (2003), the mass specific value was obtained by dividing by the density of 3.56. This yields a mass specific magnetic susceptibility of 6742 x 10^{-9} m^3/kg. The logarithm logX of this value is 3.83. This value falls in the range of the LL chondrites, as determined by Consolmagno et al. (2006). However, given the incipient weathering grade of the Hautes Fagnes meteorite, the value of 3.83 could be slightly underestimated. Even then, it would be interpreted as a LL chondrite.

7. Discussion

7.1. Classification: chondrite group and type

Based on the presence of chondrules, the size of the chondrules, the metal abundance and the mineralogical characteristics, the meteorite can be determined as an ordinary chondrite of group LL, which generally contains chondrules of about 900 µm, and 2% metal. Based on an average of microprobe analyses, the fayalite content of olivine can be estimated at about 29.3 %, and the ferrosilite content of low-Ca pyroxene at about 23.7 %. These values plot in the field of LL ordinary chondrites (Keil & Fredriksson, 1964; Brearley & Jones, 1998). As discussed above, the high Co content in kamacite, about 2 to 4%, also indicates a LL group (Kallemeyn et al., 1989). Additional evidence comes from the relative abundance of troilite, which is higher than the metal abundance. The magnetic susceptibility of 3.83 (logarithmic value) is also typical for LL chondrites (Consolmagno et al., 2006). The bulk chemical analysis confirms the general LL chondritic composition, with a tendency to a composition intermediate between LL and L chondrites for elements such as Mg, Si and P.

The Hautes Fagnes meteorite can be classified as an equilibrated chondrite of petrologic type 5 (Van Schmus & Wood, 1967), considering the poorly-defined but still visible chondrule rims, the absence of chondrule glass, the recrystallised matrix, the predominance of orthopyroxene over clinopyroxene, the homogeneous nature of olivine and orthopyroxene compositions, and the small plagioclase grains (on average 20 µm) with albitic composition (Brearley & Jones, 1998).

7.2. Shock stage

The sharp extinction characteristics of olivine, in addition to the absence of planar fractures, indicate a S1 shock stage, following the classification scheme by Stöffler et al. (1991). The absence of planar deformation features implies that the chondrite did not experience a shock pressure of 5 GPa or higher.

7.3. Weathering stage

The fact that there are only minor oxide rims around metal and troilite inclusions indicates a weathering stage W1, following the weathering scale for ordinary chondrites defined by Wlotzka (1993). Such a low weathering grade is normal for chondrites with a terrestrial age of less than a few thousands of years.

8. Conclusions

The meteorite found in Belgium in the Hautes Fagnes region around 1965 can be classified as a LL5 ordinary chondrite, based on the general texture, on the composition of olivine and low-Ca pyroxene,

	Hautes Fagnes (oxides, wt%)					Element,wt%			
	1A	1B	2A	2B	Average		H.Fagnes	L-aver.(e)	LL-aver.(e)
SiO_2	39,43	39,34	(a)	(a)	39,38	Si	18,41	18,5	18,9
TiO_2	0,117	0,113	0,116	0,121	0,117	Ti	0,070	0,063	0,062
Al_2O_3	2,22	2,21	2,26	2,29	2,25	Al	1,19	1,22	1,19
Cr_2O_3	0,533	0,546	(b)	(b)	0,540	Cr	0,369	0,388	0,374
FeO_{tot}	24,74	24,52	24,75	25,65	24,92	Fe	19,37	21,5	18,5
MnO	0,34	0,34	0,34	0,35	0,35	Mn	0,27	0,257	0,262
NiO	(c)	(c)	1,42	1,45	1,43	Ni	1,13	1,2	1,02
CoO	0,05	0,042	0,041	0,049	0,045	Co	0,036	0,059	0,049
MgO	24,03	24	24,1	24,3	24,11	Mg	14,54	14,9	15,3
CaO	1,83	1,75	1,91	1,9	1,85	Ca	1,32	1,31	1,3
Na_2O	0,92	0,92	0,94	0,95	0,93	Na	0,69	0,7	0,7
K_2O	(d)	(d)	0,11	0,11	0,11	K	0,093	0,083	0,079
P_2O_5	0,26	0,2	0,28	0,27	0,25	P	0,11	0,095	0,085
Total					*96,3*		*57,6*	*60,2*	*57,8*
						atomic ratios			
						Fe/Si	0,529	0,584	0,492
						Mg/Si	0,913	0,925	0,928
						Al/Si	0,067	0,068	0,066
						Ca/Si	0,050	0,050	0,048
						Ca/Al	0,747	0,723	0,735
						Ni/Si	0,029	0,031	0,026

Table 4. Bulk chemical composition of Hautes Fagnes meteorite, analysed with ICP-OES. 1A, 1B = sample aliquots fused with $LiBO_2$; 2A, 2B = sample aliquots dissolved in acids. (a) = Si volatilised as SiF_4; (b) = poor calibration due to incomplete dissolution of chromite in DTS-1 standard solution; (c) = Ni-rich taenite not completely dissolved in $LiBO_2$; (d) = poor precision due to blank K in $LiBO_2$ flux. At right is the element composition of Hautes Fagnes in wt %. (e) Literature average of L and LL chondrites (Hutchison, 2004; Tables 2.1 & 2.2). Below is a calculation of atomic ratios compared to literature data (ibid.).

on the bulk chemical composition, and on the magnetic susceptibility. The bulk chemical composition is intermediate between L and LL chondrites, with Si, Mg and P closer to the L chondrite average, but Fe much closer to the LL chondrite average.

The fayalite content of olivine, and the ferrosilite content of low-Ca pyroxene, clearly lie in the field of LL chondrites. The Hautes Fagnes meteorite shows little weathering (weathering stage W1), and no shock features (shock classification S1). A type specimen with a mass of 67 g is deposited in the RBINS meteorite collection.

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