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Size and textural type distributions of chondrules in three new carbonaceous chondrites: Acfer 374, HaH 337 and Acfer 366

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Abstract. — Three carbonaceous chondrites, Acfer 374 (CO 3.0), HaH 337 (CK 4) and Acfer 366 (CH 3), have been studied in detail, analizing three thin sections of each meteorite, in order to determine their chondrule sizes and typologies.

As concerns the chondrule sizes, the measurements in the sample Acfer 374 provided a mean value of 110 µm whereas the measurements in HaH 337 and Acfer 366 showed mean values of 700 and 110 µm, respectively. Chondrule typologies display remarkably valuable differences: GO and GO-pk chondrules are prevailing in Acfer 374 (68 vol%), PO is the most abundant chondrule type in HaH 337 (68 vol%) and C type is predominant in Acfer 366 (70 vol%).

These results, in agreement with the literature data, confirm the importance of the study of chondrule sizes and typologies, as well as of their distributions and relative abundances, as powerful tools for the comprehension of chondrules origin and for the classification of carbonaceous chondrites, when properly integrated with a petrographic and minerochemical characterization.

Riassunto. — Tre condriti carbonacee, Acfer 374 (CO 3.0), HaH 337 (CK 4) e Acfer 366 (CH 3) sono state studiate in dettaglio, analizzando tre sezioni sottili di ciascuna per determinare dimensioni e tipologie delle condrule in esse presenti, al fine di definire il gruppo di appartenenza di ciascun campione.

Relativamente alle dimensioni delle condrule, le misure sul campione Acfer 374 hanno prodotto un valore medio di 110 µm mentre nei campioni HaH 337 e Acfer 366 sono stati riscontrati valori medi di 700 e 110 µm, rispettivamente. Le tipologie delle condrule hanno rivelato differenze particolarmente evidenti: le condrule di tipo GO e GO-pk sono prevalenti nel campione Acfer 374 (68 vol%), la tipologia PO è la più abbondante in HaH 337 (68 vol%) mentre il tipo C risulta predominante in Acfer 366 (70 vol%).

Questi risultati, in accordo con i dati di letteratura, confermano l'importanza dello studio delle dimensioni e delle tipologie delle condrule, come pure della loro distribuzione e della loro abbondanza relativa, quali validi strumenti per la comprensione dei meccanismi di formazione delle condrule e per la classificazione delle condriti carboniose, soprattutto quando integrate con i dati petrografici e minerochimici.

Key Words: *Chondrule types and sizes, meteorites, carbonaceous chondrites, CO-CK-CH groups.*

Introduction and Background

Chondrite meteorites are characterized by the presence, in almost all subgroups, of spherical objects named *chondrules*. They are generally made up of silicates, mainly represented by

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olivine and pyroxene, sometimes associated with plagioclase. Chondrules are one of the most important components of chondrites and can account, including chondrule fragments, for up to 70% of the sample, like in the CH group.

Chondrules are primordial objects that formed in the Solar Nebula, at a distance of 0,6-2,5 AU from the Sun (Boss and Graham, 1993; Shu *et al.*, 1996), by entirely or partially melted material. Their spherical shape is a consequence of the absence of gravity or other forces.

Their genesis and evolution is still not well known and several hypotheses have been made on it (Whipple, 1966; Suess and Thompson, 1983; Wood, 1983; Levy and Araki, 1989; Hood and Horànyi, 1991; Shu *et al.*, 1996). A first classification of chondrules was given by Tschermak (1885) who divided chondrules in 8 types: olivine, pyroxene, olivine-pyroxene, augitic, plagioclase, glass, deformed (blackened) and iron-rimmed chondrules. Subsequently Merrill (1920) proposed a texture-based subdivision of chondrules among *porphyritic* and *non-porphyritic* that many years later Kieffer (1975) defined as "droplet" and "lithic", respectively, and explained as deriving from a crystallized melt and from igneous rocks residuals. The terms "droplet" and "lithic" were also used by Dodd (1978) to describe microporphyrithic metal-rich and -poor chondrules, respectively.

Another approach was followed for the first time by Mc Sween (1983), who studied chondrules of carbonaceous chondrites and divided them into three types on the basis of their mineral chemistry: type I (with FeO-poor olivine), type II (with FeO-rich olivine) and type III (non porphyritic). This classification was improved by Scott and Taylor (1983), Jones and Scott (1989) and Jones (1994), who proposed a further sub-division of type I and II chondrules into A (olivine-rich, silica-poor), B (pyroxene-rich, silica-rich) and AB (olivine-pyroxene). These authors also observed that type I chondrules are more fine-grained than type II.

As a matter of fact the classification of chondrules, defined by Gooding and Keil (1981), is entirely based on their texture and mineralogy. These authors re-adapted Tschermak's classification, describing in details the mineralogical features of chondrules and sub-dividing non porphyritic chondrules into "Cryptocristalline" (C) , "Radial Pyroxene" (RP) and "Barred Olivine" (BO) types. Table I reports their classification: for each chondrule type, the

Table 1 – *Classification of ferromagnesian chondrules according to Gooding & Keil (1981), Scott and Taylor (1983), Jones and Scott (1989) and Jones (1994).*

Chondrule types (Gooding and Keil, 1981)	Texture	Olivine/pyroxene ratios	Minerochemical classification (Scott and Taylor, 1983; Jones and Scott, 1989; Jones, 1994)
PO (porphyritic olivine)	Porphyritic	> 10	Type I/II A
POP (porphyritic olivine pyroxene)	Porphyritic	~ 1	Type I/II AB
PP (porphyritic pyroxene)	Porphyritic	≤ 0.1	Type I/II B
GP-GOP (granular pyroxene- granular olivine pyroxene)	Equigranular	> 10	Type I/II A
BO (barred olivine)	Barred	> 10	Type III A
RP (radial pyroxene)	Radial	≤ 0.1	Type III B
C (cryptocristalline)	Cryptocristalline - Microporphyritic	Sub-microscopic crystals of pyroxene	Type III B

corresponding textural features, olivine/pyroxene ratios and minerochemical classifications, based on Scott and Taylor (1983), Jones and Scott (1989) and Jones (1994) definitions, are also reported.

As concerns the terms granular olivine (GO), granular pyroxene (GP), granular olivine pyroxene (GOP) and porphyritic olivine-porphyritic olivine pyroxene (PO-POP), firstly defined by Clarke *et al.* (1970), a more detailed explanation of the terminology is required, mostly considering that the chondrule nomenclature is drastically changed during the last decades. The terms PO and POP are now used to indicate different kinds of chondrules: 1) chondrules displaying a porphyritic texture with olivine alone or olivine and pyroxene phenocrysts in a glassy mesostasis (PO, POP); 2) porphyritic chondrules with olivine and pyroxene in a poikilitic texture (POP). The meaning of the Clarke's terms GO and GOP were clearly explained by Simon and Haggerty (1979, 1980). According to these authors the term GO indicates at least three different chondrule types: 1) chondrules with euhedral olivine in a glassy mesostasis; 2) chondrules with anhedral olivine embedded in a poikilitic clinoenstatite; 3) chondrules with glassy skeletal olivine; the term GOP (or GO with clinoenstatite) indicates all the other granular olivine chondrules with anhedral or euhedral pyroxene grains. According to Gooding and Keil (1981) the terms GP and GOP are instead used to define chondrules with uniformly small-sized and generally anhedral crystals of pyroxene alone (GP) or olivine and pyroxene (GOP).

The modern terminology is somewhat confusing when used for taxonomic purposes since it doesn't allow a clear distinction between POP chondrules with a poikilitic texture and non-poikilitic POP chondrules. This distinction is fundamental for a classification of the carbonaceous chondrites belonging to the CO, CV and CK groups based on their textural features and for a better comprehesion of the genetic processes that lead to the formation of their chondrules (Olsen and Grossmann, 1978).

On the basis of Simon and Haggerty (1979, 1980) papers we therefore suggest to define the POP chondrules with a poikilitic texture as belonging to the "granular olivine with a poikilitic texture (GO-pk)" type; on the contrary we suggest to define GO the chondrules consisting of forsteritic olivine crystals with no significant mesostasis these terms will be therefore used in all the tables and figures of the present paper.

Even if this acronim doesn't perfectly fit with the description of the petrographic texture, it corresponds very well with the minerochemical classification of chondrules used by Mc Sween (1977a, b), who described our GO-pk type chondrules as chondrules with granular forsterite and twinned clinoenstatite, generally containing droplets of metal (Type I-metal rich).

As the differences among chondrules are probably due to the different physical and chemical conditions presented by the different areas of the solar nebula at the time of their formation (Sears, 2002), detailed studies of chondrule types are important not only for taxonomic purposes but also for improving the knowledge of chondrites and of their genetic relationships, especially those existing among carbonaceous chondrites.

The aim of the present work is therefore to carry out a detailed study of chondrule types and sizes of three new carbonaceous chondrites, namely Acfer 374 (Salvadori *et al.*, 2006), Hammadah al Hamra 337 (Pratesi *et al.*, 2006) and Acfer 366 (Moggi Cecchi *et al.*, 2006), belonging to the CO, CK and CH groups and to suggest a possible new approach to the textural classification of some groups of carbonaceous chondrites and to the interpretation of the genesis of their chondrules.

Samples and analytical methods

Three thin sections for each meteorite (Acfer 374, HaH 337 and Acfer 366) have been prepared in order to get a complete petrographic and compositional analysis. The sections have been obtained cutting the meteorites in three different directions in order to improve the statistical meaning of measures. The main masses and other fragments of these samples belong to the collections of the Museo di Scienze Planetarie della Provincia di Prato (catalogue numbers MSP2283, MSP1592 and MSP2273, respectively). For the petrographic study, a Carl Zeiss AXIOPLAN 2 polarizing optical microscope, equipped with an AXIO-Cam HRC digital camera and the AXIO-VISION 4.1 image-analysis software, has been used.

The thin sections of all the samples have been observed under the optical microscope both in transmitted (TL) and in reflected light (RL) and a quantitative estimate of the relative abundances of the various components (chondrules, matrix, refractory inclusions, fragments and opaque phases) has been performed on five 8.5 mm^2 wide areas of each thin section using the image-analysis software. Furthermore, quantitative data on chondrule sizes have been obtained from at least three measures for each chondrule, performed in reflected light on the same areas. This kind of illumination, was preferred since chondrule rims were more readily detectable. Over these areas detailed analyses on the texture, the mineralogical phases and the chondrule typologies have been performed.

The AXIO-VISION 4.1 image-analysis software accuracy have been determined using a graduated glass 5-mm bore provided by the Zeiss itself as standard. The precision values (2%) have been evaluated on the sample.

The Philips 515 SEM-EDS of the MEMA (Centro di Microscopia Elettronica e Microanalisi of the University of Florence), equipped with an EDAX 9100/60 multichannel system and the FRAME-C (Myklebust *et al.*, 1979) software, has been used to provide BSE images, EDS spectra and semi-quantitative analyses of selected mineral phases. Operating conditions were 25 kV accelerating voltage and 0.7 nA beam current.

The JEOL JXA-8600 EMPA of the IGG (Istituto di Geoscienze e Georisorse – Sezione di Firenze), equipped with a TRACOR NORTHERN II remote control system and operating at 15 kV and 10 nA, has been used for providing quantitative analyses of major and minor elements of previously selected mineral phases. Table 2 reports the elements analized, the counting times, the detection limits and the primary standards used for EMPA analyses.

RESULTS

Both the textural relationships among the components of these meteorites and the chondrule sizes and types have been studied. We hereby report the experimental data on the relative abundances of the components and on the chondrules/matrix ratios together with a brief petrographic description of the components themselves. The definitions of the components and of the chondrules/matrix ratios follow those given by Wasson (1974). As concerns the analysis on chondrule sizes and typologies, a review of the literature (Rubin, 1989), performed on various previously classified carbonaceous

TABLE 2 – *Counting times, detection limits and primary standards used for EMPA analyses. All the stardards were provided by Astimex Ltd, Toronto, Canada except for (a), provided by Smithsonian Institution (USNM-96189).*

Elements	Counting times (s)	Minimum detection limits (wt %)	Primary standards
Si	15	0.07	albite (68.52 wt % of SiO_2)
Ti	15	0.04	ilmenite (45 wt % of TiO_2)[a]
Al	15	0.07	plagioclase (28.53 wt % of Al_2O_3)
Cr	15	0.07	chromite (54.40 wt % of Cr_2O_3)
Fe	15	0.07	ilmenite (46.54 wt % of FeO)[a]
Mg	15	0.06	bustamite (24.31 wt % of MnO)
Mn	15	0.09	olivine (51.57 wt % of MgO)
Ca	15	0.03	diopside (25.73 wt % of CaO)
Na	10	0.07	albite (11.59 wt % of NaO)
K	15	0.02	sanidine (12.11 wt % of K_2O)

chondrites samples (ALH77003, ALH77307, ALH82101, ALH85003, Colony, Felix, Isna, Kainsaz, Lancé, Ornans, Warrenton), allowed to evaluate the numbers of chondrules required to obtain statistically meaningful data for estimating the sizes and for the analysis of typologies. The numbers chosen were 150, 22 and 170 for CO, CK and CH, respectively. Dimensional data have been plotted using frequency histograms, while chondrule typologies data have been summarized with pie chart diagrams. The widths of the frequency classes of histograms have been calculated using the Sturges' rule, which provides the best fitting of data when the statistic sample follows a log-normal distribution.

EMPA analyses were performed on olivine, pyroxene and plagioclase crystals inside chondrules that were previously selected under the optical microscope, in order to determine their minerochemical features and to compare textural and minerochemical data. The mean values and the standard deviations obtained are reported in appendix A, together with some analyses from literature.

Acfer 374: a type 3.0 CO chondrite

As concerns the general features this meteorite shows, in thin section, a marked chondritic texture, with well defined chondrules set in a dark matrix. Chondrules account for about 50% of the total volume, while matrix, refractory inclusions (Amoeboid Olivine Inclusions, AOIs, and Calcium Aluminium Inclusions, CAIs), opaque phases (Fe,Ni alloys, oxides and sulphides) and clasts (olivine and orthopyroxene) account for 30, 10, 5 and 5 vol %, respectively. A chondrules/matrix ratio of 2.3 has been calculated. A glassy groundmass (mesostasis) can be observed in some types of chondrules (PO, POP). An optically isotropic crypto-microcrystalline *matrix* has been observed in the interchondrules spaces. A low amount of *clasts*, mainly represented by olivine and orthopyroxene and with sizes ranging from 140 to 300 μm (mean value on 20 clasts = 220 μm), is present inside the matrix. No feldspars, either inside chondrules or in the matrix, have been observed. *Refractory inclusions*, mainly represented by AOIs and CAIs and with sizes <400 μm, can be also found. Among *opaque phases* troilite is prevailing on magnetite and Fe,Ni alloys: the sulphide/(oxides+alloy) ratio is 4:1. Both kamacite and taenite have been found by SEM investigations as massive aggregates or isolated grains (<40 μm in size and with anhedral to subhedral forms), both inside chondrules or at chondrules rims and in the matrix, where they are frequently associated to troilite. Magnetite is the main primary oxide and can be found in massive circular grains inside chondrules and in the matrix, sometimes intergrown with troilite grains or in very small (~10 μm) inclusions inside olivine crystals. Troilite is present as irregular aggregates or in isolated grains in the matrix or, more rarely, inside chondrules. Other rare Fe,Ni alloys like tetrataenite, $Fe_{0.5}Ni_{0.5}$, and awaruite, Ni_2Fe, have been occasionally found by SEM investigations as very small (<10 μm) grains associated to troilite. An iron-nickel phosphide, namely nickelphosphide $(Fe,Ni)_3P$ (Skala and Drabek, 2003; Geist *et al.*, 2005), has been also detected after careful optical and SEM investigations. It occurs as isolated grains (<10 μm in size) associated to or intergrown with troilite, in the matrix. The study of chondrule sizes and types was carried out on a set of 150 chondrules chosen among those present in the investigated areas of the three sections. Chondrule sizes range from 50 to 450 μm, with an arithmetic mean value of 110 μm and a geometric mean of 100 μm. The frequency distribution of the sizes is log-normal (Fig. 1). The detailed analysis of chondrule typologies allowed to determine the presence of

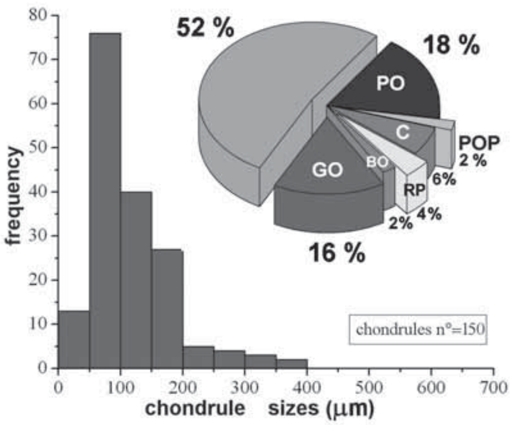

Fig. 1 – Distribution and relative abundances of chondrule sizes and types in Acfer 374.

seven different chondrule types: GO, GO-pk, PO, POP, C, RP and BO. The relative amounts of each type are plotted in Figure 1.

GO (Fig. 2a) and GO-pk (Fig. 2b) chondrules account for 68 % of the total (16 and 52%, respectively). GO chondrules have sizes ranging from 45 to 200 µm and display an equigranular texture. The contacts among crystals appear to be sharp and no mesostasis has been detected. Olivine crystals (Fo_{97-100}) have anhedral to subhedral forms, while pyroxene crystals can be seen on the chondrule rims.

GO-pk chondrule sizes range from 100 to 400 µm; they have a poikilitic texture with

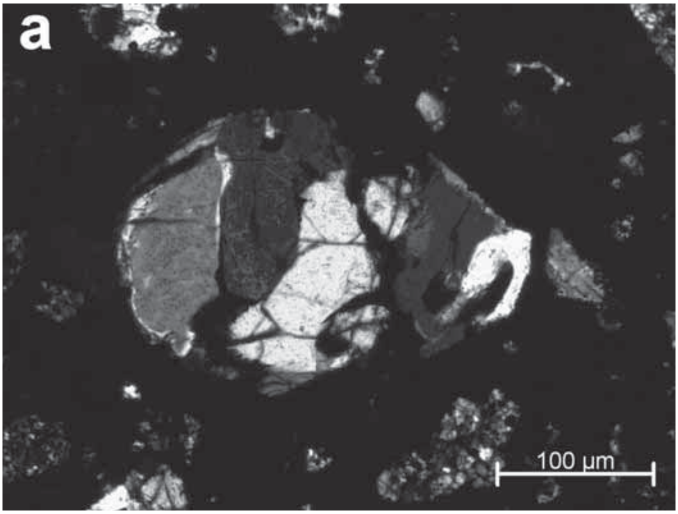

Fig. 2a – Photomicrograph of a granular olivine (GO) chondrule in Acfer 374 (transmitted light, TL, crossed polars, CP).

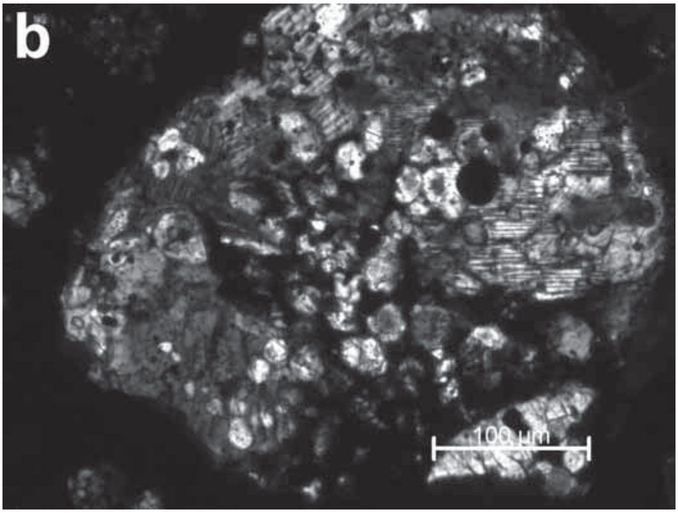

Fig. 2b – Photomicrograph of a granular olivine-poikilitic (GO-pk) chondrule in Acfer 374 (TL, CP).

anhedral to subhedral olivine (Fo_{97-100}) crystals embedded in euhedral and anhedral pyroxene ($En_{83-100}Fs_{0-9}Wo_{0-8}$) crystals. Pyroxene (clinoenstatite) displays a polysynthetic twinning and shows sometimes a deeply fractured and inclusion-rich surface. Modal percentages of olivine, pyroxene and opaque phases are generally 35, 35 and 30%, respectively, but pyroxene-rich (~50 vol%) chondrules can be also found where small anhedral olivine (20%) chadacrysts react with clinoenstatite oikocrysts (Fig. 2b).

EMPA analyses of olivines in GO and GO-pk chondrules are reported in column 1 of appendix A, while column 3 reports the analyses on low-Ca pyroxenes of GO-pk.

PO and POP (Fig. 3a) chondrules account for 20% of the total amount, and show a predominance of PO over POP type (9 chondrules out of 10). They have sizes ranging from 180 to 450 μm, are hypocrystalline and display a porphyritic texture, with extremely variable sizes of the phenocrysts (50 to 400 μm). Olivine crystals are subhedral and range from 50 to 350 μm in size, augitic-diopsidic clinopyroxenes ($En_{56-66}Fs_{0-2}Wo_{32-43}$) are euhedral to anhedral and display elongated to acicular forms, with larger dimensions (<450 μm).

EMPA analyses of olivines in PO and POP chondrules are reported in column 2 of appendix A, while column 4 reports the analyses on Ca-rich pyroxenes of POP chondrules.

The modal percentages of olivine and mesostasis in PO chondrules are 85 and 15%, respectively. POP chondrules display the following percentages: 40, 15, 30, 15 vol % for olivine, pyroxene, mesostasis and opaque phases (metal alloys, oxides and sulphides), respectively. Inside the intracrystalline matrix Fe,Ni alloys and sulphides grains with sizes ranging from 1 to 20 μm and from 5 to 20 μm, respectively, can be occasionally found.

C chondrules, made by submicrometric material, account for 6% of the total and display diameters ranging from 60 to 100 μm.

RP chondrules (Fig. 3b) account for 4% of the total and display perfectly circular shapes with fan-like extinction. They are hypocrystalline chondrules with a radial texture due to the presence of elongated pyroxene crystals radiating from an eccentric point (the so-called excentroradial texture). A Ca-poor pyroxene intergrowth with a Ca-rich mesostasis has been detected by means of SEM-EDS analyses.

BO chondrules account for 2% of the total. They are formed by a set of elongated and oriented olivine crystals intergrown with mesostasis.

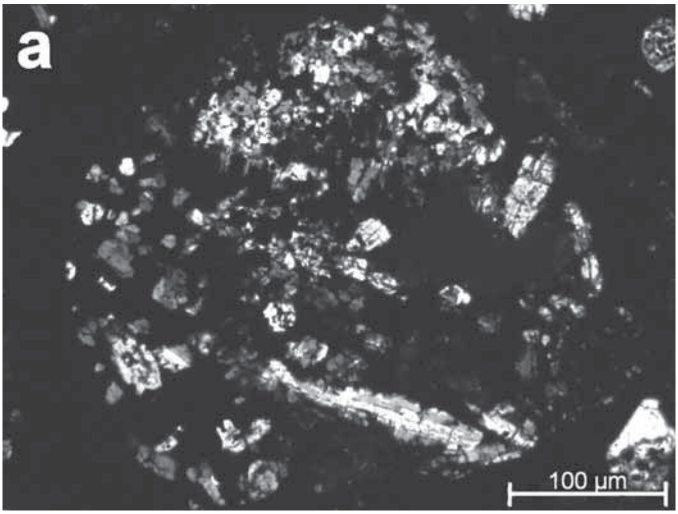

Fig. 3a – Photomicrograph of porphyritic olivine-pyroxene (POP) chondrule in Acfer 374 (TL, CP).

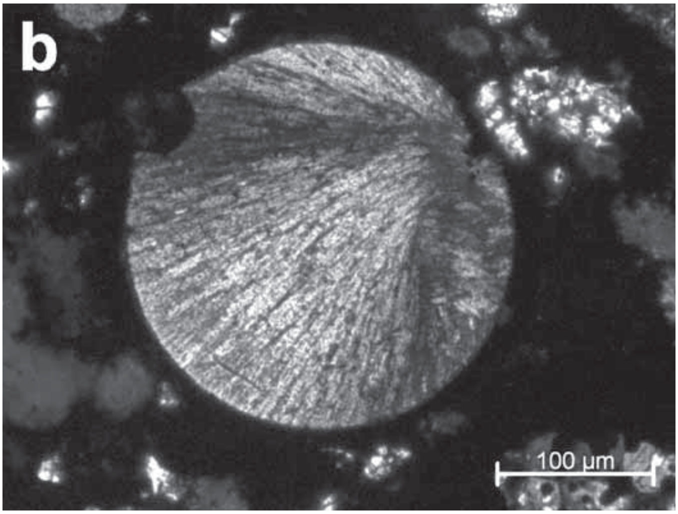

Fig. 3b – Photomicrograph of a radial pyroxene (RP) chondrule in Acfer 374 (TL, CP).

HaH 337: a type 4 CK chondrite

Regarding the general features, the thin sections of this meteorite display a chondritic texture, even if not perfectly defined. Chondrules account for about 20 vol % of the sample, while matrix, refractory inclusions plus clasts and opaque phases account for about 65, 10 and 5 vol %, respectively. A mean chondrules/matrix ratio of 0.5, remarkably lower in comparison with Acfer 374, has been calculated on 3 areas of each section. *Chondrules* are not perfectly defined due to thermal alteration and darkening and they show a devitrified and optically semi-transparent mesostasis. Anyway their rims are still well detectable in reflected light. Millimeter-sized *CAIs* are visible both in the section and in the hand size sample. The *matrix* is hypocrystalline and composed by olivine, plagioclase and pyroxene crystals with sizes ranging from 50 to 1000 µm set in a devitrified mesostasis. A dimensional analysis performed on 40 matrix grains provided an arithmetic mean value of 100 µm. Silicate phases inside chondrules and, more frequently, in the matrix are darkened. Olivine crystals have subhedral forms and sizes ranging from 10 to 200 µm (mean 100 µm). Plagioclase is present as euhedral or anhedral crystals with a mean size of 150 µm. Pyroxene occurs as euhedral crystals with sizes ranging from 100 to 400 µm in length. Rare opaque phases grains can be found in the matrix. A devitrified *mesostasis*, displaying irregular forms like globular or fibrous-radiated aggregates, can be found both inside chondrules and in the matrix. Primary oxides, overall represented by *magnetite*, are the main opaque phase. It can be found, inside and around chondrules, as granular masses with maximum dimensions ranging from 30 µm inside chondrules and 50 µm around them. *Sulphides* are rare and mainly represented by pyrrothite and pyrite massive aggregates of grains inside the matrix or, more rarely, as isolated subhedral grains inside chondrules. Metal alloys are rare (less than 1 vol %), and can be found as small (<10 µm) grains of kamacite and taenite inside olivine crystals. Extremely rare findings of magnetite-sulphides spherical aggregates have been noticed (Fig. 4). These chondrules display a granular texture, with grains ranging from 10 to 50 µm in size and they are rimmed by magnetite grains <5 µm in size. Very small (~5 µm) and rare grains of a platinum telluride (chengbolite, $PtTe_2$) have been detected by SEM investigations.

Since the thin sections of the sample HaH 337 contain a very low amount of chondrules, all of them (22) were measured and analyzed. Chondrule sizes range from 200 to 2000 µm (Fig. 5), with an

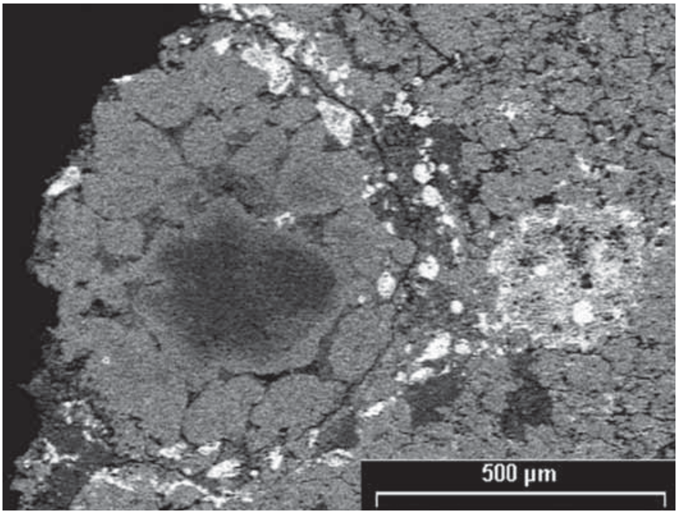

Fig. 4 – SEM-BSE image of a porphyritic olivine (PO) chondrule (left) and of a magnetite-sulfides chondrule (right) in HaH 337.

arithmetic mean of 700 μm and a geometric mean of 650 μm. The detailed analysis of chondrule types put in evidence a distribution completely different from that of Acfer 374: the chondrule types detected were PO, POP and GO-pk. The relative abundances are reported in Fig. 5.

PO chondrules (Fig. 4 and 6) are the most abundant and account for 68% of the total. Their sizes range from 390 to 1150 μm. They are hypocrystalline chondrules displaying a porphyritic, sometimes serial, texture. The mineralogical phases detected are olivine and plagioclase, with a relative modal abundances ratio of 3:1.

Olivine crystals (Fo_{68-75}) are subhedral and display sizes ranging from 20 to 80 μm. Plagioclase crystals are commonly distributed on chondrule rims. The plagioclase (An_{20-45}) shows neither euhedral forms nor polysynthetic or Albite-Karlsbad twinning. Equant to euhedral magnetite grains are visible outside and inside the chondrule. Sulphide and metal alloys are rare: kamacite is occasionally diffused as small inclusions (<5-10 μm in size) inside olivine crystals. EMPA analyses of olivines in PO and POP chondrules are reported in column 5 of appendix A, while column 9 reports the analyses on plagioclase of PO chondrules.

POP chondrules are less abundant than PO and account for 14 % of the total. They display sizes ranging from 350 to 1800 μm and are characterized by a porphyritic texture with olivine crystals ranging from 50 to 300 μm in size. Pyroxene ($En_{36-61}Fs_{0-17}Wo_{34-50}$) is usually euhedral and displays sizes ranging from 50 to 500 μm. The mesostasis, olivine, pyroxene and plagioclase account for 20, 60, 10 and 10 vol % of each chondrule. Magnetite can be observed on chondrule rims. Olivine

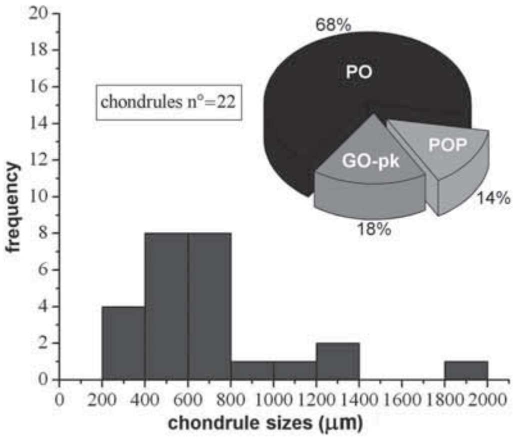

Fig. 5 – Distribution and relative abundances of chondrule sizes and types in HaH 337.

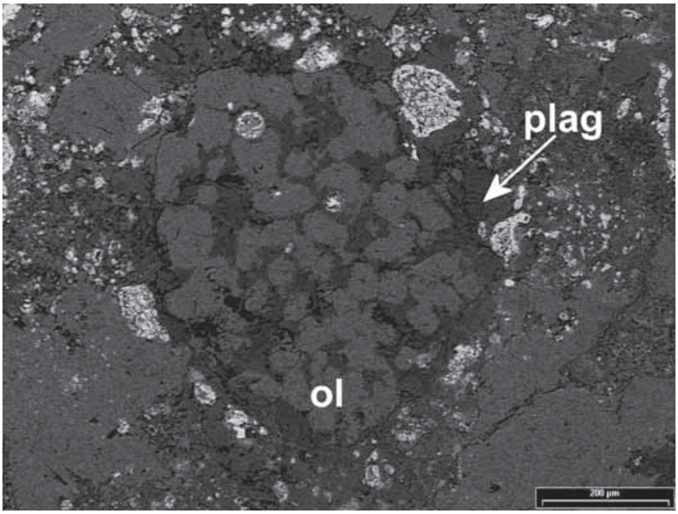

Fig. 6 – SEM-BSE image of a porphyritic olivine (PO) chondrule in HaH 337; plag = plagioclase, ol = olivine.

crystals of both PO and POP chondrules are compositionally zoned, with Mg-rich cores. The mesostasis appears dark and displays an anorthitic composition (An_{45}). EMPA analyses of Ca-rich pyroxene in PO and POP chondrules are reported in column 8 of appendix A.

GO-pk chondrules account for 18 % of the total. Their dimensions range from 120 to 800 µm and they display a poikilitic texture, with subhedral olivine (Fo_{68-75}) crystals enclosed in euhedral pyroxene ($En_{83-97}Fs_{0-12}Wo_{0-3}$) crystals with sizes ranging from 50 to 200 µm. The relative abundances of pyroxene and olivine inside GO-pk chondrules are 70 and 30 vol %, respectively. EMPA analyses of olivines and low-Ca pyroxene in GO-pk chondrules are reported in column 6 and 7 of appendix A, respectively.

Groundmass is almost absent, while magnetite grains are frequently seen both at chondrule rims and inside them. Sulphides and Fe,Ni alloys are rare.

Acfer 366: a type 3 CH chondrite

The thin sections of this meteorite display a chondritic texture, with completely different relationships among the components when compared with those of the previously described meteorites. Chondrules account for about 35 vol % of the sample, while opaque phases, clasts, refractory inclusions and matrix account for about 25, 30, 5 and 5 vol % of the sample, respectively. A mean chondrules/matrix ratio of 19 has been calculated on 3 areas of each section. *Chondrules* are well defined and a glassy isotropic mesostasis can be occasionally found in some types. *Fragments* are represented by olivine and orthopyroxene, the former in subhedral crystals and the latter in elongated euhedral crystals, often recrystallized; their sizes range from 65 to 350 µm, with a mean value of 130 µm (calculated on 50 fragments). They often display fractures and undulated extinction. The matrix displays a cryptocrystalline texture and is optically isotropic; it is mainly distributed inside fractures and between chondrules and fragments. *Opaque phases* are abundant and mainly represented by Fe,Ni alloys (mostly kamacite and occasionally taenite, tetrataenite and awaruite), which account for 20 vol % of the sample. Kamacite can be found in irregular massive aggregates with sizes ranging from 10 to 200 µm mainly in the spaces between chondrules and in the matrix or, more rarely, inside PO-POP or GO-pk chondrules. Several goethite and lepidocrocite rims due to terrestrial alteration can be found around the metal. *Sulphides* (5 vol

%) are mainly represented by a Ni-rich (0-2 wt. %) troilite which forms irregular aggregates, mostly in the spaces between chondrules or (more rarely) inside chondrules, whose sizes range from 10 to 150 µm. Small (<10 µm) troilite inclusions can be occasionally found inside kamacite grains.

All of the thin sections of Acfer 366 show an amount of chondrules comparable with that of Acfer 374. A total amount of 170 chondrules has been chosen both for the dimensional analysis and for the study of chondrule types. Their sizes range from 35 to 450 µm (Fig. 7), with an arithmetic mean value of 110 µm and a geometric mean of 100 µm. The chondrule types detected were C, POP, GO-pk and BO. The measured relative abundances are plotted in Fig. 7. The most abundant typology is represented by C chondrules, which account for 70% of the total and display a cryptocrystalline or microporphyrithic texture, with different sizes (50-200 µm and 100-300 µm, respectively). Cryptocrystalline chondrules display submicroscopic (less than 1 µm) crystals of pyroxene. On the contrary microporphyrithic are characterized by the presence of up to 10 µm-wide pyroxene grains set in a cryptocrystalline groundmass.

C chondrules (Fig. 8a) show well defined circular shapes, with a great amount of fractures filled with matrix and oxides. Opaque phases are extremely rare inside them while, more frequently, they are surrounded by metal alloys.

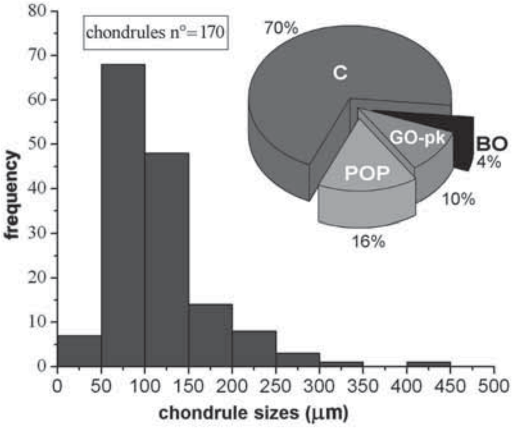

Fig. 7 – Distribution and relative abundances of chondrule sizes and types in Acfer 366.

POP chondrules account for about 16% of the total. The modal abundances of olivine and pyroxene inside chondrules are variable from 40 to 90 and from 10 to 60 vol %, respectively. Olivine crystals (Fo_{60-90}) are subhedral and display a mean dimension of 100 µm.

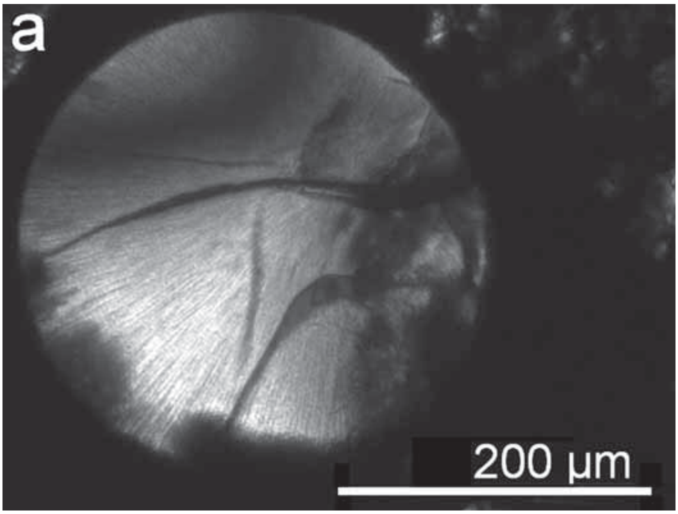

Fig. 8a – Photomicrograph of a cryptocristalline (C) chondrule in Acfer 366 (TL, CP).

Pyroxene ($En_{91-97}Fs_{0-3}Wo_{1-8}$) is present as elongated euhedral crystals with dimensions ranging from 50 to 150 µm. A fibrous-radiating microcrystalline mesostasis can be observed in the intergranular spaces. Subhedral grains of plagioclase with mean sizes <50 µm settled in the glassy mesostasis and showing an anorthitic composition (An_{75-100}) are occasionally found. EMPA analyses of olivines, low-Ca pyroxenes and plagioclase in POP chondrules are reported in columns 11, 12 and 13 of appendix A.

GO-pk chondrules account for about 10 % of the total. Their dimensions range from 75 to 350 µm and they are characterized by a poikilitic texture. Olivine crystals (Fo_{90-100}) display euhedral or subhedral forms and their modal abundances account for a volume percentage variable from 20 to 80 %, even if an olivine/pyroxene ratio of 1:1 is more common. Pyroxene displays anhedral forms, is polysynthetically twinned and shows a poikilitic texture with forsterite chadacrysts. Opaque phases, mainly represented by Fe,Ni alloys, oxides and sulphides are present in anhedral or circular forms with sizes <50 µm. EMPA analyses of olivines in GO-pk chondrules are reported in column 10 of appendix A.

BO chondrules (Fig. 8b) have sizes ranging from 50 to 300 µm. They are characterized by fractures and alterations that sometimes hide the typical barred texture. Opaque phases are almost absent, even if they can be occasionally found outside chondrules and on their rims.

Discussion

The high amount of data on general features, minerochemical compositions and chondrule sizes and typologies of the three meteorites allowed us to univocally classify them.

Several data point to a classification of the sample Acfer 374 as a CO 3.0 chondrite: the chondrules/matrix ratio (2.3) is in good agreement with Wasson (1974) data; the presence of kamacite and taenite as aggregates inside chondrules or at chondrule rims was reported for other CO chondrites by Imae and Kojima (2000); tetrataenite and awaruite were already reported in CV and CO carbonaceous chondrites by Brearley and Jones (1998). Literature data for the mineral phases of chondrule types of CO chondrites (Scott and Jones, 1990; Noguchi, 1989) are in agreement with our EMPA data.

From a textural point of view the arithmetic mean of chondrule sizes (110 µm) is in good agreement with literature data for CO chondrites (Rubin,

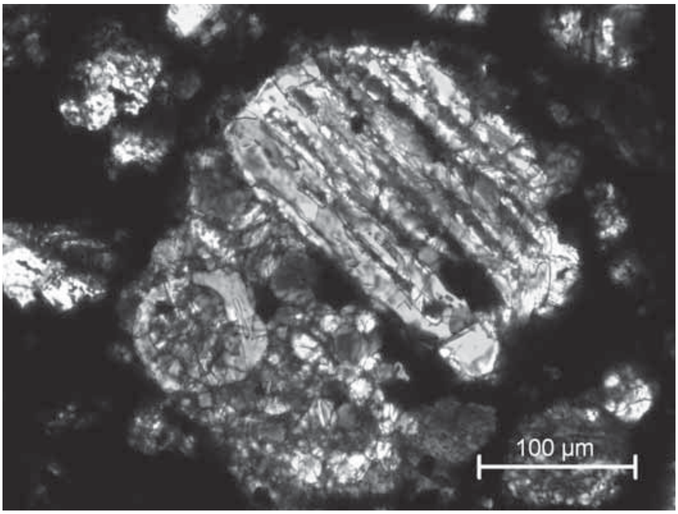

Fig. 8b – Photomicrograph of a barred olivine (BO) chondrule in Acfer 366 (TL, CP).

1989). The relative abundances of chondrule types correspond to those indicated by Brearley and Jones (1998) and Rubin (1989) for CO chondrites. Moreover, as already indicated by Mc Sween (1977a, 1977b, 1977c), GO-pk chondrules of CV and CO groups also contain metallic phases like kamacite and taenite.

As concerns HaH 337 the classification as CK4 is based on petrographic observations like the arithmetic mean value (100 μm) of matrix grains size, which is in agreement with Noguchi (1993) data on CK4-6 carbonaceous chondrites, as well as on the "darkening" of silicate phases inside chondrules and matrix, already reported by Tomeoka *et al.* (2001) for CK chondrites. Chondrules poor definition, which suggests a petrologic type 4, is a consequence of the reaction between them and the matrix, owing to the thermal alteration. The rarity of Fe,Ni alloys (less than 1 vol %), is in agreement with Brearley and Jones (1998) data for CK chondrites. Another characteristic, indicated by Rubin (1993) as typical of CK chondrites, is the presence of extremely rare findings of the spherical aggregates of opaque phases called "magnetite-sulphides chondrules", as well as the presence of chengbolite (Geiger and Bischoff, 1995). EMPA data on the mineral phases of various kinds of chondrules are in agreement with literature data for CK chondrites (Rubin *et al.*, 1988; Noguchi, 1993; Keller *et al.*, 1992).

As concerns chondrule sizes the arithmetic mean value of 700 μm is in agreement with literature data for CK chondrites (Rubin, 1989), as well as the total amount (18%) of GO-pk chondrules (Kallemeyn *et al.*, 1991).

For Acfer 366 the classification as CH3 chondrite arose from textural features like the high abundance of fragments (which are related to the fragmentation of C and BO chondrules, Weisberg *et al.*, 1988), often displaying fractures and undulated extinction (Bischoff *et al.*, 1993) as well as from the analysis of chondrule sizes and typologies. The chondrule sizes mean value (110 μm), the ranges (35-450 μm) and the relative abundances of chondrule types fit well with Bischoff *et al.* (1993) and Weisberg and Kimura (2004) data on CH chondrites. Furthermore EMPA data are in agreement with literature data for CH chondrites (Grossman *et al.*, 1988; Krot and Keil, 2002).

Conclusions

Chondrule sizes play an important role in the taxonomy of carbonaceous chondrites. For example the assignment to the CH group, as Acfer 366 can be easily performed on the basis of chondrule sizes, since the CH and CB groups, which display similar chondrule types and similar relative abundances, have extremely different mean chondrule sizes. Moreover chondrule sizes can be important for discriminating CO, CV and CK groups.

From a genetic point of view, the dimensional analysis on chondrules shows that, in most cases, their sizes follow an asymmetric distribution (log-normal). This distribution was indicated by several authors (Nelson and Rubin, 2002; Nettles and Mc Sween, 2005) as due to the influence of various genetic (chondrules coalescence, presence of relic grains acting as condensation nuclei, presence of electromagnetic fields or of thermal shocks) or post-genetic processes (like the chondrule fragmentation inside parent-bodies) that play contrasting roles in defining chondrule mean sizes. Chondrule mean sizes are also different for the various chondrule types since the extreme variability of circumstances in which they can be formed or modified, both before and after the accretion in parent-bodies, reflects on their mean sizes.

On the other hand the study of chondrule typologies is one of the few available tools for the distinction between groups displaying similar chondrule sizes, like oxidized CV's and CK or CO and CH. Our proposal of a new acronym (GO-pk chondrule type) allows a better distinction among different chondrule types that may significantly improve the textural classification of carbonaceous chondrites based on chondrule typologies. As a matter of fact, the use of this new acronim along with the compositional data on mineral phases in chondrules, helped us to univocally assign the meteorite HaH 337 to the CK group and the meteorite Acfer 374 to the CO group. To a further extent the distinction between CO and CH groups, which display similar chondrule sizes, is relatively straightforward on the basis of chondrule typologies.

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Although this special issue is entirely dedicated to Dr. Filippo Olmi, nevertheless we wish to remember again Filippo as a scientist, a colleague and, above all, a friend. His help, even in this paper, was fundamental to solve several analytical problems. This paper was supported by the PNRA 2004-2006 and RAS Paneth Trust funds.

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Appendix A

EMPA analyses on selected mineral phases inside various chondrule types. The numbers on column tops are referred to the text; numbers of analyses are in brackets; bdl = below detection limit; SD = standard deviation. Reference data are from the following papers: A-B) Scott and Jones (1990); C-D) Noguchi (1989); E) Rubin *et al.* (1988); F-G-H) Noguchi (1993); I) Keller *et al.* (1992); J-K) Grossman *et al.* (1988); L) Krot and Keil (2002).

	Acfer 374											
	(GO/GO-pk)			2 (PO-POP)			3 (GO-pk)			4 (POP)		
	Olivine			Olivine (FeO-rich)			Pyroxene (low-CaO)			Pyroxene (high-CaO)		
Oxide (wt %)	Ref. A	Mean (15)	SD	Ref. B	Mean (15)	SD	Ref. C (22)	Mean (10)	SD	Ref. D (11)	Mean (15)	SD
SiO_2	41.90	42.3	1.02	37.6	38.3	1.32	58.4	58.1	1.75	56.06	53.0	3.23
TiO_2	bdl	0.08	0.05	0.01	bdl	bdl	0.2	0.21	0.16	0.96	0.84	0.18
Al_2O3	0.06	0.17	0.11	0.06	bdl	bdl	1.2	1.23	1.11	3.88	5.42	4.44
Cr_2O_3	0.42	0.26	0.16	0.36	0.41	0.05	0.7	0.78	0.31	0.85	0.82	0.32
FeO	1.30	2.45	3.56	28.2	25.1	8.97	1.26	2.17	1.56	1.96	0.76	0.34
MnO	0.18	0.19	0.02	0.29	0.16	0.08	0.16	0.19	0.07	0.23	0.22	0.09
MgO	56.2	55.3	2.89	33.7	37.1	7.13	38.02	36.6	1.92	21.03	21.2	2.96
CaO	0.25	0.28	0.19	0.25	0.18	0.10	0.98	1.46	1.06	18.54	18.6	1.22
Na_2O	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.07	0.02	0.03
K_2O	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.07	bdl	bdl	bdl	bdl
Tot	100.46	100.77		100.47	101.08		100.94	100.77		100.57	100.85	

	HaH 337														
	5 (PO-POP)			6 (GO-pk)			7 (GO-pk)			8 (PO-POP)			9 (PO)		
	Olivine			Olivine			Pyroxene (low-CaO)			Pyroxene (high-CaO)			Plagioclase		
Oxide (wt. %)	Ref. E (67)	Mean (15)	SD	Ref. F	Mean (18)	SD	Ref. G	Mean (16)	SD	Ref. H	Mean (17)	SD	Ref. I	Mean (14)	SD
SiO_2	42.2	42.60	1.03	37.46	38.0	0.70	52.7	53.3	0.97	55.35	56.8	2.2	56.8	60.3	2.18
TiO_2	bdl	bdl	0.05	bdl	0.07	0.04	0.34	0.47	0.60	0.1	0.2	0.0	bdl	0.02	0.03
Al_2O3	bdl	bdl	0.13	0.02	0.06	0.09	1.66	2.86	2.59	1.56	0.9	0.6	26.9	24.5	1.68
Cr_2O_3	0.21	bdl	0.2	bdl	0.12	0.03	0.35	2.61	0.06	0.27	0.8	0.7	bdl	0.05	0.06
FeO	2.8	1.18	0.9	26.4	26.3	2.20	6.65	5.28	3.21	11.01	7.2	4.2	1	0.65	0.64
MnO	0.09	bdl	bdl	0.18	0.23	0.05	0.13	0.09	0.02	0.14	0.1	0.0	bdl	0.01	0.03
MgO	54.8	55.50	1.2	35.1	36.3	1.79	15.47	16.7	3.50	30.33	34.0	2.6	0.07	0.62	1.37
CaO	0.28	0.75	0.15	0.04	0.19	0.20	22.31	21.5	3.66	1.02	0.7	0.6	8.2	6.69	1.35
Na_2O	bdl	bdl	bdl	0.02	bdl	0.00	0.17	0.11	bdl	0.02	0.0	bdl	6.6	7.21	0.68
K_2O	bdl	bdl	bdl	0.01	bdl	bdl	bdl	0.02	bdl	0.01	0.0	bdl	0.6	0.12	0.11
Tot	100.38	100.03		99.81	101.19		99.86	99.72		99.91	100.0		100.17	100.16	

	Acfer 366										
	10 (GO-pk)			11 (POP)		12 (POP)			13 (POP)		
	Olivine			Olivine		Pyroxene (low-CaO)			Plagioclase		
Oxide (wt %)	Ref. J (76)	Mean (18)	SD	Mean (10)	SD	Ref. K (15)	Mean (15)	SD	Ref. L	Mean (15)	SD
SiO_2	41.9	41.5	2.5	36.9	0.8	55.8	57.3	1.87	45.6	45.4	0.22
TiO_2	bdl	0.0	0.0	bdl	bdl	0.17	0.18	0.08	0.12	0.08	0.05
Al_2O3	bdl	0.1	0.1	bdl	bdl	2	1.06	0.55	34.0	33.6	0.64
Cr_2O_3	0.46	0.4	0.2	bdl	bdl	0.77	0.52	0.39	bdl	0.02	0.05
FeO	2.63	7.4	11.6	32.8	3.0	3.15	2.74	2.61	0.33	0.89	0.49
MnO	0.13	0.1	0.2	0.41	0.09	0.24	0.17	0.02	bdl	0.00	bdl
MgO	54.8	51.4	9.9	30.5	2.5	35.2	37.2	2.40	0.61	0.55	0.10
CaO	0.28	0.3	0.1	0.08	0.03	1.8	1.71	1.14	19.9	19.0	0.37
Na_2O	bdl	bdl	bdl	bdl	bdl	bdl	0.08	bdl	0.45	0.39	0.15
K_2O	n.d.	bdl	0.0	bdl	bdl	bdl	0.02	0.00	bdl	0.01	0.01
Tot	100.20	101.3		100.68		99.10	100.05		100.1	99.96	