Arquivos do Museu Nacional, Rio de Janeiro, v.66, n.3-4, p.611-629, jul./dez.2008
ISSN 0365-4508

STUDIES OF BRAZILIAN METEORITES OF THE MUSEU NACIONAL - I: PETROGRAPHY AND MINERALOGY OF THE SANTA VITÓRIA DO PALMAR, RIO GRANDE DO SUL, L 3 CHONDRITE METEORITE [1]

(With 24 pictures)

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ABSTRACT: The Santa Vitória do Palmar chondrite was found in 2003 in Rio Grande do Sul State, Brazil (33°30'56"S, 53°24'65"W). It consists of three masses (34kg, 4.34kg and 1.57kg). Showing, a black rusty-colored fusion crust and several distinct depressions (regmaglypts). It is not know if this find is correlated with a bright fireball seen in 1997 at the same region. Optical investigation shows that the meteorite has a well developed chondritic texture typical of type 3 chondrite. There are chondrules of different types (radial-pyroxene, barred-olivine and cryptocrystalline; porphyritic olivine, porphyritic pyroxene and porphyritic olivine-pyroxene; granular olivine, and compound chondrules) very well delineated many times surrounded by troilite and Huss matrix. Mineralogical studies reveal that the meteorite contains chiefly olivine Fa $_{(0.5\text{-}35.2)}$, pyroxene Fs $_{(0.5\text{-}31.6)}$, with small amount of Fe-Ni metal (kamacite, taenite and plessite) and troilite. Based on texture features and chemical data, the Santa Vitoria do Palmar meteorite is classified as an unequilibrated member of the L group chondrite. The well defined chondritic texture and the presence of glassy material indicate a petrologic type of 3 subtype 3.4-3.6, shock-stage S3/4 and weathering grade W1/2.

Key words: Petrography. Mineralogy. Meteorite. Chondrite. Santa Vitória do Palmar.

RESUMO: Estudo dos meteoritos brasileiros do Museu Nacional – I: petrografia e mineralogia do meteorito condrito l3 Santa Vitória do Palmar, Rio Grande do Sul.

O condrito Santa Vitória do Palmar, foi achado em 2003 no Estado do Rio Grande do Sul, Brasil (33°30'56" S, 53°24'65"W). Consiste em três massas (34kg, 4,34kg e 1,57kg), exibindo crosta de fusão preta e enferrujada e várias depressões (regmaglitos). Não se sabe se o achado está correlacionado com o bólido brilhante observado em 1997 na mesma região. Investigações microscópicas mostram que o meteorito apresenta textura condrítica bem desenvolvida típica do tipo 3. Apresenta côndrulos de diferentes tipos (piroxênio-radial, olivina-barrada, criptocristalino; olivina-porfirítica, piroxênio-porfirítico, olivina-piroxênio porfirítico, olivina granular e côndrulos compostos) muito bem delineados, por vezes, circundados por toilita e matriz Huss. Estudos mineralógicos mostram que o meteorito contém principalmente olivina Fa $_{(0.5\text{-}35.2)}$, piroxênio Fs $_{(0.5\text{-}31.6)}$, com pequena quantidade de Fe-Ni metálico (kamacita, taenita e plessita), troilita. Com base nas feições texturais e dados químicos, o meteorito Santa Vitória do Palmar está classificado como membro inequilibrado do grupo L condrito. A textura bem definida e a presença de material vítreo indicam o tipo petrológico 3 e subtipo 3,4-3, 6, com estágio *de* choque S3/4 e grau de intemperismo W1/2.

Palavras-chave: Petrografia. Mineralogia. Meteorito. Condrito. Santa Vitória do Palmar.

INTRODUCTION

This paper is the first of a series of systematic studies of meteorites housed in the meteorite collection of the Department of Geology and Paleontology of the Museu Nacional, Universidade Federal do Rio de Janeiro. The collection consists of 15 falls and 25 finds taken from the 55 known Brazilian meteorites. Although many of the stone meteorites of the collection were described in many papers at the 1970s that culminated with the book Brazilian Stone Meteorites (Gomes & Keil, 1980), some new meteorites arrived and remain without descriptions and others are not well known.

Chondrites are complex and poorly understood, there are few studies of their internal textures being the dominating chondritic studies resumed in chemical and isotopic analyses.

[1] Submitted on April 12, 2007. Accepted on July 18, 2008.
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Due to the lack of information about this matter and by the intention of this article be the first of a series, a brief review of chondrules types is given here to serve as a reference to assist and incentive newly interested researches on meteoritics in Brazil.

The newest Brazilian chondrite, found in Santa Vitória do Palmar, Rio Grande do Sul, is described here based on optical and electron microscope analyses.

History

A mass of 34kg was found on March 25-26th, 2003 by Roberto Maciel while searching for indian arrow heads in the Holocene sand-dunes along Mirim lagoon in the vicinity of Santa Vitória do Palmar city at Rio Grande do Sul State (Fig.1). The find is a remarkably large black and rusty-colored stone exhibiting several distinct depressions (regmaglypts). These characteristics made Maciel suspect that he had, in fact, found a meteorite. He continued his search in the following weeks and found two other smaller masses of 4.34kg and 1.57kg.

Some years before, on June 25, 1997 (07:00h), a bright fireball accompanied by a loud series of thunderclaps and a black smoke trail was seen by many witnesses along the border of Brazil and Uruguay. The following day, *Zero Hora* (a newspaper based in Porto Alegre) ran headlines reading "*Objeto luminoso intriga moradores de duas cidades*" ("Fiery object intrigues citizens of two cities"). It seemed that the bolide came out of the north, following along the edge of Mirim lagoon and heading towards Chui city, at frontier with Uruguai. The probable impact zone was situated between Santa Vitória do Palmar and northern Chui. Many eyewitnesses agreed that the object fell in an area known as the "*Chácara dos Pinhais*". A day-long search for the meteorite was made on the Brazilian side of the border by civil police officer Luiz Cavalheiro in the area of Santa Vitória do Palmar, without results. After, officials of the airbase Santa Maria revealed that their radar had not registered any objects in the sky on the day of the fall and the search was terminated.

Maciel's find did not call the attention of the rural community as at the bolide event some years before. Only José Maria Monzon Pereira, the curator of the local museum became very interested in the find as soon as he heard about it and succeeded in acquiring the two smaller masses for his museum, the *Museu Municipal Coronel Tancredo F. de Mello Brazil.* Pereira also documented the location and circumstances of the find and it has been due to his work that both masses have been preserved. Unfortunately, the larger find, supposedly in the possession of a professor of one University of Rio Grande do Sul, who had borrowed it for study and disappeared. Maciel has since died and no one else remembers this professor's name or where the meteorite might be.

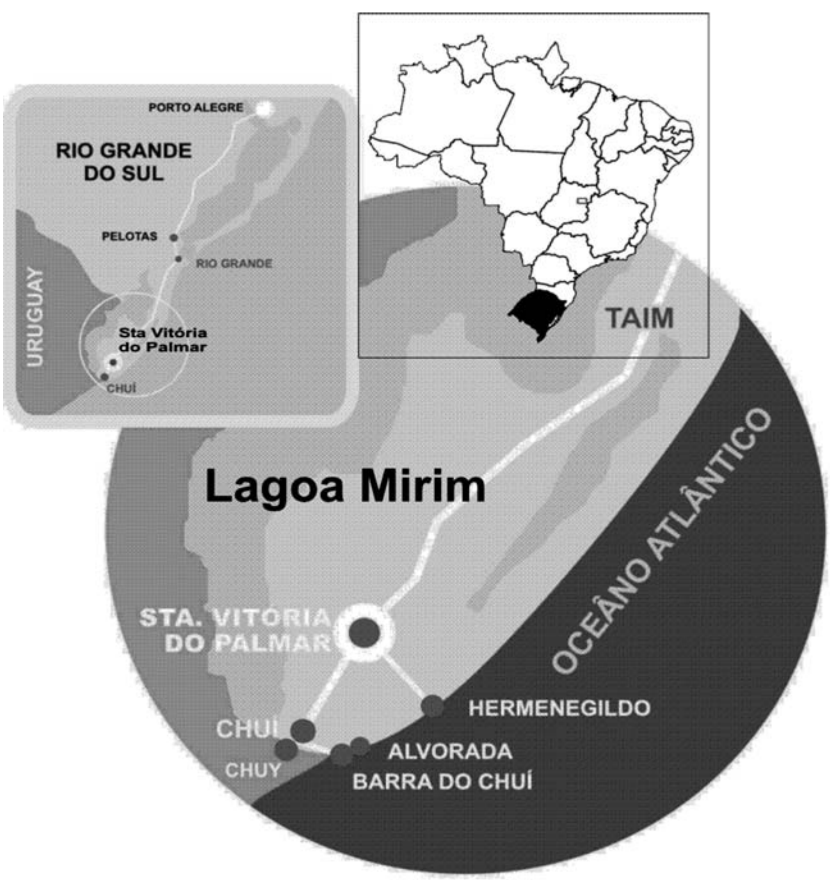


Fig.1- Location map of the recovery site of the Santa Vitória do Palmar meteorite at the frontier Brazil-Uruguay.

On February 14, 2004, a new mass weighing 10.45kg was found at 33°30’56”S 53°24’65”W by Laurato Correa, a local rock-hound and fossil expert, while out searching for fossils. Correa recognized the object’s regmaglypts and its similarities to the meteorites found earlier and he sent a sample of the mass to Germany. The meteorite was analyzed by Dr. Ansgar Gresshake and submitted to the Nomenclature Committee (NomCom) of the Meteoritic Society. The results of the analysis were published in the Meteoritic Bulletin Nº 91 (Gresshake, 2007), but correlation between the observed fireball and the meteorite find was not widely accepted.

MATERIAL AND METHODS

A thin slice sample of Santa Vitória do Palmar meteorite (SVP) with 26g was donated by José Maria Monzon to the Meteorite Sector of Museu Nacional. From this sample a piece was cut and two polished thin sections were prepared. They were photographed and studied by optical microscopy in transmitted and reflected light, and analyzed by x-ray diffraction and scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS).

RESULTS

The degree of exterior weathering of SVP could not be verified since the fusion crust was not present in the received section. As informed in the Meteoritical Bulletin Nº 91, all fragments recovered are at least partly covered with fusion crust. The affordable published pictures of the meteorite show that part of the fusion crust is still preserved; there are also visible many finger prints (regmaglypts), which helped the finders to recognize the meteorite nature of the rocks.

Chemical Analyses

The chemical analyses were performed by Dr. Ansgar Greshake from Berlin Museum of Natural History at Humboldt University of Berlin and submitted to the Nomenclature Committee (NomCom) of the Meteoritical Society and published in the Meteoritical Bulletin Nº 91. Olivine and Pyroxene analyses yielded Fa0.5-35.2 and Fs0.5-31,6 respectively. Classification: Ordinary Chondrite (L3), S3/4, W2.

Petrographic Description

Texture

On an overview of Santa Vitoria do Palmar (SVP) under hand lens observation revealed a very developed chondritic texture characterized by the presence of abundant deformed chondrules (Fig.2). Despite this, it displays a wide variety of intact sharply defined chondrules ranging from all sizes but most between 0.2 to 1.0mm in apparent size, with the largest 4.5mm which are typical of type 3 ordinary chondrites (van schmus & wood, 1967; zanda, 2004). This chondrite specially shows a great variety of chondrules types.

The chondrules are somewhat elongated and surrounded by: opaque rims of troilite-silicates-oxides set into a very few matrix of mineral fragments: Fe-Ni-metal; glass; iron oxide and hydroxides. Broken and deformed chondrules are abundant and the few matrix is composed, at least in part, of crushed chondrules silicates. Many chondrules contain glass which may be turbid or clear. Terrestrial weathering is visible in persuasive reddish staining of crystals, by veins and larger patches of hydroxides.

The Matrix

This chondrite shows few matrix in which most chondrules are molded around each other without any matrix separating them resembling to compound chondrules. In SVP there are three different interrelations among chondrules, isolated minerals and fragments of minerals and chondrules.

1) Chondrules rimmed by opaque minerals, mostly troilite. The opaques sometimes fill all the interstitial space between two or more chondrules (Fig.3).

2) Fe-rich silicate matrix quite opaque, typical of type 3 chondrites, also referred as “Huss matrix” (Huss & Keil, 1981) (Fig.3).

3) Coarse-grained silicate, clastic groundmass characterized by well-defined patchy areas and sometimes by different colors, showing crystals from crystalline to coarse crystalline material of similar bulk mineralogy. This matrix is somewhat translucent with a multitude of black opaque inclusions (metallic iron-nickel, troilite and iron oxides) numerous angular and euhedral grains of olivine, pyroxene and glass. Sulfide (troilite), metal (plessite-kamacite-taenite) and iron oxides and hydroxides surround most of chondrules and also appear as veins permeating the matrix (Fig.3).

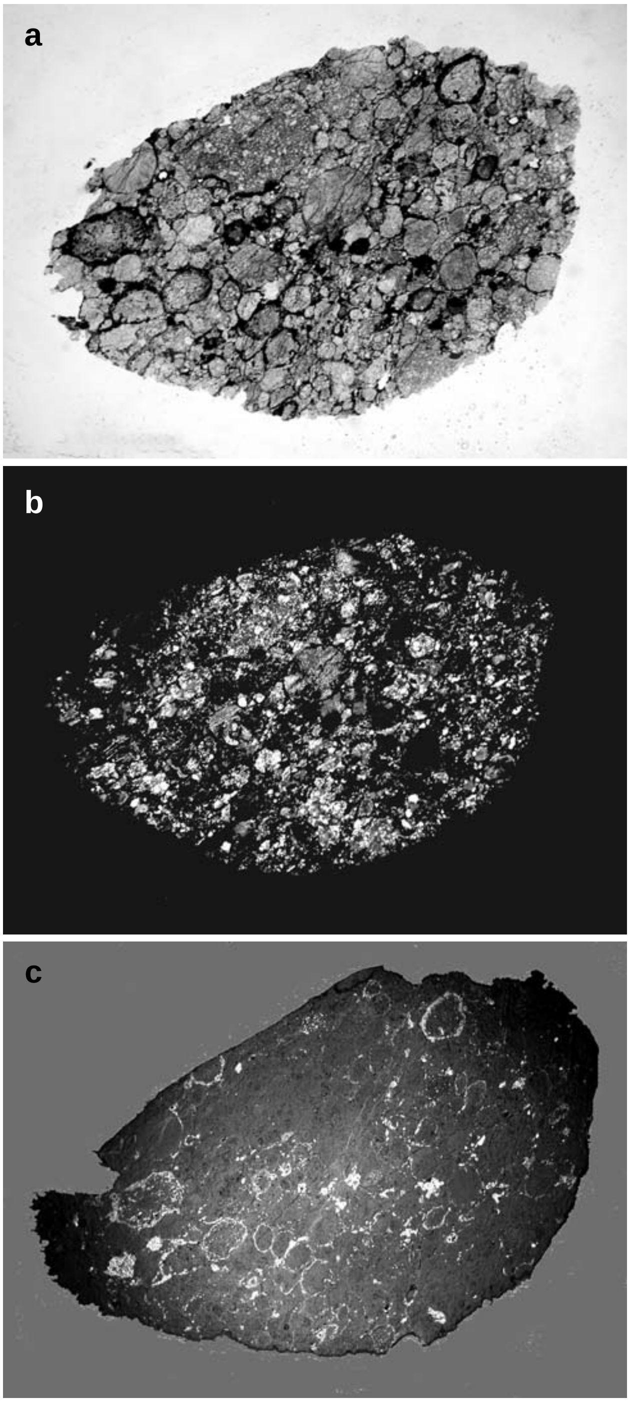


Fig.2- The whole thin section of Santa Vitória do Palmar (SVP) photographs: a) in transmitted light, b) polarized transmitted light and c) reflected light; showing abundant well defined and deformed chondrules surrounded by metal and troilite. Most chondrules are molded around one another resembling a compacted "sediment" of sub-spherical particles and a fine-grained silicate matrix. This structure is typical of type 3 ordinary chondrites. Length of field 2.0cm.

The Chondrules

Chondrules are the most abundant component of the chondrites. The majority of chondrules are sub-millimeter-sized, igneous spheres or ellipsoids consisting predominantly of ferromagnesian silicate material (olivine, pyroxene and a feldspathic glass). The most important feature to a chondrule characterization is that they must show clear evidence of having been partially or completely melted, this means that they must show the presence of glass, a texture showing quenching, and a spherical or ellipsoidal or partially spherical-ellipsoidal form which is evidence of the original liquid-droplet (Sorby, 1877).

Although the origin of chondrules is not very well understood, there is a consensus that they have formed from precursor dustballs in the proto-solar nebula, by condensation of liquid droplets directly from the dust and gas. Chondrules have a ferromagnesian variable composition, formed from a fine grained homogeneous mixture of cosmochemically nebular components such as silicates, refractory silicates, etc. Chondrules were completely molten or partly molten for very brief period; some chondrules with coarse grained rims and compound barred olivine indicate that most chondrules experienced two or more brief heating events to melt a fraction of the chondrule, pointing to a nebular region having a high dust/gas ratio.

The source of this large scale heat source is not known but should be associated to the lightning powered by the differential rotation between the nebular gas and the thin dust midplane of the T-Tauri stage of the Sun. Temperature, time and other important restricts on chondrules-forming process are largely based on mineralogical and textural studies of chondrules of meteorites of petrologic classification grade 3 of Van Schmuss & Wood (1967) as the Santa Vitória do Palmar.

Chondrules Classifications – Textures and Composition

Under crossed-polarized light microscope the chondrules show a wide variety of structures and textures that depends upon its mineral composition, cooling rates, degree of melting, and secondary reheating (Norton, 2002). There are several classification schemes for chondrules, but the most used is the one proposed by Gooding & Keil (1981), based on observable petrographic features in a similar way to that used to describe igneous rocks. They introduced seven chondrules categories: radial-pyroxene (RP), barred-olivine (BO) and cryptocrystalline (C); porphyritic olivine

(PO), porphyritic pyroxene (PP) and porphyritic olivine-pyroxene (POP); granular olivine (GO), and compound chondrules.

Other very used classification scheme (McSween, 1977) divides chondrules in Type I (Fe-O-poor, reduced chondrules) and Type II (FeO-rich, oxidized chondrules) and also uses type III for RP chondrules. Scott et al. (1982) introduced a textural scheme to include all types of chondrules, with subdivisions A and B referring to olivine-rich and pyroxene-rich chondrules, e.g. type IAB chondrules are initially FeO-poor and contain olivine and pyroxene phenocrysts, type IIA chondrules are initially FeO-rich and contain predominantly olivine phenocrysts. The distinction between type I and II is somewhat arbitrary.

In this paper the Gooding & Keil (1981) petrographic model will preferred used for the chondrites descriptions of Museu Nacional meteorites.

Chondrules in Santa Vitoria do Palmar Meteorite

The chondrules are dispersed more or less uniformly throughout the thin section. They vary, the majority being rounded, sub-rounded, droplet, or elongated in shape (when not broken) and range from 0.2 to 1.9mm in size within three average size groups: small (0.5mm), medium (1.0mm) and large (1.4mm). The largest chondrule is 5.0mm long. Many fragmented grains and compound chondrules are also present. The volume is 90% composed of fine-grained matrixes with opaque material dispersed between them (Fig.4).

Below is a description of each kind of chondrules present in chondrites which is illustrated with an exemplar of Santa Vitoria do Palmar.

Non-porphyritic chondrules (RP, C, BO)

This group of chondrules is characterized by fully molten during formation: that is, they condensed perhaps as fluffy snowflakes like masses and then rapidly heated to a liquid state forming liquid spheres. These spheres then crystallized as spherical chondrules before being rapidly quenched, “igneous chondrites”:

1) Radial pyroxene (RP) chondrules - are sometimes quite perfectly rounded and sometimes appear scalloped like a sea shell. They are composed of thin fibers or laths of pyroxene in a radiating fan, usually from an eccentric nucleation point near the surfaces of the chondrule. Each chondrule may have more than one nucleation point leading to mutually intersecting and interfering sets of fans. Some exhibit planar fracture, which under crossed-polarized light shows a second order birefringence in shades of gray and the extinction moves across the chondrule as the stage is rotated. Some pyroxene show host of orthopyroxene with lamellae of clinopyroxene (clinoenstatita). They may also contain minor olivine and interstitial mesostasis similar to porphyritic chondrules. Sometimes the laths are so thin that share a certain transitional textural features with cryptocrystalline chondrules.

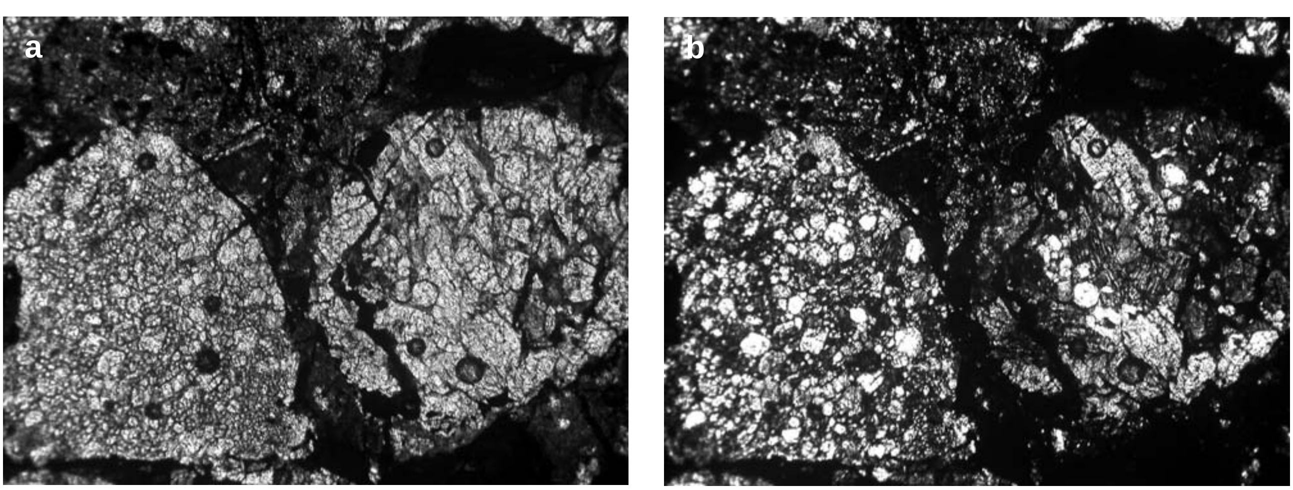
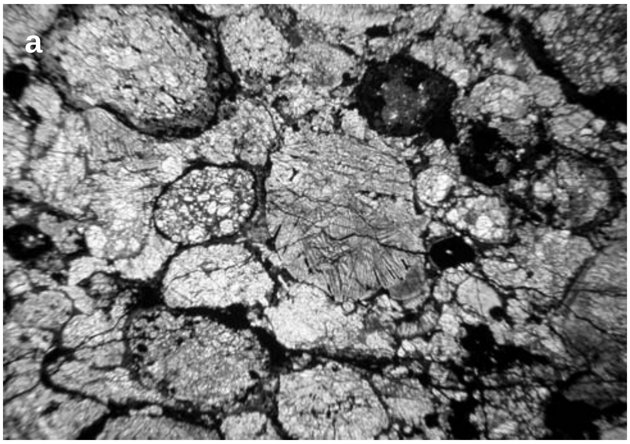


Fig.3- Transmitted plane and crossed polarized light photomicrographs showing two porphyritic chondrules, Huss matrix (fine-grained silicate matrix) and opaque troilite surrounding some chondrules. Huss and opaque matrix dark gray to black. There is also a translucent matrix (yellow to brown under crossed polarized light) seen here as medium gray containing olivine and pyroxene crystals, microcrystals and some opaque minerals. Length of field 0.7mm.



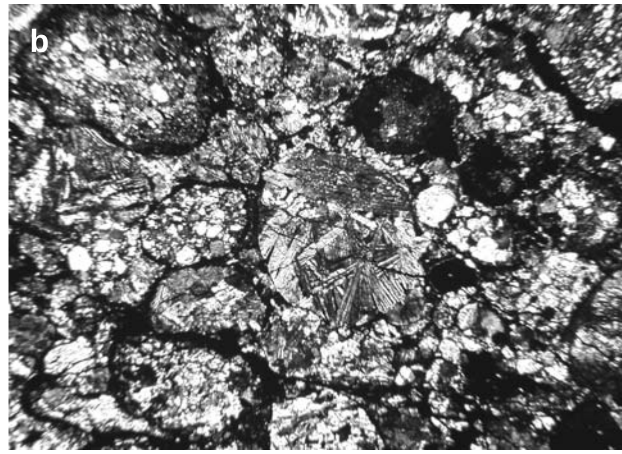


Fig.4- Transmitted plane and crossed polarized light photomicrographs showing a variety of chondrules in plane and crossed polarized light. Noticeable is the preferred orientation of the elongated chondrules. Length of field 5.5mm.

The SVP presents one large radial pyroxene chondrule that under plane and crossed polarized light, shows typical microcrystalline elongated laths of clinoenstatite radiating from an eccentric point. A second order birefringence in can be seen at figure 5 as shades of grey with extinction moving across the chondrule as the stage rotates. There are others smallers RP chondrules.

2) Cryptocrystalline chondrules (C) - are generally devoid of recognizable, systematic structure but may exhibited pyroxene-like bulk compositions (as determined by EDS analysis) which overlap those of RP chondrules It consists of extremely fine-grained intergrowth (grain < 2µm) of pyroxene and glass. Interstitial material in most chondrule textural types, commonly termed mesostasis, is frequently glassy in unequilibrated chondrites as SVP. In many cases, mesostasis glass contains quench microcrystallites, commonly Ca-rich pyroxene. Completely glassy chondrules are extremely rare. In fact some C chondrules observed in thin section under crossed polarized transmitted light exhibit extinction waves similar to that of RP chondrules but at different times demonstrating that there are domains where the grains are oriented differently. This feature strongly indicates a transitional textural relationship between some C and fine grained RP chondrule.

There are few cryptocrystalline pyroxene chondrule in SVP, This meteorite shows under plane and crossed polarized light an extremely fine grained intergrowth of pyroxene and glass (Fig.6).

3) Barred olivine chondrules (BO) – show an unmistakable texture under the microscope. They are composed of one or more sets of elongated parallel bars or plates of olivine arranged set in a glassy matrix. Some chondrules are boarded by a rim of the same material. The olivine bars as well as the rims occur in parallel orientation and most of which exhibit coincidental extinction under cross-polarized transmitted light, suggesting a single crystal. Barred olivines are considered as a special case of PO chondrules having crystallographically oriented phenocrystals. Some BO chondrules sometimes contain minor pyroxene crystals.

In SVP, are seen some barred olivine chondrules in Fig.7 can be seen a typical BO chondrule. In the crossed polarized light condition its noticeable the rim border of olivine is in the same crystallographic orientation as the internal sets of olivine bars.

Porphyritic chondrules (PO, PP, POP)

This group of chondrules are composed of relatively large, well formed olivine and/or pyroxene grains of euhedral or subhedral shapes, many of which contain turbid or clear colorless glass. The porphyritic chondrules are the most common types and show the greatest variation in textures, that including diverse combination of barred/porphyritic, barred/granulitic and porphyritic/granulitic types. They are named according to the dominating mineral and considered to have formed from droplets that were extensively melted, but in which abundant heterogeneous nucleation sites were preserved during the chondrule melting event. They probably formed around tiny grains, acting as condensation nuclei within the solar nebula (Lofgren, 1996).

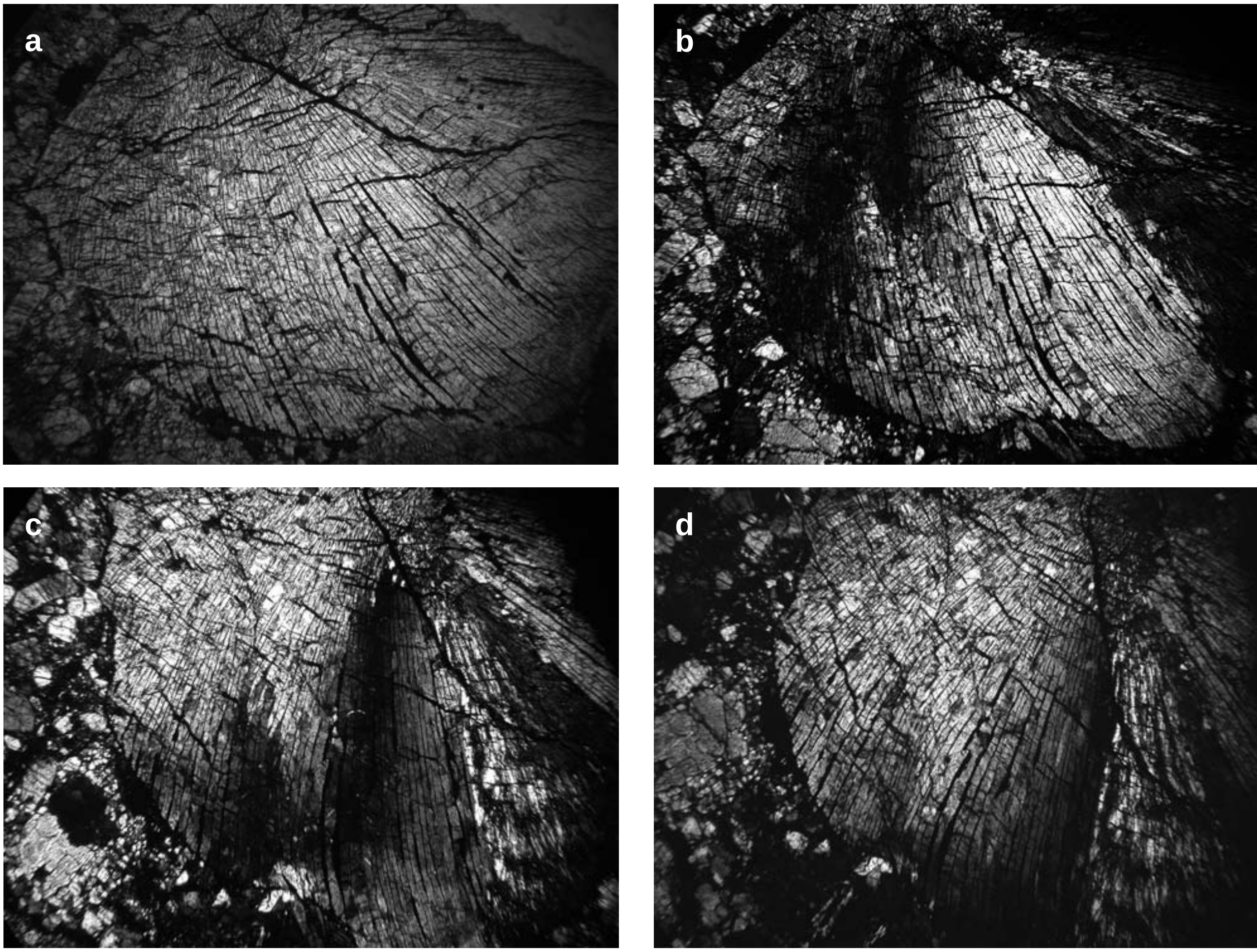


Fig.5- Transmitted plane and crossed polarized light photomicrographs showing a radial pyroxene chondrule formed by microcrystalline elongated laths of clinoenstatite radiating from an eccentric point. Birefringence is seen in shades of grey with the extinction moving across the chondrule as the stage rotates (b-d). Length of field 1.7mm.

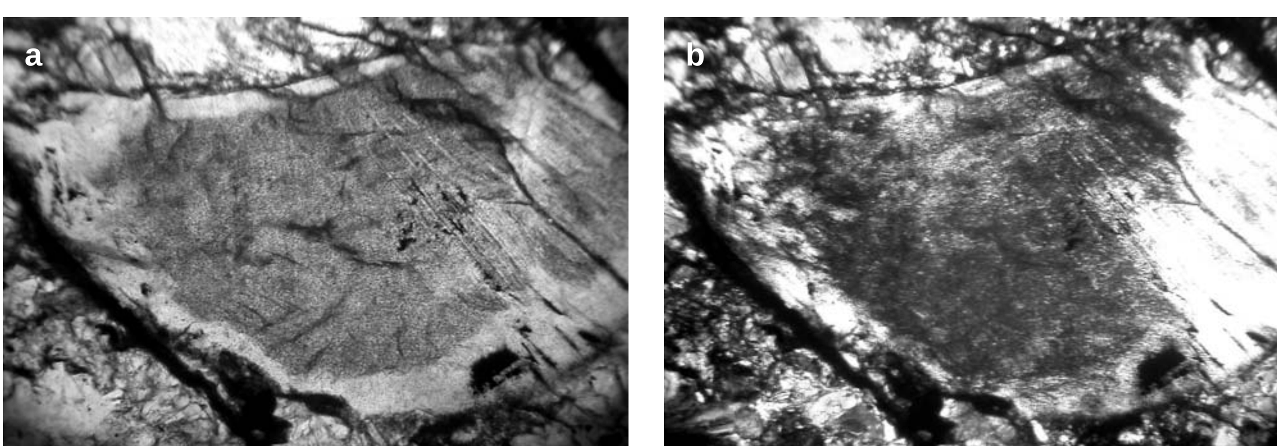


Fig.6- Transmitted plane and crossed polarized light photomicrographs showing a cryptocrystalline pyroxene chondrule with an extremely fine grained intergrowth of pyroxene and glass. Length of field 0.9mm.

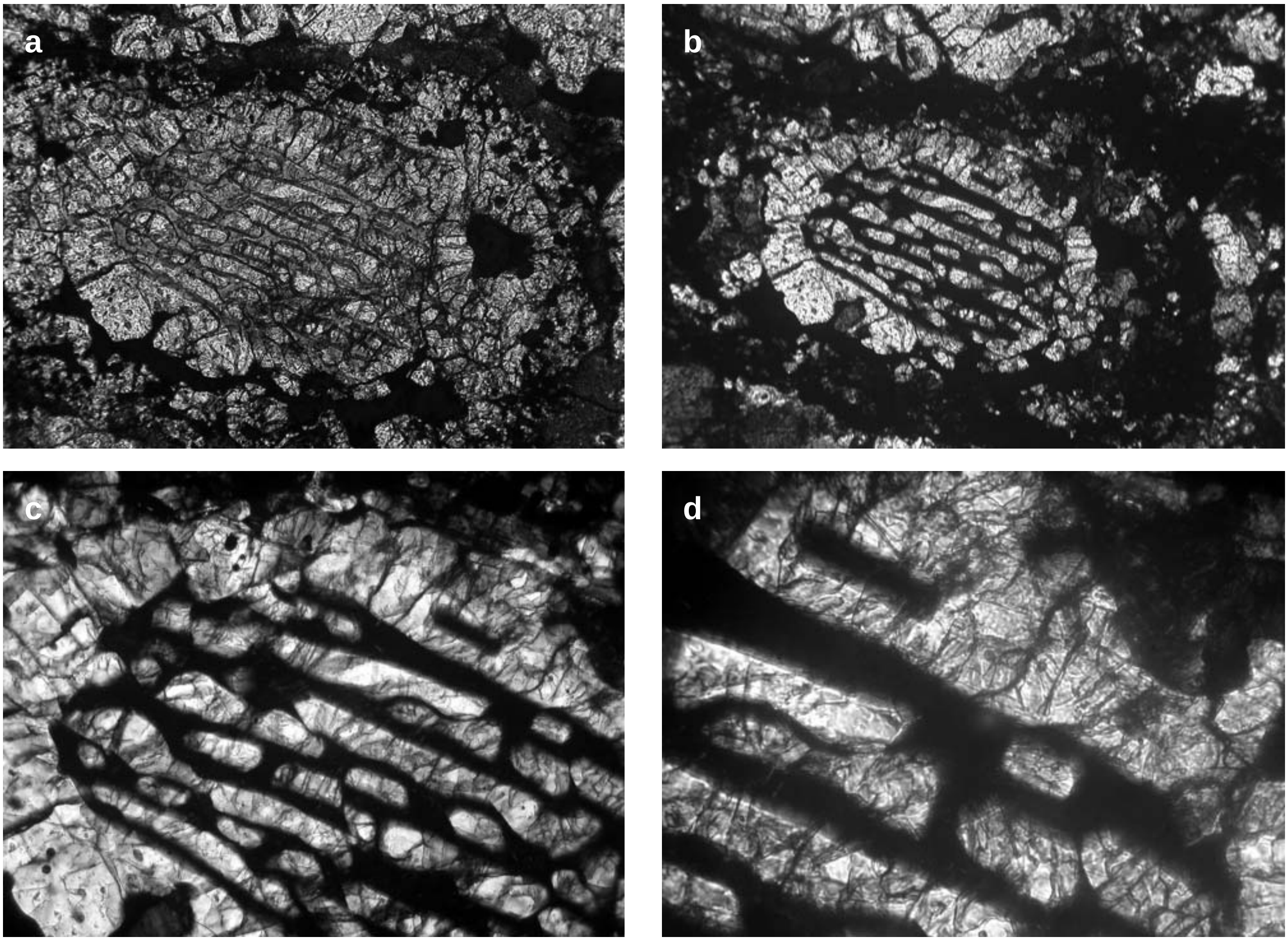


Fig.7- Transmitted plane and crossed polarized light photomicrographs showing a barred olivine chondrules with their unmistakable texture composed of one set of elongated parallel bars of olivine arranged in a glassy matrix: a-b) plane and crossed polarized light, showing the rim border of olivine in the same crystallographic orientation. Length of field 1.7mm; c) the same chondrule crossed polarized in a larger magnification showing the olivine bars embedded by glass. Length of field, 0.45mm; d) the same as c) in a larger magnification revealing transversal fractures, length of field 0.22mm.

1) Porphyritic olivine chondrules (PO) - contain well-formed olivine crystals from euhedral to anhedral set in microcrystalline or glassy mesostasis appearing dark (isotropic) under crossed–polarized light or light brown in plane polarized. In SVP many olivine grains show undulatory extinction and irregular random fractures sometimes filled with reddish iddingsite. It has bright second and third order interference colors seen under crossed polarized light.

In SVP there are many porphyritic olivine chondrule (PO) showing olivine euhedral to anedral grains in a quite isotropic microcrystaline mesostasis and opaques mostly troilite riming the whole chondrule (Fig.8).

2)Porphyritic pyroxene chondrules (PP) - In the type 3 chondrites, those chondrules are basically composed of low Ca pyroxene and clinoenstatite. They are recognized by their low birrefrigent colors. The pyroxene crystals often show under crossed polarized light the polysynthetic twining on (100) planes. They also have shrinkage cracks perpendicular to the twinning. Sometimes tiny colorful crystals of olivine can be seen enclosed within the pyroxene grains this textures is called poikilitic.

The SVP exhibits many PP chondrules, a typical one is seen in figure 9. Large tightly packed grains that under crossed-polarized light show second order birefringence colors seen here in shades of gray and polysynthetic twinning planes, most of them with undulatory extinction sometimes resembling plagioclase.

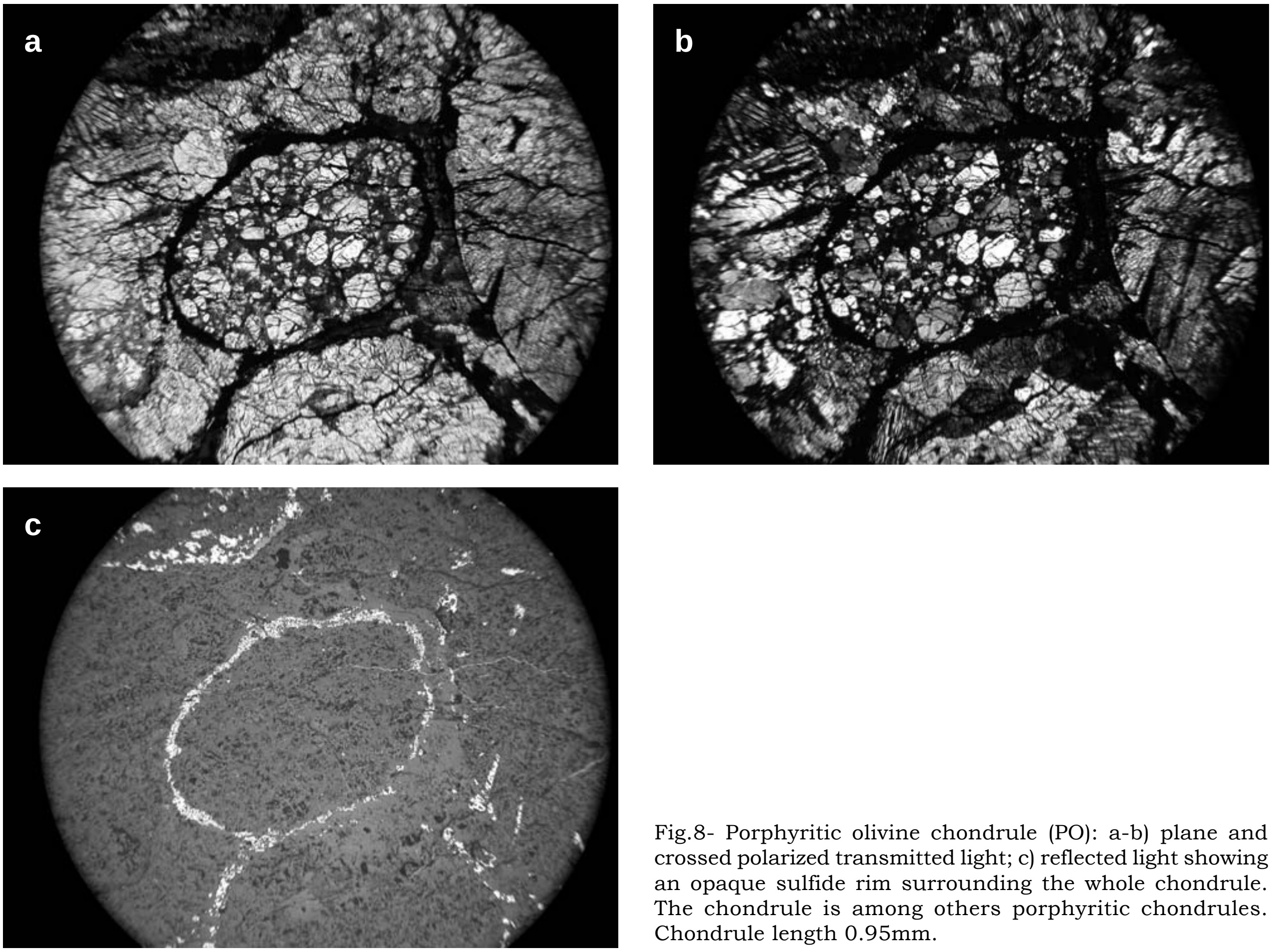


Fig.8- Porphyritic olivine chondrule (PO): a-b) plane and crossed polarized transmitted light; c) reflected light showing an opaque sulfide rim surrounding the whole chondrule. The chondrule is among others porphyritic chondrules. Chondrule length 0.95mm.

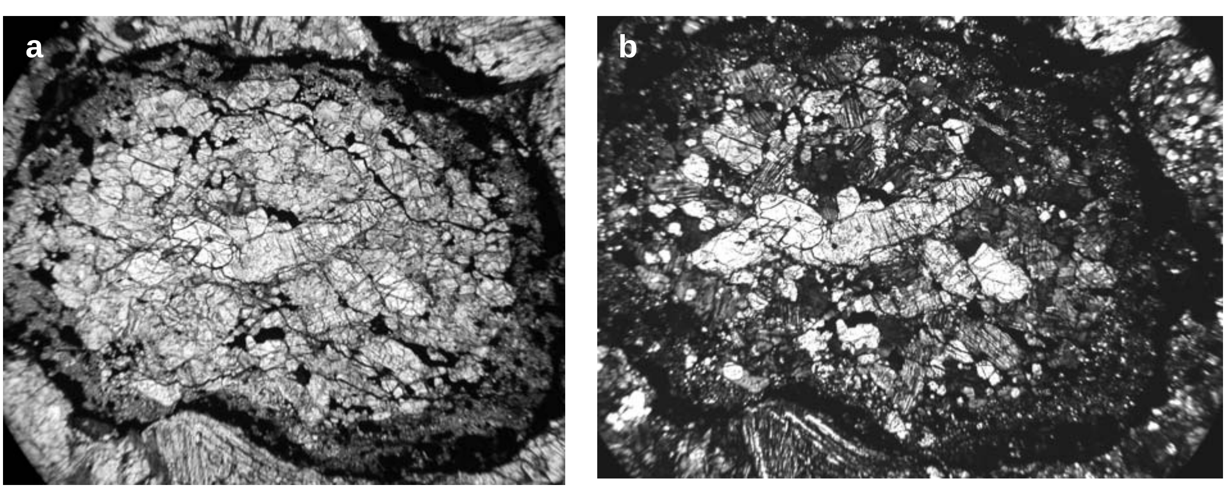


Fig.9- Porphyritic pyroxene chondrule (PP): a) plane polarized transmitted light, pyroxene crystals tightly packed, surrounded Huss matrix and sulfide; b) the same in reflected light showing a distinction between Huss matrix and sulfide (light gray). The sulfides seen as white and Huss matrix in medium gray. There are also some irregular troilite grains inside chondrule. Length of field 1.7mm.

Contain pyroxene crystals from euhedral to subhedral. The grains are tightly packed and the mesostasis are more visible near the border with Huss matrix and troilite rim. It also presents poikilitic texture.

3)Porphyritic olivine-pyroxene chondrules (POP) - are the most common type; contain mixture of both olivine and pyroxene. Often the interior of the chondrule is occupied by small olivine grains which are surrounded by large pyroxene crystals.

In SVP there are many POP chondrules, most shows under crossed-polarized light small colorful euhedral to subhedral olivine grains associate with large lath-shaped gray to bluish pyroxene. In Fig.10 a typical SVP POP chondrule is seen in crossed polarized condition both pyroxene and olivine are seen in shades of gray. The crystals are also less imbricated in each other but there are junctions bounded with light brown mesostasis (medium gray) or a glassy matrix which is isotropic under crossed polarized light.

Granular olivine-pyroxene chondrules (GOP)

The GOP is the rarest type of chondrule comprising only about 3% of the total chondrules. Granular chondrules may consist of fine-grained pyroxene or olivine and pyroxenes. This type is quite similar to the POP chondrules differing only in their uniformly small grains size.

In Fig.11 a GOP chondrule is recognized by its visible tightly packed mix of olivine and pyroxene, with anhedral grains of very small size set in a glassy mesostasis or Huss matrix (black or dark gray under crossed polarized light).

Other types of chondrules

Polysomatic barred olivine chondrules - are the same as BO but showing several sets of parallel olivine prisms with distinct optical orientations, resulting in different interference colors and extinction points. A large polysomatic barred olivine is present in SVP (Fig.12) revealed under crossed polarized transmitted light. The sets of olivine bars are seen in different shades of gray. The laths are separated by isotropic glass.

Metallic chondrules (M) - are probably the rarest type of chondrule, consist mostly of Ni-Fe metal but usually contain accessory sulfides along with phosphates and/or phosphides and oxides and silicate fragments. There is no consensus if those metallic droplets are considered chondrule as most authors prefer to use the term chondrules for silicate rich objects only. In the Museu Nacional sample of SVP there is a spheroidal troilite grain with silicate inclusions which remember metallic chondrule (Fig.13).

Compound chondrules (CC) - are those with attached or partially imbedded chondrule-like object of smaller size. Most consist of a small hemisphere attached to a large sphere, although two or more hemispheres are sometimes observed. Most compound chondrules are comprised of components having similar bulk composition and textures. In SVP a illustrative compound chondrule can be observed in Fig.14.

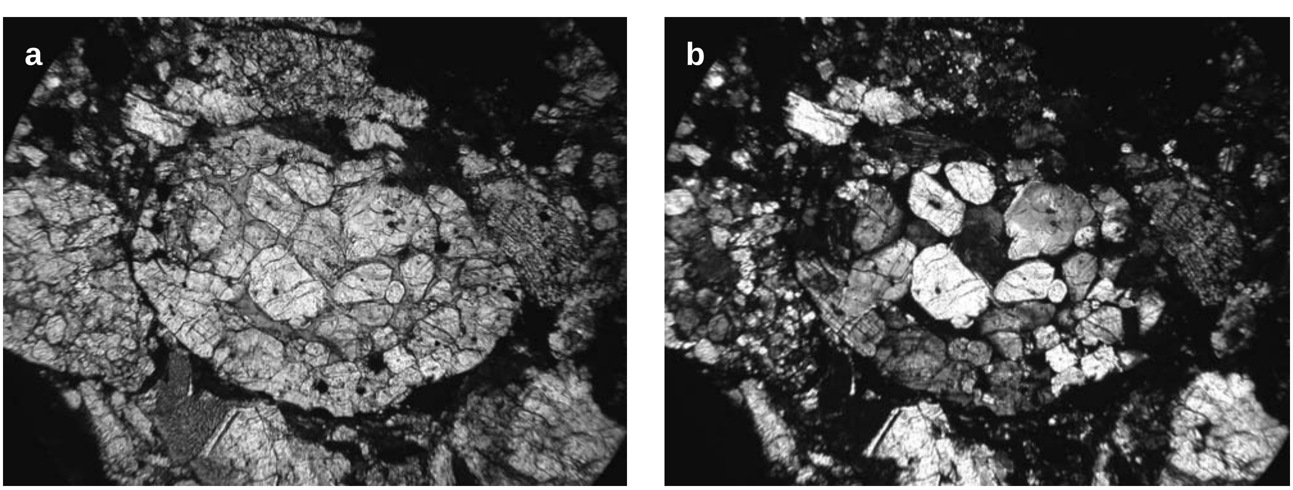


Fig.10- Porphyritic olivine-pyroxene chondrule (POP): a-b) plane and crossed polarized transmitted light, showing olivine and pyroxene. Crystals are less embedded in each other but are set in a light gray mesostasis or glassy matrix which is isotropic under crossed polarized light. Length of field 0.9mm.

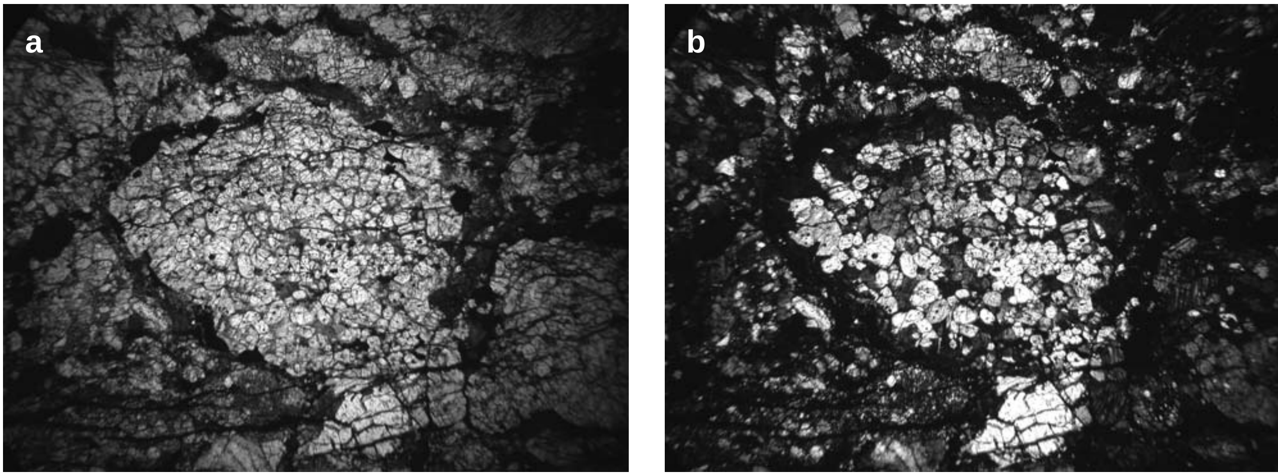


Fig.11- Granular olivine-pyroxene chondrule (GOP) in plane and crossed polarized transmitted light a-b showing a tightly packed mix of anhedral olivine and pyroxene in grains of very small size (shades of gray) set in a glassy mesostasis or Huss matrix seen black under crossed polarized light . Length of field 0.7mm.

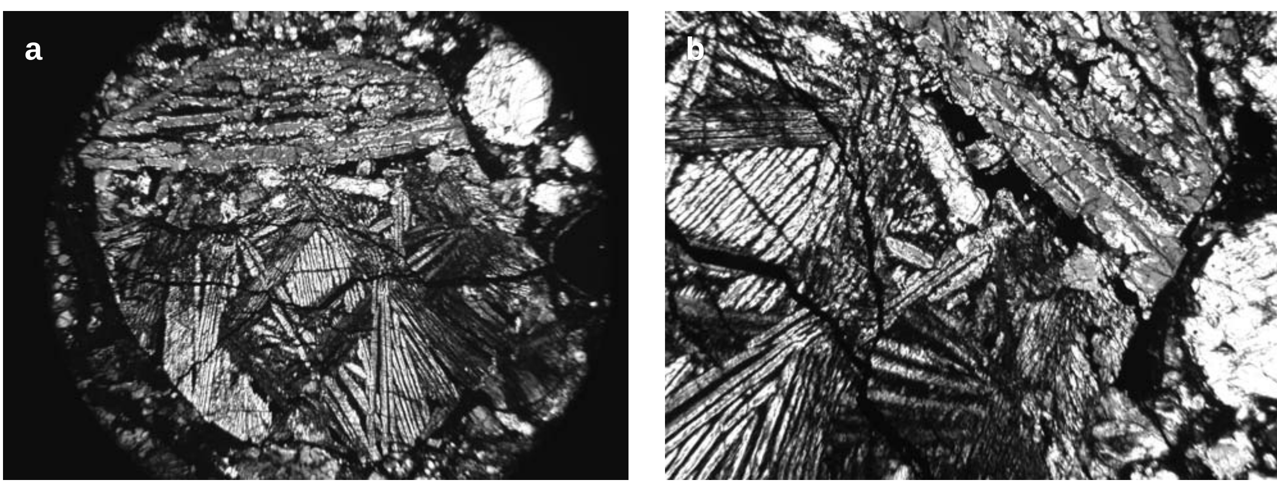


Fig.12- Polysomatic barred olivine (BO): a) crossed polarized transmitted light showing several sets of parallel laths with distinct optical orientation marked by the different interference colors seen here in different shades of gray. Length of field 1.7mm across; b) a BO chondrule border in a larger amplification. Length of field 0.5mm.

Mineralogical Composition

The essential minerals are the ferromagnesians, pyroxene and olivine; the accessory minerals are troilite, metal phases Fe-Ni (taenite, plessite and kamacite), magnetite, chromite, plagioclase and glass. The secondary minerals formed during terrestrial weathering are hematite and iron hydroxides.

Essential minerals

Olivine - olivine grains are present on the matrix and chondrules as barred, euhedral to anhedral forms. In transmitted crossed polarized light are easily distinguishable by crystal shape and interference birefringence third order colors, from pale yellow to magenta. The SVP olivine crystals show cleavage cracks and undulatory extinction and are permeated by fine random and well developed cracks, sometimes filled with iddingsite. At the type 3 unequilibrated chondrite the compositions vary widely. In SVP this composition varies from Fa 0.5 to Fa 35 (mol% Fe_2SiO_4). Eventually, crystals show microscopic zoning from border to center (Fig.15).

Pyroxene: ortho and clinopyroxene appears in chondrules and in the matrix. The clinopyroxene (mostly clinoenstatite) in transmitted crossed-polarized light display low interference colors in shades of gray and some grains show exsolution lamellae. Larger grains of clinopyroxene exhibit polysynthetic twinning planes, most with undulatory extinction (Fig.16). The orthopyroxenes (mostly hypersthene) display bright interference colors ranging from the middle to the upper end of the second order, or from blue to magenta. Occurs as well-formed crystals of very small size, from euhedral to anhedral and as thin fibers or laths. EDS analysis gave a very wide range of iron content from Fs 0.5 to Fs 31.6 (mol% $FeSiO_3$) configure an inhomogeneous composition corresponding chiefly hypersthene and twinned clinoenstatita (Fig.17).

Fig.13- Reflected light photomicrography showing a troilite grain in a spheroidal shape with silicate inclusions, resembling a metallic chondrule. Length of field 0.7mm.

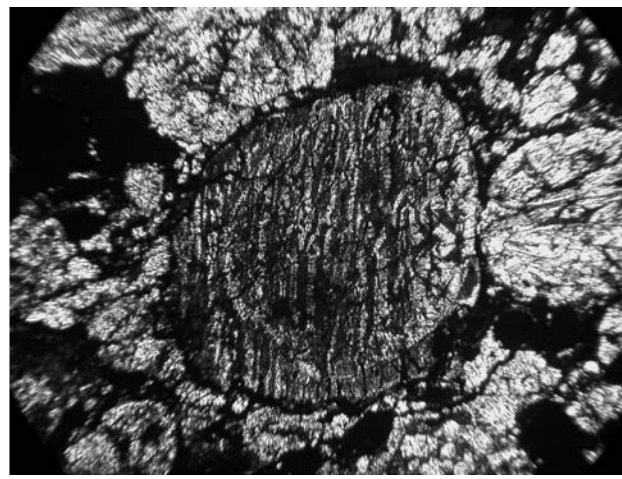


Fig.14- Transmitted plane polarized light photomicrographs showing a compound pyroxene chondrule. A smaller second pyroxene chondrule composed of pyroxene laths appears enclosed within the larger chondrule and share the same crystallographic orientation. Length of field 1.5mm.

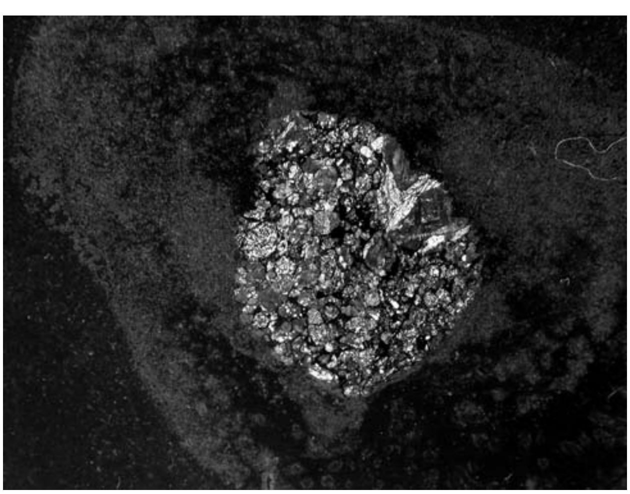


Fig.15- Transmitted crossed polarized light photomicrographs showing zoning olivine crystal. The zoned color range from the crystal's rims to the center of the crystal is an indication of zoning characterized by the change in the mineral composition. Length of field 0.45mm.

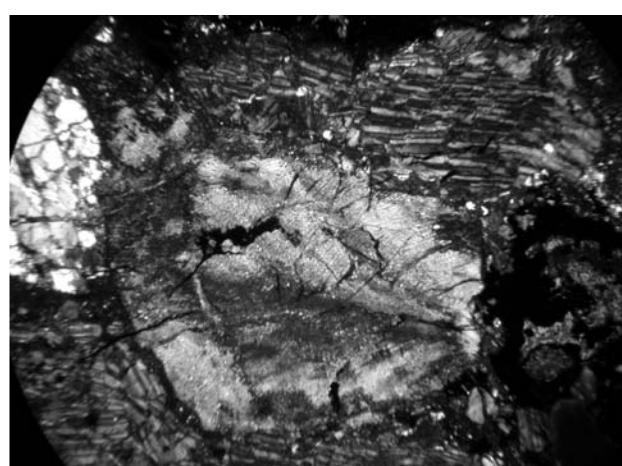


Fig.16- Transmitted crossed polarized light photomicrographs showing undulatory extinction on a pyroxene crystal. Length of field 0.4mm.

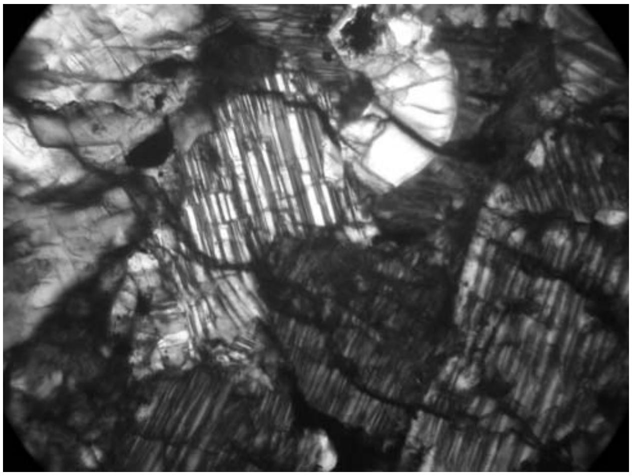


Fig.17- Transmitted crossed polarized light photomicrographs of Clinoenstatite pyroxene grains showing the characteristic polysynthetic twinning planes. Length of field 0.45mm.

Accessories minerals

Opaque minerals consist of troilite, iron-nickel (taenite, kamacite and plessite). Magnetite and chromite. Troilite, taenite, plessite and kamacite are common in SVP, with the troilite being the dominant phase followed by taenite with less plessite. Irregular metal and sulfide grains occur more commonly as irregular shapes individually or associated.

Troilite (FeS) is easily recognized by the characteristic bronze-yellow color and is very common surrounding mostly of large chondrules sometimes performing a whole ring (Fig.8). It is also present in rounded or without any form grains scattered throughout the matrix or on the chondrules. It appears as large grains, as clusters, alone or associated with metal or in veinlets (Fig.18). In SVP the troilite occurs also as porous, spongy and compact distinct grains or associated with Fe-Ni metal and silicates. Some troilite are polycrystalline showing 120^o intersections at the grain boundaries and some grains exhibited two sets of straight and very narrow lamellae (<10nm). The lamellae form sensible half lozenges, the troilite with this structure shows different color (gray) from the troilite grains without this pattern, but they have the same composition (fig.18a-b), The only possible similar structure published in the literature was described by JOREAU et al.(1996) and TÖPEL-SCHADT & MÜLLER (1982). Some troilite grains show a pronounced mosaicism under partly crossed polarized observation and others an unindentified maybe fizzed structure (Fig.18a).

A same thin section of SVP contains undistorted monocrystalline grains, grains with strong pressure effects and still partially recrystallized material. Pressure effects are manifested by deformation, by twin lamellation of different forms, by undulant extinction, and by all degrees of brecciation.

Metal phases - are present in less quantity than troilite. When etched by a solution of 2% of nitric acid in alcool (nital 2%) revealed the iron-nickel phases, which are composed by taenite, plessite and kamacite. Those phases occur inside and outside chondrules, and either free or associated with troilite.

Taenite (austenite, γ-iron) - occurs in the form of small oblong bands or spotted granules. Discrete taenite grains are more common than composite grains. Larger taenite are zoned with clear Ni-rich rims of tetrataenite with a dark taenite to plessite interior. Polycrystalline taenite is very common and marked by patches of cloudy taenite cores and tetrataenite rims separated by kamacite (Fig.19). Relative homogeneous tetrataenite (ordered Fe-Ni 50:50) is rare but occur inside and outside the chondrules.

Plessite is not a mineral but a fine grained intergrowth of kamacite and taenite which occurs widely in unshocked and shocked equilibrated chondrites. In SVP plessite occurs quite indistinctly from cloudy taenite (Fig.19).

Kamacite (ferrite, α iron) - is the less abundant iron constituent of SVP but occurs associated to larger and polycrystalline taenite plessite complex. Some kamacite has Ni-poor zones identified by the darkness (Fig.20).

Phosphides: Schreibersite $(Fe,Ni)_3P$ - few small crystals of was observed in the examined sections but it was not verified in the SEM exhamination.

Oxides: chromite ($FeCr_2O_4$) - is the dominant oxide in ordinary chondrites; ilmenite ($FeTiO_3$) and rutile (TiO_2) occurs as rare phases. In SVP chromite occurs as tiny grains embedded in a mesostasis in some porphyritic chondrules and also as dark oxide.

Plagioclase: in SVP very few plagioclase is present, under crossed polarized light it is usually mixed with pyroxene in the chondrules and also in the matrix, been mismatched with the very abundant clinopyroxenes laths.

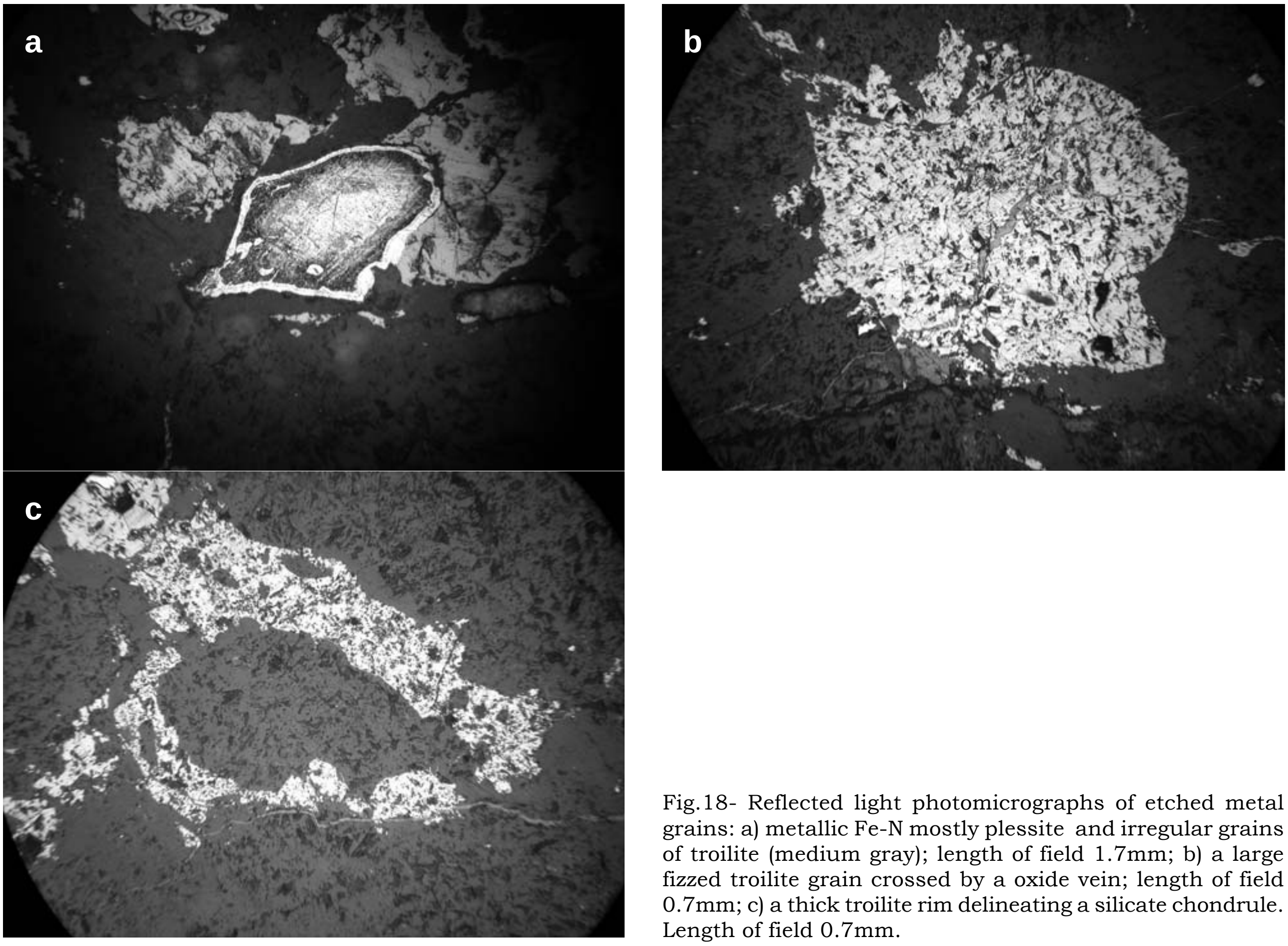


Fig.18- Reflected light photomicrographs of etched metal grains: a) metallic Fe-N mostly plessite and irregular grains of troilite (medium gray); length of field 1.7mm; b) a large fizzed troilite grain crossed by a oxide vein; length of field 0.7mm; c) a thick troilite rim delineating a silicate chondrule. Length of field 0.7mm.

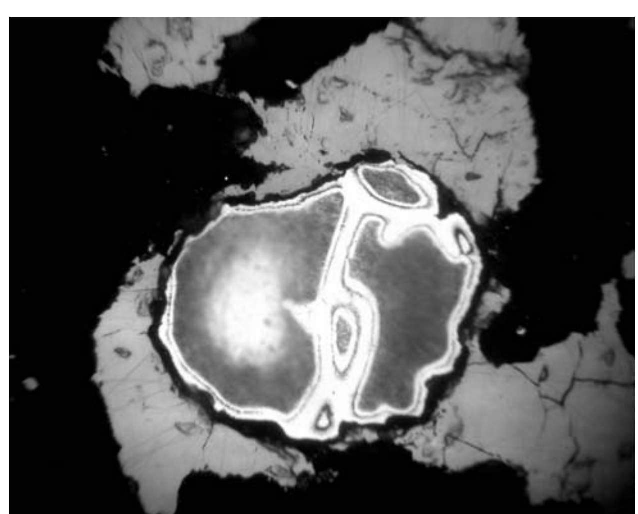
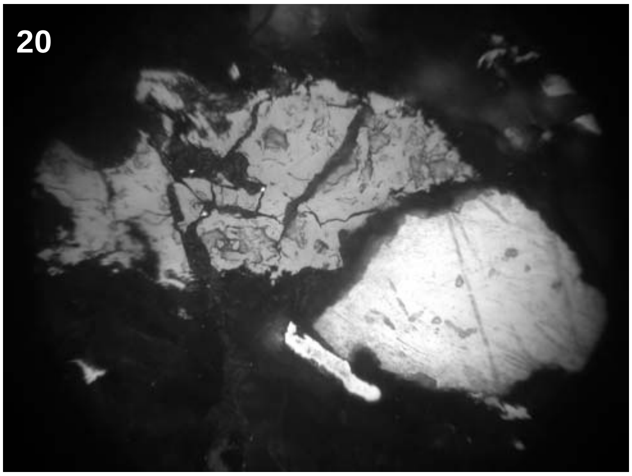


Fig.19- Reflected light micrograph of a well-developed metal inclusion surrounded by troilite grains. When etched by nital 2%, it exhibits a pattern formed by polycrystalline taenite, plessite and tetrataenite between areas of cloudy taenite. Cloudy taenite tends to occur in the smaller taenite grains. The largest grain is plessite with the outer part of cloudy taenite and tetrataenite border. Reflected light, oil immersion view, length of field 0.2mm.



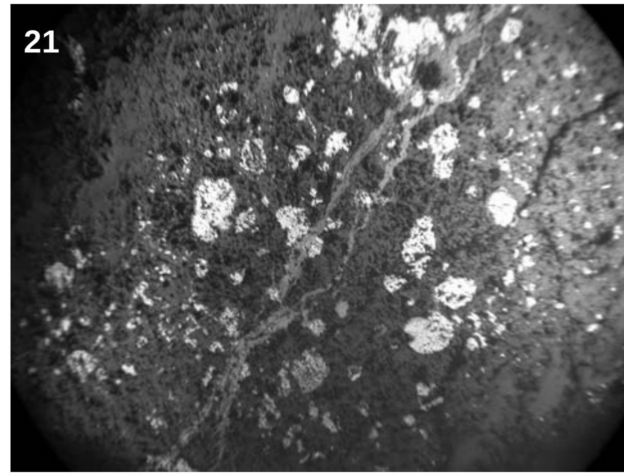


Fig.20- Reflected light photomicrograph exhibiting metal-sulfide assemblage contain, kamacite, troilite and taenite. The etched kamacite exhibits Neumann lines (light gray); fractured polycristalline troilite (medium gray) and taenite which occurs as a lath (light gray). Oil immersion, length of field, 0.2mm. Fig.21- Reflected light photomicrograph showing oxide veins, silicate (medium gray) and troilite grains (light gray). Length of field, 0.3mm.

Glass and Huss matrix: glass and an opaque matrix composed of micron to submicron size silicate grains mixed with an apparently amorphous material with small amount of submicron metallic FeNi and troilite. Due to the extremely small grain size and opaque mixture this phase is quite opaque in thin sections (Fig.22).

Secondary minerals: chondrites were formed and stay in a reductive environment till it arrive at Earth soil, all the secondary minerals in ordinary chondrites they are the product of terrestrial weathering that occurs after their fall. They are formed from Fe-Ni minerals such as: iron oxide hematite (Fe_2O_3), hydrated iron oxide minerals as goethite α Fe (OH), lepidocrosite γ Fe (OH), iddingsite, and others; from FeS such as pentlandite and heazlewoodite. In SVP, some iron oxides occur riming chondrules, opaque grains and filling irregular fissures and veins (Fig.23). Iddingsite also occurs permeating fractures and irregular fissures in olivine crystals (Fig.24).

Shock Effects

The shock effects in ordinary chondrites vary with increasing shock intensity and characteristic of shock metamorphism. These effects can be recognized and arranged on a relative scale of increasing degree of deformation and transformation of constituent mineral phases. Therefore, a particular ordinary chondrite sample can be assigned to a specific "shock stage" (Stöffler *et al.*, 1991). The shock effects in chondritic silicates for which an accurate shock pressure calibration is available, include the following major deformation and transformation phenomena in olivine, plagioclase, and pyroxene under petrographic microscope observations.

Progressive stages of shock metamorphism of ordinary chondrite according to Stöffler et al.(1991):

1- Mechanical deformations - a) undulatory extinction in olivine, pyroxene and plagioclase; b) planar fractures in olivine and planar deformation features in olivine and plagioclase; c) mechanical twinning in pyroxene; d) mosaicism in olivine and pyroxene.

2- phase transformations - a) transformation of plagioclase into dialectic glass (maskelynite); b) melting of plagioclase and formation of (normal) glass; c) solid state recrystallization of olivine; d) melting of olivine and formation of fine-grained polycrystalline olivine; e) transformation of olivine and pyroxene into ringwoodite and majorite, respectively, and/or dissociation of olivine into several crystalline or glassy phases.

Metal as well as silicates can also be used to determine the metamorphic grade in chondrites. Fe-Ni is the most sensitive indicators for lower grades of metamorphism due to the higher diffusion rates of Ni in metal (Kimura et al., 2006). A shock indicators list of criteria establishing the degree of shock metamorphism using opaque phases was determined by Bennett & Mcsween (1996), specially for L chondrite considering the petrologic type (or degree of thermal metamorphism).

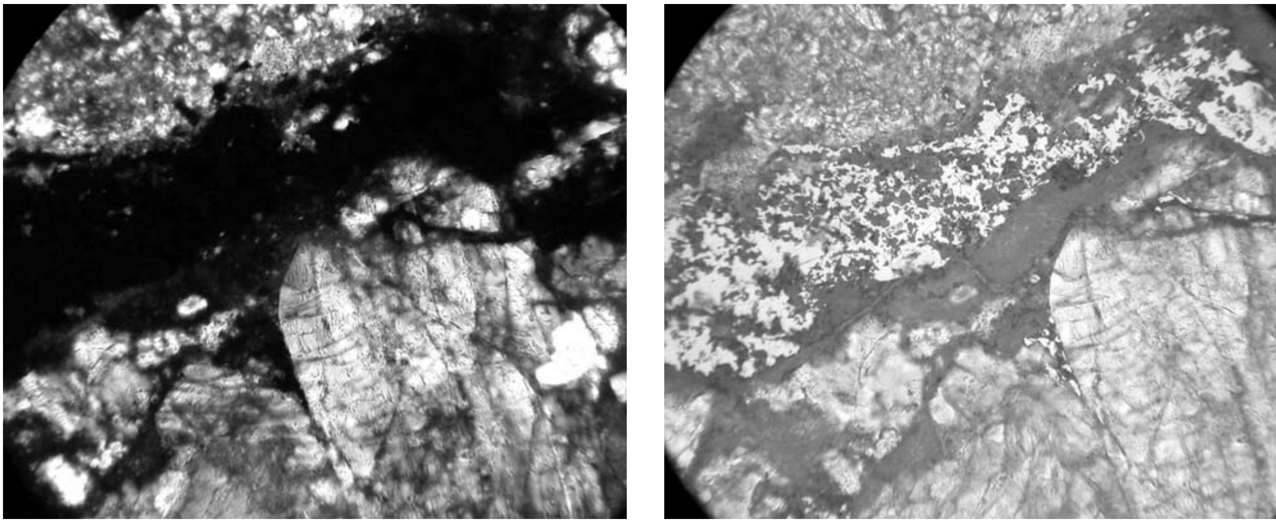


Fig.22- Photomicrographs of chondrule showing in detail a troilite bordered chondrule interface with matrix, a) transmitted crossed polarized light, matrix (top left), a dark zone interface and the chondrule interior (bottom); b) under concomitant reflected and transmitted, shows that the dark interface is composed of troilite and Huss matrix. Length of field 0.2mm.

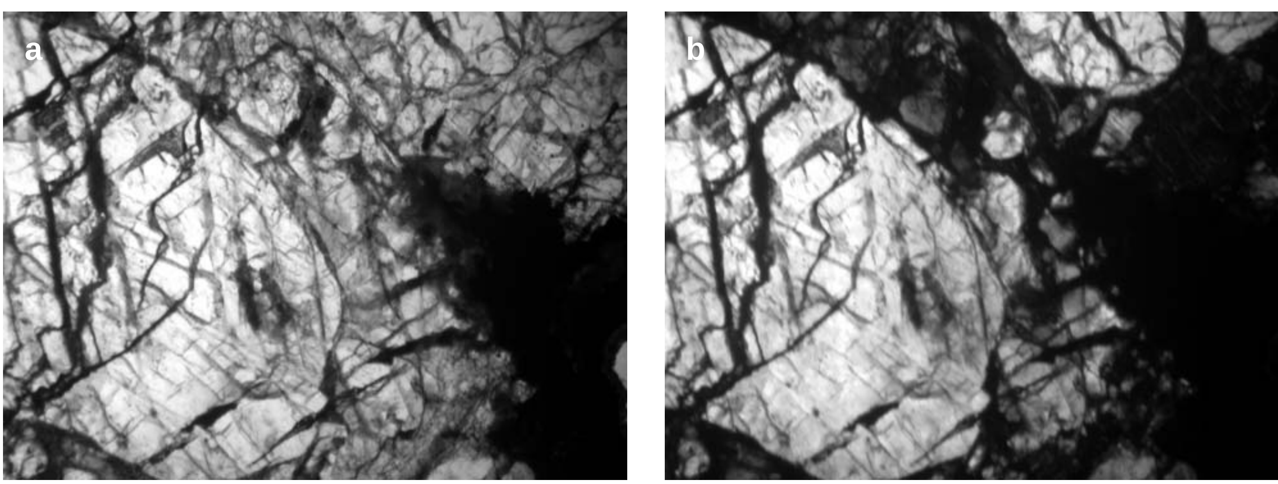


Fig.23- Transmitted light photomicrographs in plane and crossed polarized light. Olivine with one set of parallel plane fractures and undulatory extinction. These features are indicative from weakly shocked S3 to moderately shocked S4, also present mosaicism more visible at the lower right olivine crystal. Length of field 0.35mm.

Although postdates thermal metamorphism should occur since L chondrites are known to have a complex shock history, with at least two major shock events.

Unshocked to weakly shocked (S1-S3) L chondrites contain Fe-Ni metal and troilite that display textures related to normal, slow cooling. Above shock stage S3 (S4-S5), selected melting of Fe-Ni metal and troilite produces melt droplets. At these higher shock levels, the abundance of others shock-induced features, such as polycrystalline kamacite, sheared and fizzed troilite, coarse-grained pearlitic plessite, polycrystalline troilite, and polymineralic melt veins serve as textural criteria that can be used as an aid for shock classifying L chondrites.

At SVP the following metamorphism features were observed: olivine with undulatory extinction: irregular fractures and planar fractures (Fig.23) and melted metal sulfide droplets along planar fractures in olivine (Fig.24). Those characteristics indicate the estimated shock degree of this chondrite be S3 (weakly shocked).

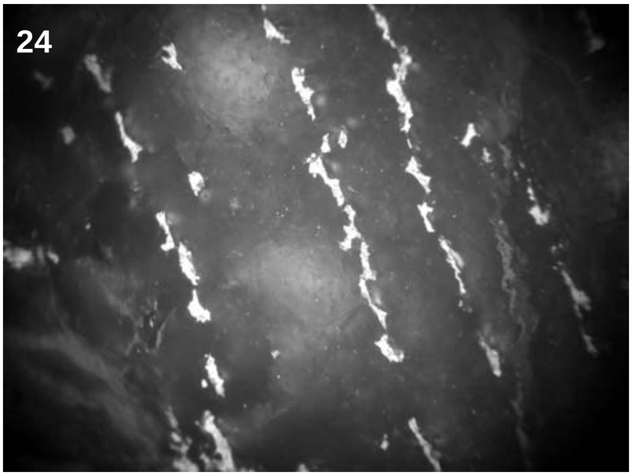


Fig.24- Concomitant reflected and transmitted light photomicrography. Metal-sulfide melt drops and troilite along plane fractures in olivine. Length of field 0.2mm.

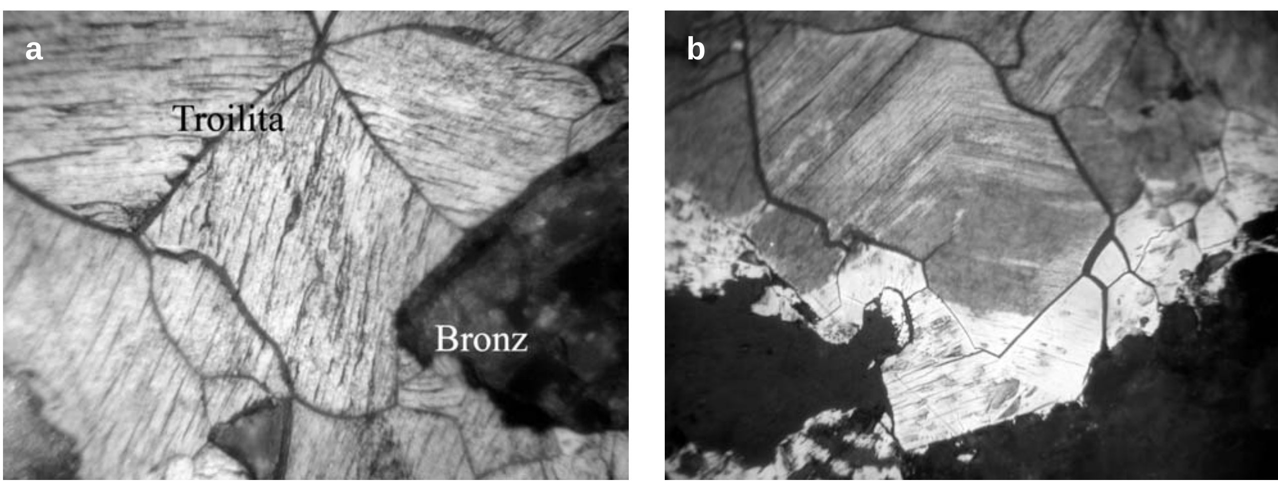


Fig.25- Reflected light photomicrographys: a) Polycrystalline troilite indicative of strongly shock with two bronzite crystals (dark gray) inclusions; b) - Polycrystalline and twinned troilite indicative of strongly shock. Length of field 0.2mm.

The troilite is very susceptive to shock pressures and temperatures (Fig.25). The polycrystalline troilite the pronounced mosaicism, twin lamellation of different forms are signs of pressure effects S4 or upper. The lozenge-shaped domains as observed in figure 25b can be considered a PDFs produced by shock in troilite.

Indeed at the same thin section that contains undistorted monocrystalline grains there are others grains with strongly pressure effects and others with partially recrystallized material, meaning different shock classification parameter. Sheared troilite occurs with polycrystalline troilite in meteorites of relatively high shock stage (above S4) (Marvin et al., 1996). The presence of metal-sulfide melt droplets may indicate several shocks and partial melting above 950º.

The shock features observed in SVP are: olivine (undulatory extinction, mosaicism, irregular and multiple sets of planar fractures), metal-sulfide droplets along planar fractures, metal particle chemically zoned and polycrystalline troilite. By those observed features lead to a shock classification estimated as S3 or upper by the scheme proposed by Stöffler et al.(1991). Although Bennett & Mcsween (1996) remarked that it is common for L groups that the degree of shock could varies in the same thin section.

Weathering

Meteorites come from outer space, a reductive environment. When they fall in Earth they are exposed to water and oxygen being subject to the same mechanical and chemical weathering as terrestrial rock. As meteorites are more fragile than most of terrestrial material, their minerals rapidly transform to more stable phases, tending to be quickly destroyed.

The weathering of olivine and pyroxene are essentially the same as basic and ultrabasic terrestrial rocks. The Fe^{2+} is oxidized by atmospheric oxygen to Fe^{3+}, which combines with water and precipitates such as the yellow-brown substances goethite and lepidocrosite.

The reactions transform the meteorite's exterior color from black or dark brown to reddish brown. A bright red substance also often invades the interior along fractures extending from the fusion crust. This material is iddingsite which is an aqueous alteration of iron-bearing olivine. Its presence is a sure sign that it was under weathering conditions (Fig.26). As weathering evolutes, the exposed interior of the meteorite turns reddish brown.

A weathering scale for ordinary chondrites was proposed by Wlotzka (1993) with seven progressive weathering grades labeled from W0 to W6: W0 = no visible oxidation of metal or sulfide, some staining; W1 = minor oxide rims around metal and troilite, minor oxide veins; W2 = moderate oxidation of about 20-60% of metal; W3 = heavy oxidation of metal and troilite, 60-95% being replaced; W4 = complete oxidation of metal and troilite, but no oxidation of silicates; W5 = beginning alteration of mafic silicates, mainly along cracks; W6 = massive replacement of silicates by clay minerals and oxides. Altogether massive veining with iron oxides also develops independently of weathering grade. The degree of weathering appears to be correlated with terrestrial age but is also associated with terrestrial climatic conditions.

Fig.26- Transmitted crossed polarized light microphotograph showing medium gray veins of the hydrated iron oxide iddingsite (bright red under the microscope) invading the interior of the meteorite along fine cracks and veins. Length of field 0.35mm.

Indeed the meteorite was classified as W2 by Gresshake (2007), the authors support a W1 classification as the oxidation of metal of SVP is under 20 %. The presence of iron oxides in some veins that lead to a W2 classification is also pointed by Wlotzka (1993) to be present in any weathering grade

Classification

The Santa Vitória do Palmar is an Ordinary Chondrite (L3, subtype 3.4-3.6), S3/4, W1/2.

The sample is an unbrecciated chondrite with unequilibrated olivine and pyroxene, and Fe-Ni metal. The chondrules are well defined but elongated and of large variation in the textural types including BO, BP, PO, POP, and PP

CONCLUSIONS

Compositions of olivine $Fa_{(0.5\text{-}35.2)}$ and pyroxene $Fs_{(0.5\text{-}31.6)}$ support the classification of the Santa Vitoria do Palmar meteorite as an unequilibrated member of the L group chondrite. Semi-quantitative analyses performed with an EDS at SEM attest a great variation in fayalite (Fa) and for ferrosilite (Fs) content in different individual grains of olivine and low Ca pyroxene. This variation is also noted between grains inside the same chondrule. Some grains also present a pronounced compositional zoning. The well defined chondritic texture and the presence of glassy material indicate a petrologic type 3.

Based on metal-sulfide interrelation texture inside and outside chondrules appearance, a sub-classification of L3.4 to L3.6 is suggested.

By the weathering grade scheme proposed by Wlotzka (1993), the SVP is situated between the grades W1 and W2 or W1/W2. This relative weathering state impossibilitated the SVP be correlated with the observed bright fireball of 1997 at the same region. Although the meteorite committee, didn't considered the climactic conditions of a tropical weathering environment as occur in the Brazilian south climate.

The meteorite presents an evident preferred orientation in elongated chondrules. This indicates that some event caused the normally spherical chondrules to be squished into elliptical shapes by some unknown force.

The SVP texture is unusual with a marked orientation defined by the alignment of elongated chondrules. This feature has been previously cited in Leoville carbonaceous chondrite.

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