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Micro-spherules near the Kamil crater

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Abstract. A large number of metallic micro-spheres has been found near the 45 m Kamil crater (22°01′06″N, 26°05′15″E), produced about 5000 years ago by an extraordinary metallic meteorite (20% Nickel, 0.5% P as shreibersite). A complex SEM inspection inside and outside these micro-spherules provided some good indication about the source and the mechanism of formation of the spherules.

Key words. Meteorites – impact craters

1. Introduction

A large amount of the extraterrestrial material falling yearly to the Earth (about 50,000 ton) consists possibly of micro-spherules of dimension between 20 and 400 micron (CS, Cosmic Spherules) (Brownlee 1998). They form when a meteoritic object enters the atmosphere: it disintegrates by frictional heating, producing an amount of micro-fragments that naturally gain a spherical or oblate shape when the local temperature rises up to 1500° C. Depending on the kind of original meteorite, CSs can be made up of metals or glass. Unfortunately, also the human activity produces micro-spherules (both metallic and glassy); so it is often difficult to find the real source of CSs, except when they should be recovered in regions of the Earth well away from any human activity. Some examples of this kind are the deserts of sands (Sahara) and ice (Antartica) (Taylor et al. 2000) or very old sediments, that formed well before the beginning of any human activity (Maurette et al. 1987).

In general, CSs tend to increase where there is indication of important cosmic impacts. It is the case of big meteoric storms or of the cruscing of big fireballs during the passage in atmosphere (Klekociuk et al. 2005). It is the case of the Tunguska event (June 30, 1908) (Longo et al. 1994) and of asteroidic impacts that gave rise to mass extinctions. A classical example is the K/T boundary, connected with the dinosaurs extinction of 65 million of years ago (Bohor et al. 1998).

A more recent example (Le Compte et al. 2012) is related to the discovery of an excess of metallic CSs inside the Murray Springs sediments (an archeologial site of Clovis culture, in south-western Arizona) dating about 12,900 years ago: a possible indication of the landing of a cosmic object that promoted the end of Clocis culture. Against this backdrop, it is clear that the boundaries of a meteoric crater, better if quite young, discovered in a desert region and never explored before, appear as the best location for the discovery of CSs. An ideal crater of this kind, is the Kamil crater, a round track of 45 meters, created few thousands year ago, by an iron meteorite 1.3 meter in diameter, on the border between Egypt and Sudan (22°01′06″N, 26°05′15″E). The Kamil crater was identified by V. de Michele (the former curator of the Mineralogical Section of Natural History Museum of Milano) in pictures taken by QuickBird satellite on October 2005 (Folco et al. 2011). A couple of italo-egyptian geophysical expeditions, undertaken on February 2010 and 2011, revealed that the crater is surrounded by a large amount of big and small iron meteoritic fragments of extraordinay composition (Ni=19.8%, Co=0.75%, P=0.5%, Ir=0.39 ppm) (D'Orazio et al. 2011). The morphological properties of the crater are indication of an impact age of about 5,000 years (Urbinim et al. 2012). During the February 2011 expedition R. Cogliati drew many samples both inside and outside the crater (1), in order to check for the possible presence of metallic CSs, produced by the melting of the iron meteorite during its passage trough the atmosphere. This paper is devoted to the search for CSs inside these samples and to a careful SEM study in order to understand their mechanism of formation and also their origin.

2. Experimental part

The SEM search for metallic micro-meteorites directly inside sand samples from the Kamil crater was quite impossible: indeed, having the SEM a very small field of view, the finding of CSs should be the same as the checking for some ants in the entire Milan Duomo Square... So it was necessary to make a concentration of possible micro-meteorites by manually exploring many sand samples under optical microscope. This action was made by a difficult but efficient technique, developed by F. Martegani (GAT, Tradate): all micro-particles of metallic appearance were drawn by a wet small stick (a toothpick is very good), so avoiding the systematic zipping off of the electrified micro-particles at the moment of the capture. Each single particle so caught was stored on the surface of a standard SEM sample-holder (a 5 mm graphitic bi-adhesive disc). A following careful SEM exploration was made under many different purposes:

- first at all, we checked for the presence of CSs and for a study of their chemical composition.
- second, we made a control of the external appearance of all possible CSs to compare their morphological properties (Guaita & Martegani 2008) with those discovered in the past for similar objects, recovered from rain waters inside and outside the Italy. These surface morphologies, often linked to dimension, can be summarized in four main patterns 1) compact as orange-skin 2) crystalline 3) polygonal as soccer ball 4) filigreed. For this research we used a SEM Jeol JMS-5610LV located at the Mineralogical Section of Natural History Museum of Milano, utilizing both the BSE detector (backscattered electrons) and the SE detector (secondary electrons, specially suited to surface studies); the SE detector worked at the best if the surface of the spherules was coated by a gold or graphite thin layer under vacuum
- Thirdly, we would understand the MECHANISM of formation of these spherules, studying, if possible, also the INTERNAL structure. The SEM scrutiny inside some spherules was really very difficult. We succeeded in this operation thanks to two special methods of sample preparation. In the first method, we embedded some CSs (dimension= 30-100 micron) at different depths inside a matrix of araldite (a thermosetting resin); after, we polished with great care, under continuous control by optical microscope, in order to stop the work as soon as the polishing scraped off about half of a single spherule. In the second method, we carefully pressed some spherules between two slides, after having chosen them under optical microscope. Sometimes we were able to break up the spherules in fragments that, being enclosed between the slides, could be recovered for a following SEM inquiry.
- Eventually, we would try to understand the SOURCE of these spherules, checking for

a possible link (a priori very reasonable) with the metallic meteorite that produced the Kamil crater, around which a large amount of iron fragments was found (for an estimate of about 1.7 ton).

3. Results and discussion

In summary, we can say that near the Kamil crater (without big differences between inside and outside) a large number of metallic (basically Fe3O4) CSs were found. All surface morphologies yet known in the past were also recognized. On the interior, the micro-spherules appeared always hollow. *Even if it is beyond doubt the cosmic origin of these micro-spherules, surprisingly they don't show any link to the impact that produced the crater* $5,000$ *years ago*. Here's how we reached for this conclusion.

3.1. Presence of micro-spherules

An abundant presence of CSs of dimension between 10 and 200 micron was attested: their geometric shape is always very regular. No quantitative difference was noticed (in the amount of CSs) between sand collected inside and outside the Kamil crater. The CSs (investigated by the SEM-EDS probe) appeared always composed of oxidized iron (mainly magnetite) without any trace of Nickel. The glassy micro-spherules (that's composed of stony material) were very rare (and very small). The same iron composition was yet verified in the past for other spherules of uncertain origin (Guaita & Martegani 2008), but, now, this fact appears even more surprising taking in account the great amount of Nickel contained in the Kamil meteorite (about 20%). An anthropogenic origin of these spherules can be surely excluded, because of the remote and never explored location where they were found. So only two other possibilities remained: the spherules could result from meteoric material of the crater under some strange selection process that favoured Fe (against Ni) during the melting/solidification phase, or the spherules could have a (cosmic) origin NOT linked to the presence of the crater.

3.2. Surface morphologies

The surface morphologies of the metallic spherules (investigated by SEM with BSE and SE detectors) showed the four main known patterns linked to magnetite crystals (Fig. 2, 3, 4, 5, 6). Furthermore, for the first time, a new intermediate morphological form was observed, consisting of polygons (*soccer ball* type), structured as rows of elongate micro-crystals (Fig. 7). An other interesting observation is related to the formation of the crystals. Often the crystalline structure appears to start from a local irregularity/contamination and from here it appears to gain a star shape all over the remaining surface (Fig. 8): it is clear the impression that just local impurities are involved in promoting the crystallization process or its acceleration.

3.3. Interior of the microspherules

One of the more interesting results of this work was the first ever inspection of the internal structure of metallic CSs. When broken CSs were casually encountered, some of them seemed to show an empty interior (or, what is the same, a very thin surface crust) (Fig. 9); others, on the contrary, seemed to show a compact interior (Fig. 10). What was really going on there? It was a matter of two different solidification processes or of two different aspects of the same process? To understand this point, we explore with the SEM the interior of some CSs prepared with the two methods described in the experimental part (polishing of spherules embedded in Araldite and breaking of spherules between two slides under optical microscope). The basic result of this work can be summarize as so: the CSs always show an internal cavity of variable dimension and position. In our opinion, the air enclosed during the formation of micro-drops of melted material, expands for thermic reasons and, again for thermic reasons, becomes very reactive towards the Fe of the spherule (oxidizing it to magnetite). Very often the internal soul is off centre, and so the walls of the spherules could seem very thin in some zones and very thick in other zones: being the thinnest walls also the most frag-

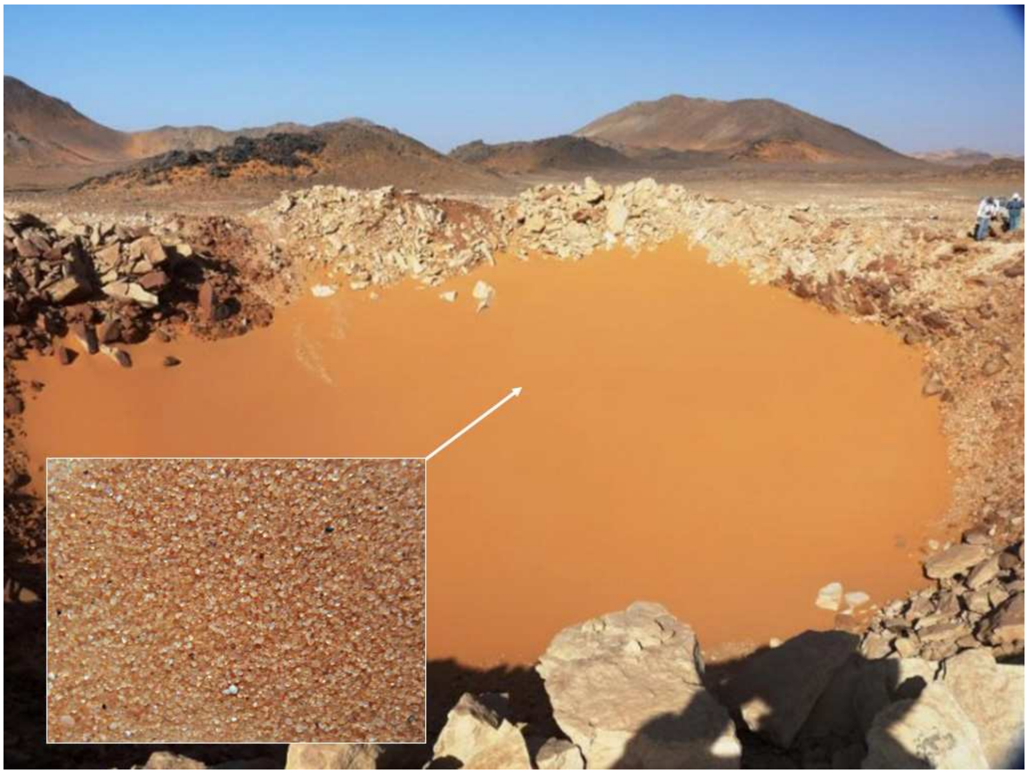

Fig. 1. The Kamil crater and an enlargement of the internal sand, where some glimpses of metallic micro-spherules are visible.

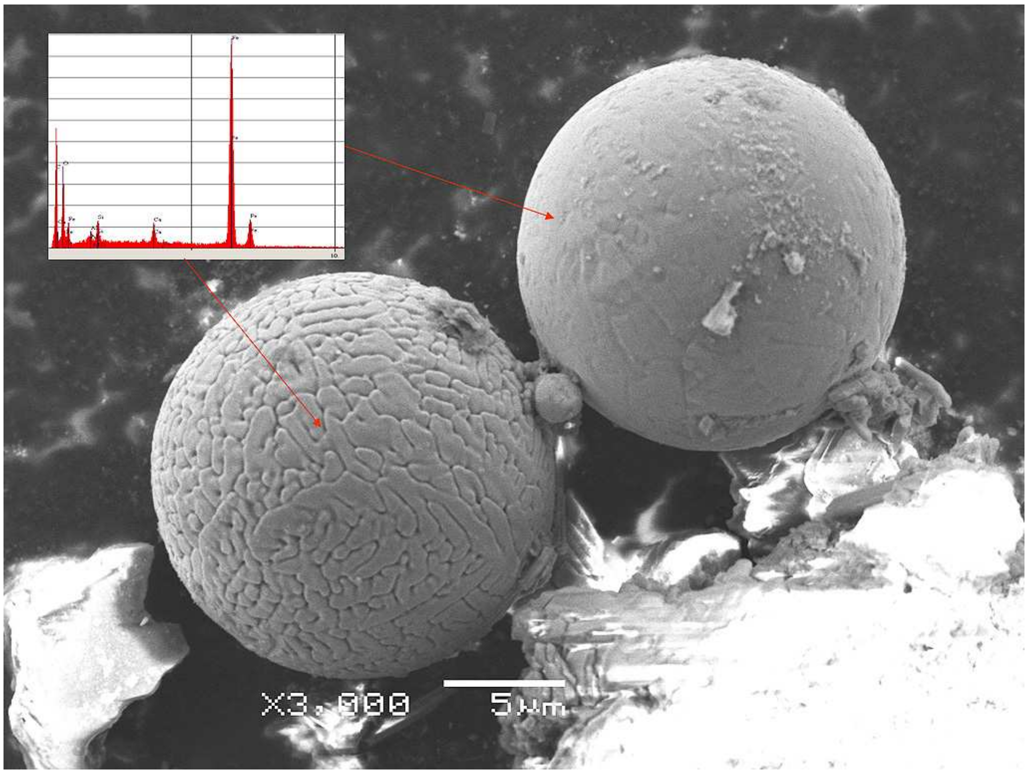

Fig. 2. Two *filigreed* micro-spherules, that show a metallic composition (oxidized Fe) (the C peak on the left is due to a graphitic layer applied to improve the SEM response).

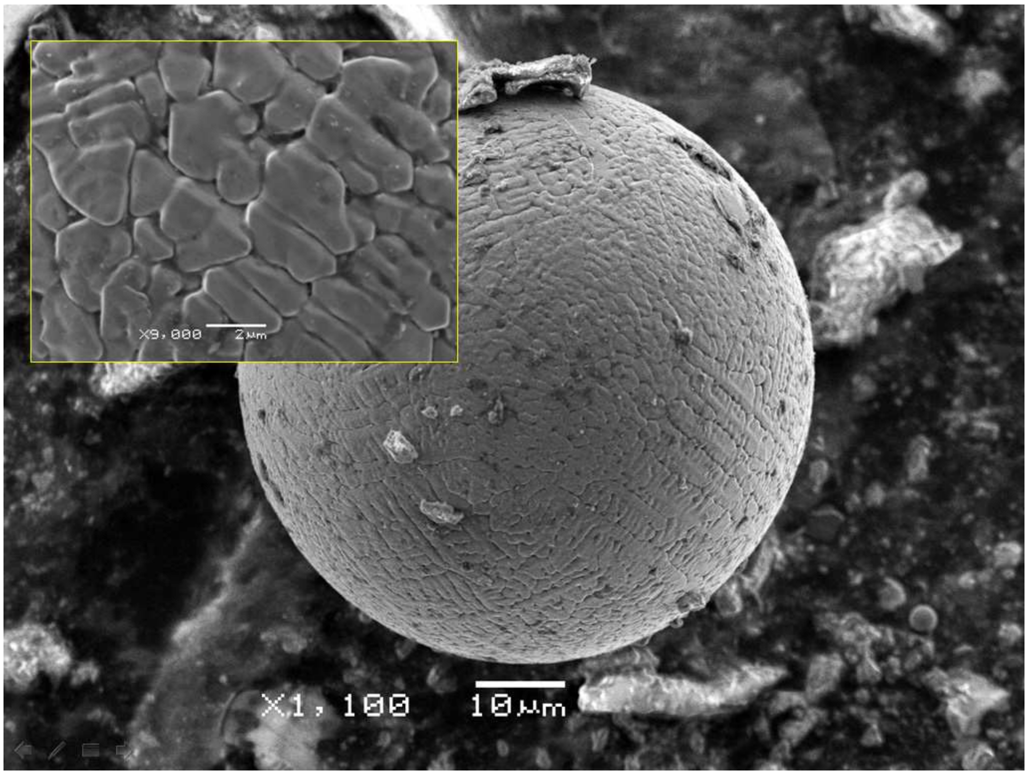

Fig. 3. A *filigreed* micro-spherule with an enlargement on the complex morphology of the surface.

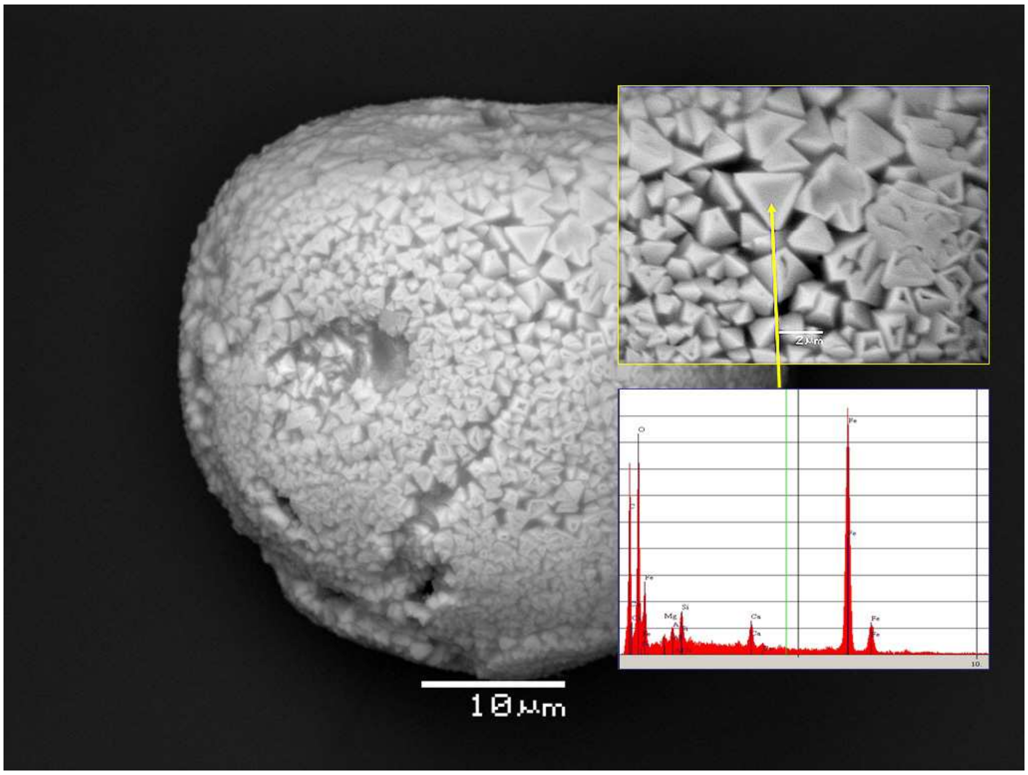

Fig. 4. A distorted micro-spherule with the surface covered by wonderful magnetite crystals.

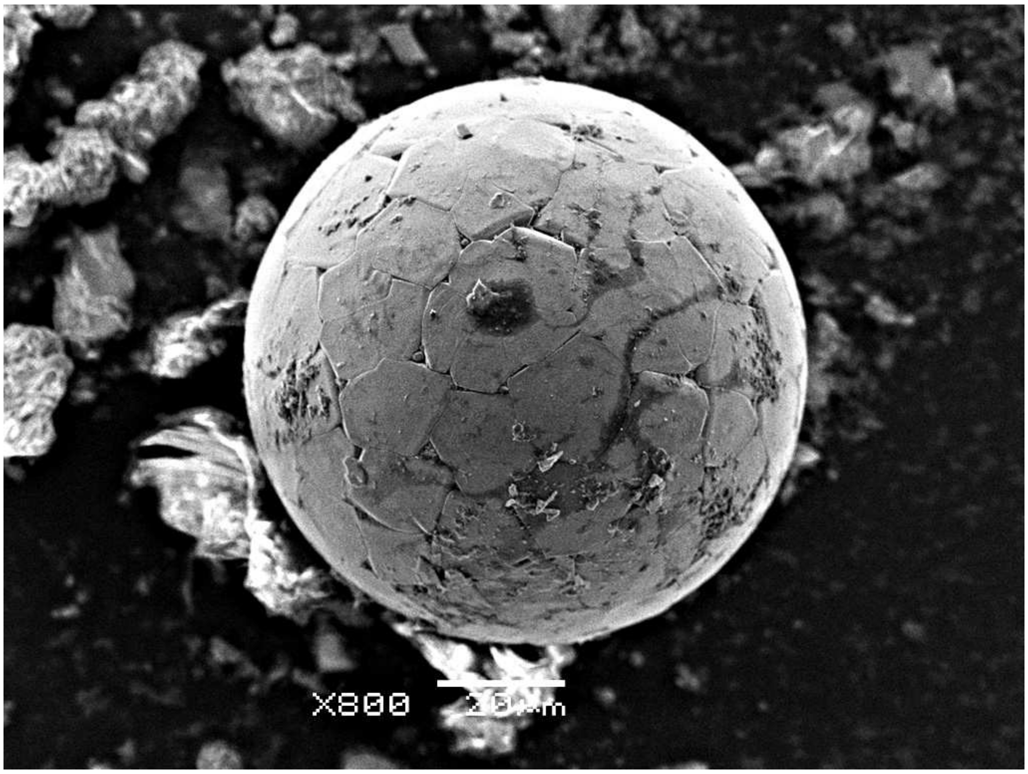

Fig. 5. A micro-spherule with a polygonal (*soccer-ball* type) surface morphology.

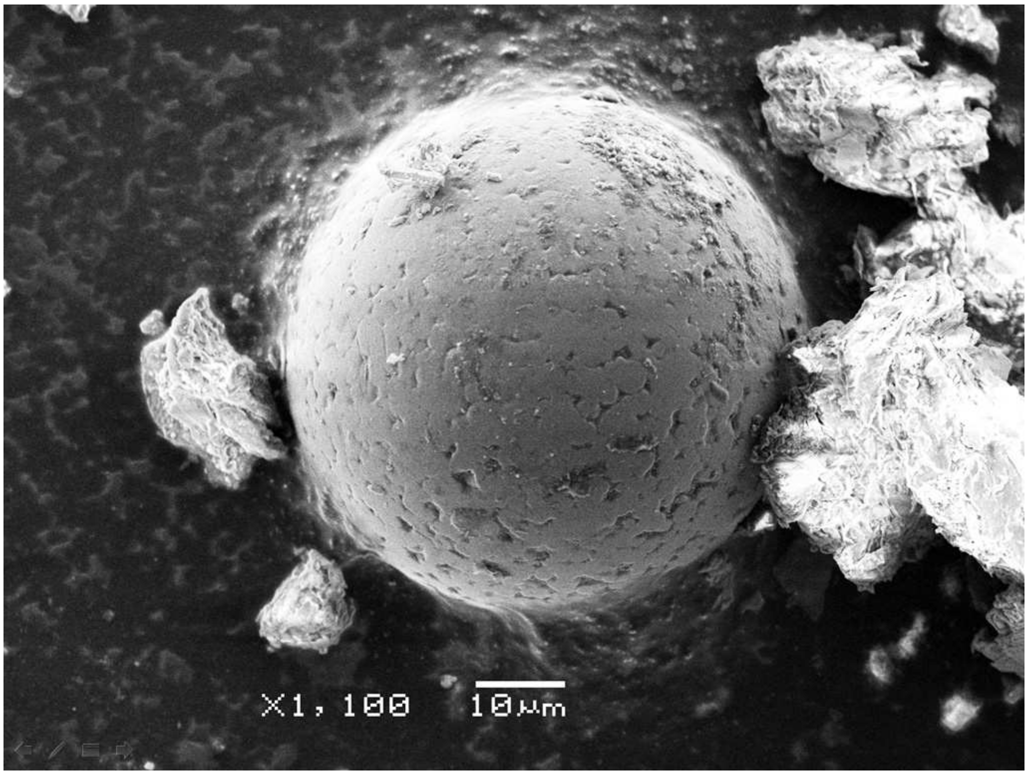

Fig. 6. A micro-spherule with a quite compact (*orange-skin* type) surface morphology.

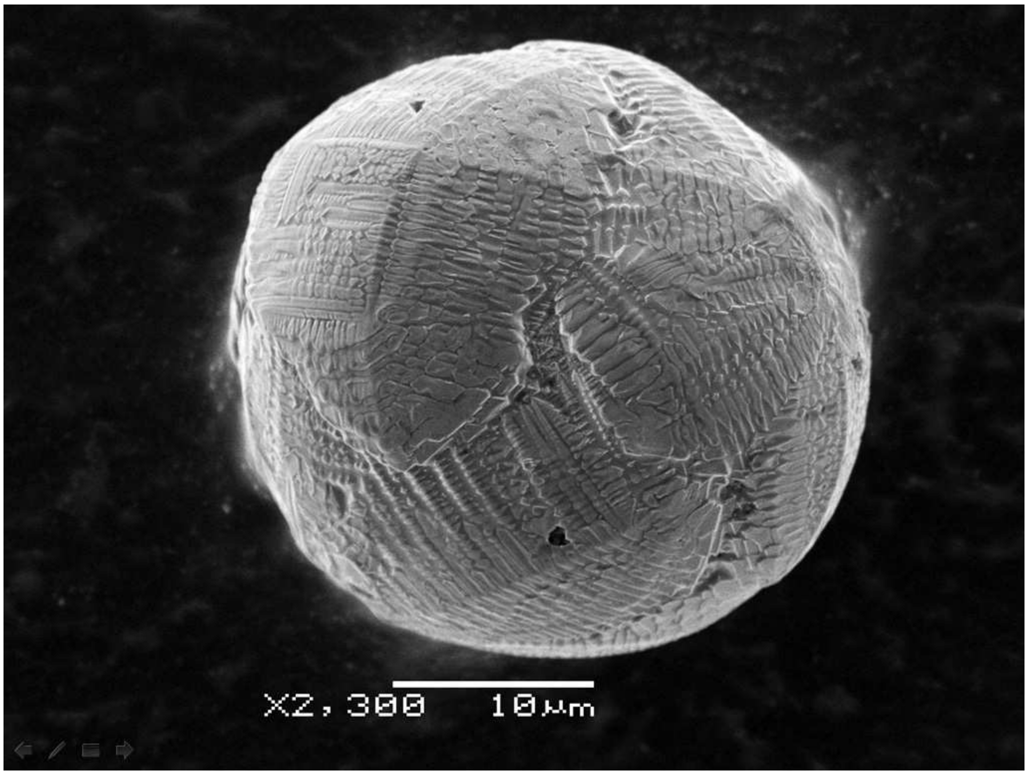

Fig. 7. A micro-spherule with a new kind of surface morphology, in which *soccer-ball* and *orange skin* patterns are mixed.

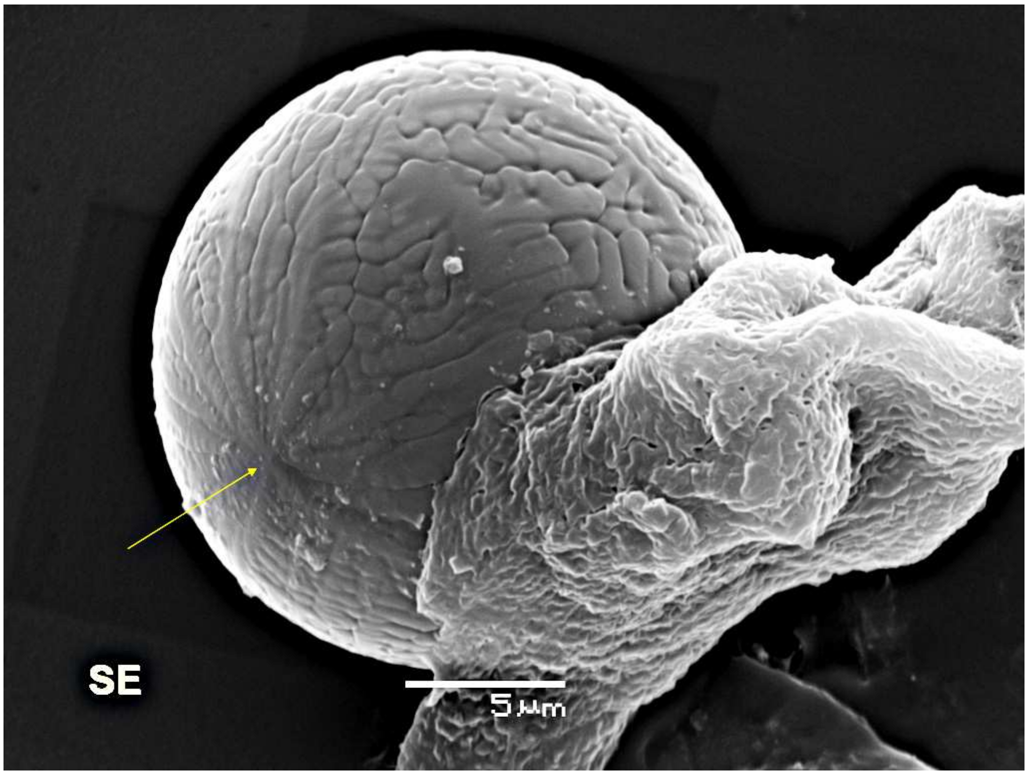

Fig. 8. A micro-spherule with a surface where a foreign body could have seeded a star-crystallization.

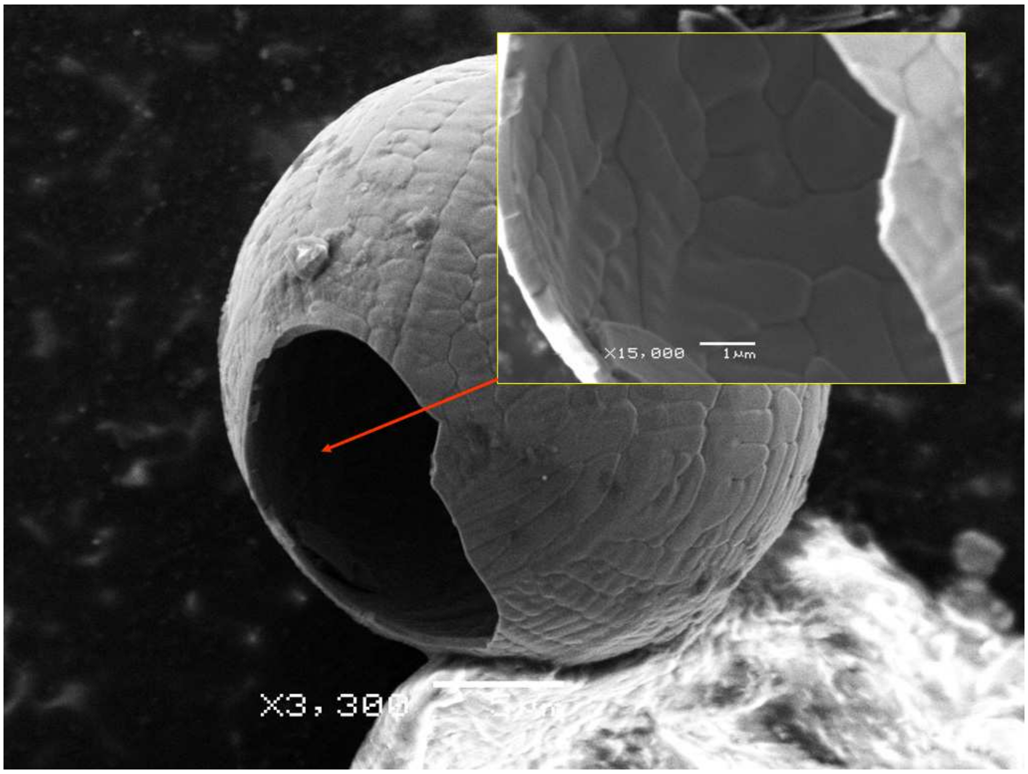

Fig. 9. A broken micro-spherule, with a similar inside and outside morphology. Apparently the sphere is hollow and its crust is very thin.

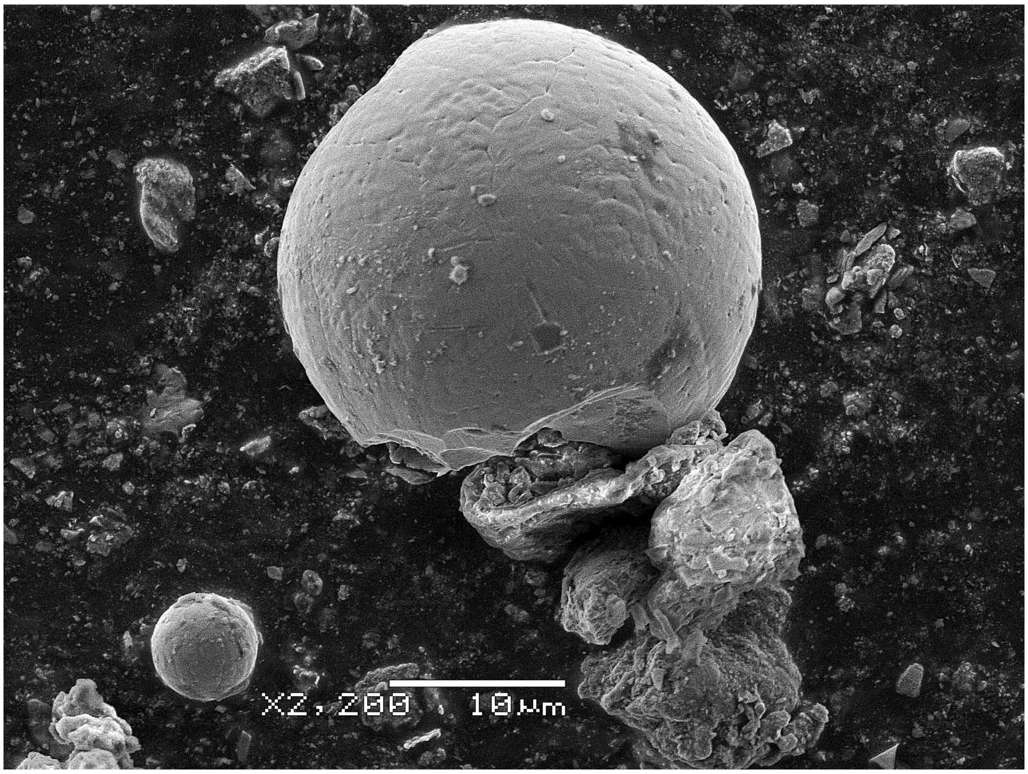

Fig. 10. A broken (filigreed) micro-spherule, that apparently shows a compact interior.

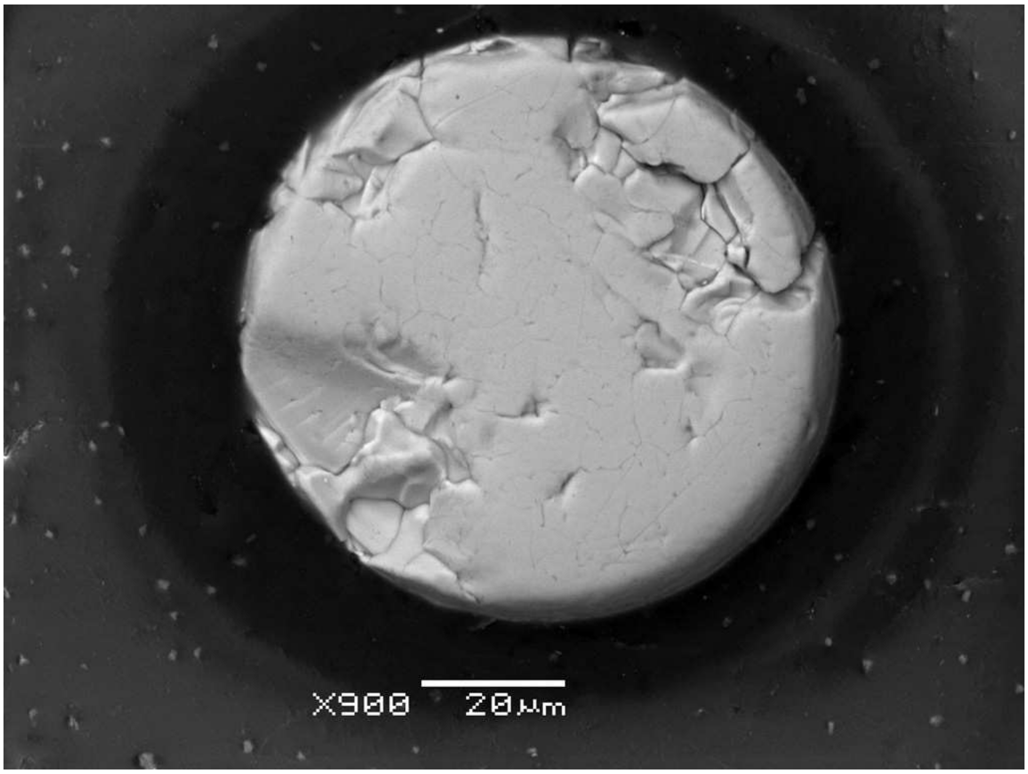

Fig. 11. A polished micro-spherule. Apparently, the matrix is compact but, actually, the polishing etched only the most thick part of its crust.

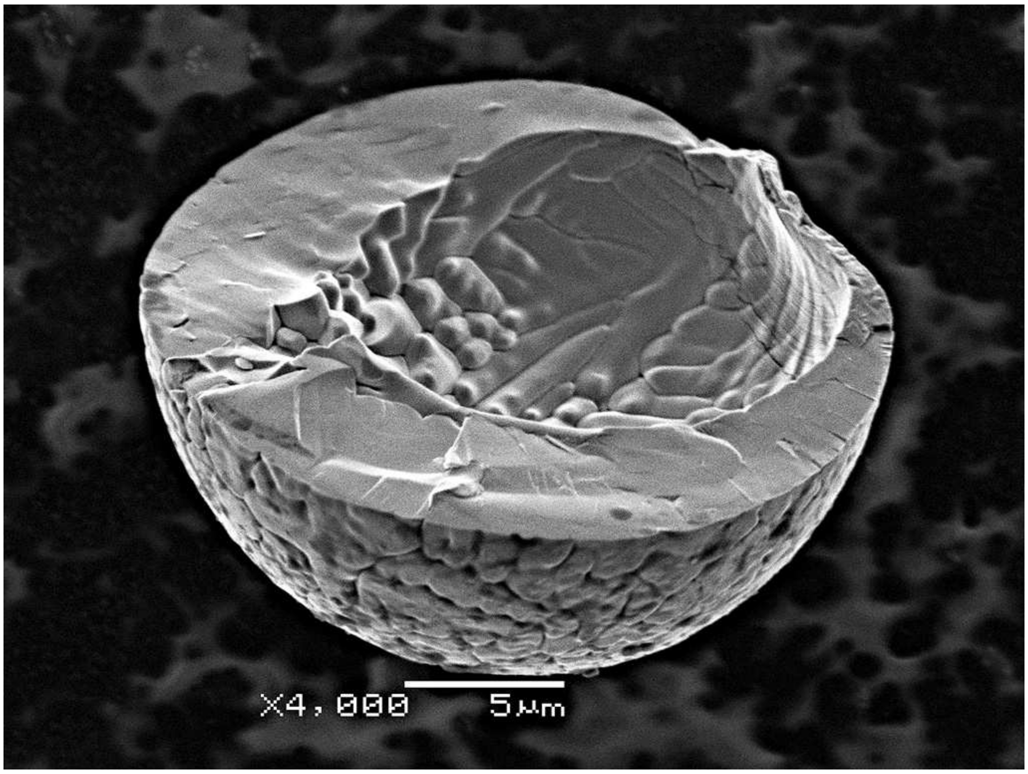

Fig. 12. This impressive picture support the idea that all micro-spherules has a cavity inside. Because this soul isnt normally located rightly at the centre, some part of the walls appears as thick and some other part appears as thin.

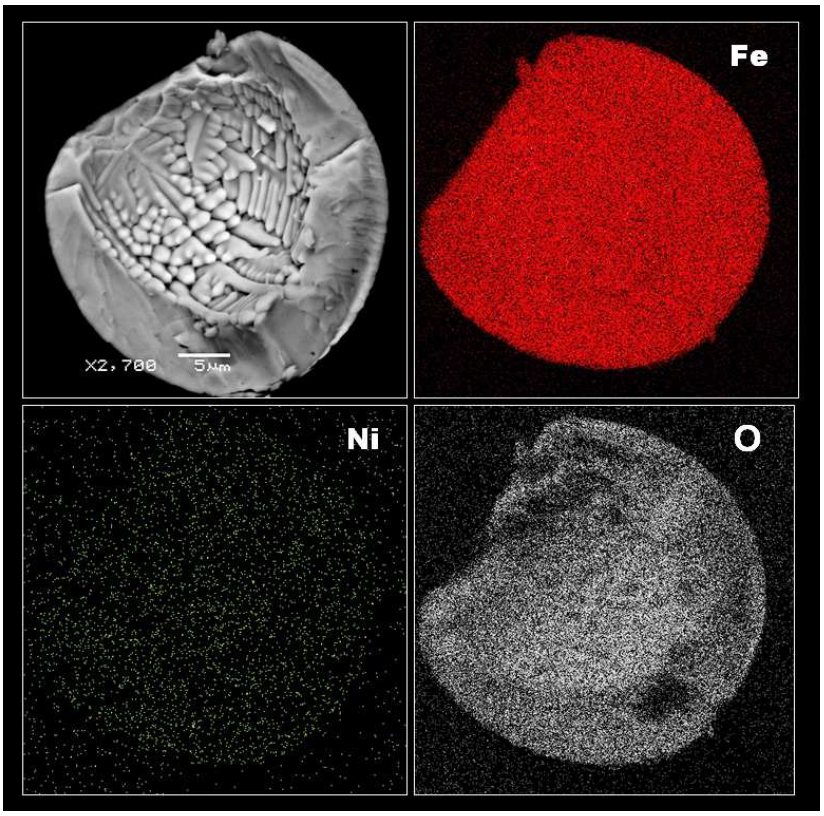

Fig. 13. SEM-EDS map of the interior of a broken micro-spherule: it is clear that also the interior has an iron composition, without real presence of Nickel.

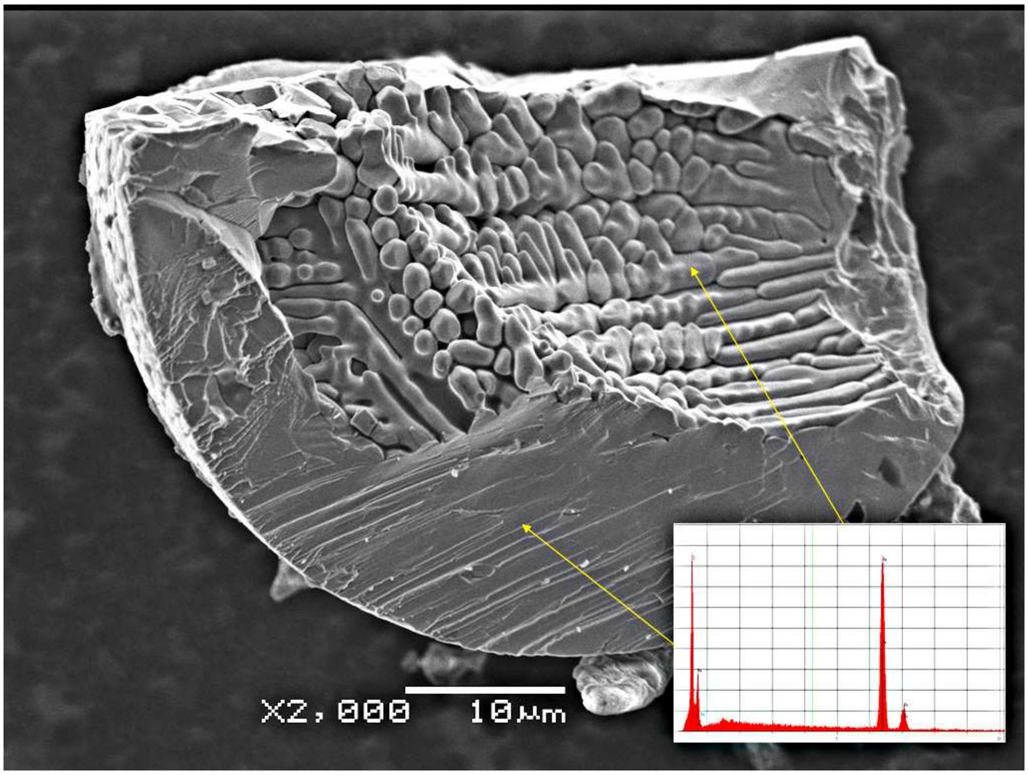

Fig. 14. SEM picture of the thick wall of a broken micro-spherule: under the EDS probe, both the wall and the internal crystals show an iron composition.

Fig. 15. Micro-spherules collected by Roberto Cogliati in the sand of the Amguid crater.

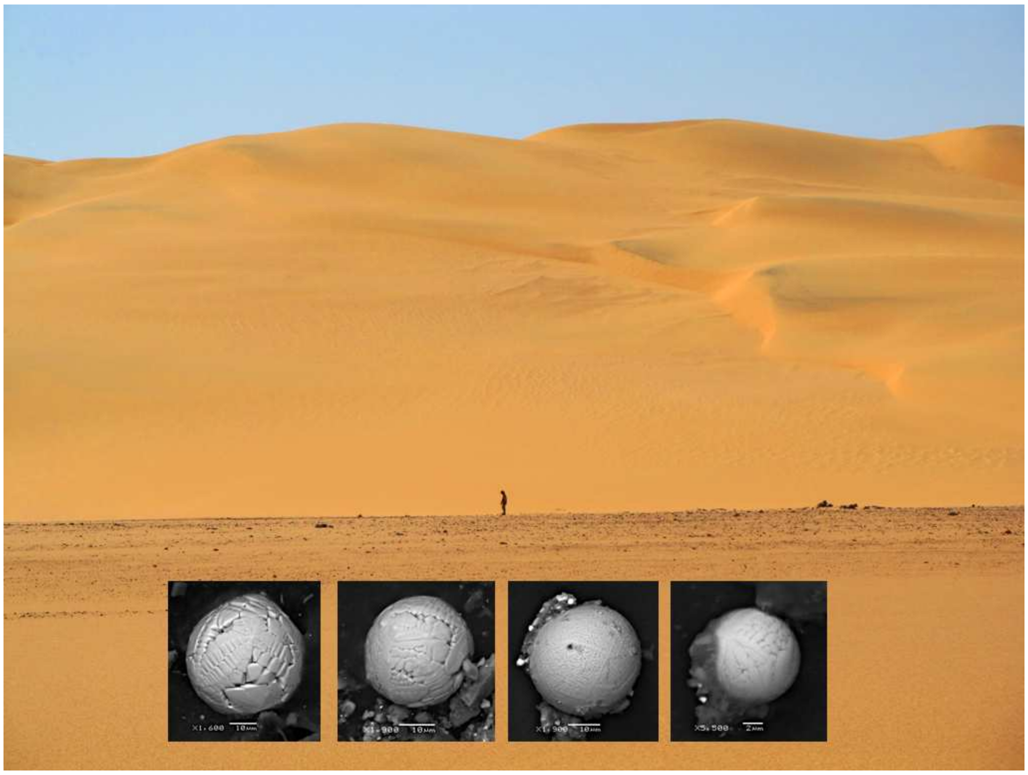

Fig. 16. Micro-spherules found in the sand of the Libian Desert Glass.

ile, it is obvious that the CSs showing natural breaks on the surface could also seem totally hollow inside. On the other hand, it is obvious that a CS polished on its thick wall (Fig. 11), will appears fully compact inside. The SEM-SE pictures clearly attested that the same external crystalline structure is present also inside, with features exactly enabled by the available space. Furthermore, we also observed inside the same examples of seed-promoted star-crystallization yet found on the surface. The availability, between hundreds of fragments, also of CSs exactly half-splitted permitted to demonstrate unambiguously the presence of a asymmetric internal soul, because the walls of a single spherule could often appear very thick in some positions and very thin in other positions (Fig. 12). We were also able to enter the interior of the CSs with the SEM-EDS probe, so verifying that the magnetite was the main component both for the internal crystalline structures and for the wall connecting the inner and the outer surfaces (EDS analyses on single internal crystals and Fe, Ni, O micro-maps) (Fig. 13 and Fig. 14).

3.4. *Origin of the micro-spherules*

As already mentioned, an anthropogenic origin of the micro-spherules recovered around the Kamil crater, can be rule out, being this desert location away from any human settlement and probably never explored before February 2010. So the origin of the spherules has to be cosmic. The information (EDS probe) that the spherules are practically Ni-free makes very difficult a link with the metallic meteorite the created the Kamil crater, whose Ni content is about 20% . Above all, two other observations seem very revealing. First (Fig. 15), we have checked for and found the same kinds of CSs also in a sand sample recovered (R. Cogliati, April 2011) inside an other saharian crater: the Amguid crater (26°05′15.3″ Nord, 4°23′42.7″ Est), 500 m diameter and 100,000 year aged. Second (Fig. 16), we found the same CSs also in a sand sample that R. Cogliati recovered in the Libian Desert Glass, more than 500 km away from Kamil and Amguid craters. The meaning of all these observations is clear: the saharian CSs are present everywhere, so their cosmic origin is not linked to the material of specific impact craters, but arises from a continuous influx from the upper atmosphere, where meteoric material melts under frictional heating, producing melted submillimeter particles so light that their surface tension (that tends to confer a spherical shape) far overcomes the gravity.

4. Conclusions

The main result of this research is the (more than likely) demonstration that the primary source of the metallic micro-spherules found everywhere in the world is of cosmic nature. But because there are also some human activities that produce micro-spherules, the finding of them in densely urbanised areas (for example by the classic recovery from rain water) makes their origin quite uncertain. Now, on the contrary, with the discovery of the same micro-spherules in samples of saharian sand drawn in regions very far apart, both near and away from impact craters, the cosmic origin of the spherules seems unquestionable. According to the most recent estimates, almost a cosmic micro-particles of 10-50 micron falls daily and almost a cosmic micro-particle of 100-200 micron falls yearly, over each m^2 of terrestrial surface. This kind of estimates, normally made recovering and melting artic/antartic ice or exposing to space particular capture equipments (McDonnell et al. 1984), are impossible to be made in a desert ambient as Sahara. In any case, since we found hundreds of CSs of 10-300 micron in samples of few hundreds grams of saharian sand, this means that these CSs piled up slowly during hundreds (or thousands) of years. But the contribution of the impacts to the presence of CSs, even if reasonable in general, is in this case very difficult to evaluate, both because the same CSs have been found also away from the impacts and because the impact areas taken in account (Kamil and Amguid), even if very young geologically speaking (5000 and 100,000 years), had plenty of time to be overcome by the fall of natural CSs. Furthermore, there is a very troublesome concern about the Kamil crater: the fact that the spherules are systematically composed of oxidized Fe without any trace of Ni, whereas the Ni content of the abundant siderite material spread all around the crater reaches for about 20%. On this point we are still working theoretically (can an alloy Fe/Ni 80/ 20 keeps apart pure Fe during the melting?) but also experimentally. This means that we will try to produce synthetic micro-spherules starting from the sideritic material of the Kamil meteorite, in order to compare their morphological and compositive properties with those of the micro-spherules found on the field.

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