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MORPHOLOGY AND INTERNAL STRUCTURE OF ANTARCTIC COSMIC DUST SPHERULES: POSSIBLE LINKS TO METEORITE FUSION CRUSTS

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Abstract: Petrographic and SEM comparison of the outer morphology of different Antarctic spherules with their internal structure helped to distinguish those spherules that resulted from melting of micrometeorites from the ablation products of meteorites. A chain of possible transformations beginning with unmelted micrometeorites was recognized. Such structural transformations could begin from unmelted cosmic dust of olivine aggregates through granular spherules, to vitrophyric spherules with ghost-olivine glassy ovoidal objects, to vitrophyric, and to skeletal spherules. The fusion crusts of meteorites studied, showed that ablation can also produce a variety of spherules. Achondrites could produce glassy smooth, and internally compact holohyaline spherules, whereas chondrites could generate spherules of the rough glazed, dendrite decorated morphological types.

1. Introduction

Cosmic dust spherules are the degassed and droplet-shaped ultimate products of atmospheric heating of micrometeorites (KURAT *et al.*, 1993), or products of ablation/explosion of meteoroids that pass through the atmosphere. As estimated by YIOU *et al.* (1991), the average flux of spherules (>50 μm) was about 1500 tons/year during the past 100000 years. According to KURAT *et al.* (1993), most micrometeorites have a CM-similar composition but some could possibly be planetary in origin, and also interstellar matter could be present. However there is strong evidence that the 0.1–1 mm cosmic dust particles that survive atmospheric entry are predominantly and perhaps exclusively asteroidal in origin (BROWNLEE *et al.*, 1991).

As discussed by BRADLEY *et al.* (1988), interplanetary dust particles do not represent primordial material of the solar system. According to the Poynting-Robertson effect, dust particles about 10 μm in size can exist in the inner solar system no longer than 10^4 years. Because of this, the present dust cloud should be continuously replenished by influx of new particles derived from different sources. Most of this dust is the result of asteroidal collision, but some particles have been ejected from comets. Such cometary dust streams are generated from comets by solar heating in the inner solar system. According to infrared observation of distant stars, dust disks are a common feature in the universe.

Cosmic dust particles that bombard the Earth may survive passage through the atmosphere with different degrees of success dependent on their entry velocity, composition and structural features. Due to the friction of air molecules the surfaces of entering extraterrestrial objects are heated rapidly, and temperatures of thousands of degrees are reached in a fraction of a second. Because the heating rate near the surface may reach 2600°C per s (Zbik *et al.*, 1989), some minerals do not have time to react completely, and hence persist as relicts that can be observed in melted micrometeorites (Christophe Michel-Levy and Bourot-Denise, 1992) and meteorite fusion crusts (Zbik *et al.*, 1989).

Most micrometeorites evaporate during passage through the atmosphere; others melt partly or wholly forming droplet-shaped spherules. A few percent of small dust particles with comparatively low entry velocities are heated insufficiently to meit, and survive as unmelted micrometeorites. It is also possible that unmelted micrometeorites were frozen in ice that protected them against heat, and were liberated into the atmosphere. Both melted and unmelted micrometeorites have been collected from the stratosphere, Greenland and Antarctic ice sheets, deep sea sediments, as well as soil and sedimentary strata.

Little is known about cosmic dust and its accretion onto the Earth. Remarkable differences exist in the chemical composition of micro-objects collected in stratosphere compared to those from other sources, such as the sea floor and ice sheets. Beckerling *et al.* (1991) have found that the relationship between texture and composition of Antarctic spherules is less clear than those from Greenland. Furthermore, the genetics links between Antarctic spherules and the ablation products of meteorites are not clear. Also unknown is the influx of micrometeorites that are the result of large planetary impacts (Gostin and Zbik, in preparation), and influx of the general interstellar medium (Bering III, 1993). Because of the above reasons there is a growing interest in the study of micrometeorites that confirm the uniqueness and importance of these objects.

The aim of the present study is to compare morphology of the outer shells of different Antarctic spherules with their internal structure. In addition, the structure of meteorite fusion crusts is shown for comparison with the structure of studied spherules. This could help to distinguish those spherules that result from melting of micrometeorites and the ablation products of meteorites.

2. Samples and Experimental Technique

Twenty two spherules were separated from a few mg of mixed dust sample obtained from the "EUROMET" (Maurette *et al.*, 1992). This sample was collected in Antarctica during the January–February 1991 field season. Spherules, glued onto the stage were coated by carbon and investigated using a Cambridge Scanning Electron Microscope (SEM) equipped with EDAX system. After SEM investigations of the spherule outermost morphology, the sample was covered by epoxy glue and a polished section was made. SEM investigations of the internal structure and microprobe analyses were conducted on that section.

The chemical compositions was determined with a JEOL electron microprobe at the National Institute of Polar Research, Tokyo. Analyses were made using an accelerating voltage of 15 kV, a sample current of 3 nA, and a beam width of 5 μm. A polished section from the ablation fusion crust of several different meteorites was also prepared, and the texture of the outermost parts of these fusion crusts was studied by SEM and optical microscope.

3. Results

3.1. Outermost morphology and internal structure of spherules

The investigated spherules show different groups of morphology. There are five surface morphological types, and four types of internal structure:

Morphological types:	Structural types:
1) Smooth glassy.	1) Compact holohyaline.
2) Barred.	2) Skeletal.
3) Dendrite decorated.	3) Vesicular vitrophyric.
4) Octahedron decorated.	4) Porous granular.
5) Rough glazed.	

Investigated spherules are 60 to 120 μm in diameter. Most of them are spherical in shape but some are slightly elongated with egg like shapes, and one is irregular with a skull like shape. Some spherules represent more than one morphological type and are mixtures of two or more types. The morphology of all investigated spherules was presented in ZBIK and GOSTIN (1994).

The smooth glassy morphological type is represented by a large spherule shown on Fig. 1. Conchoidal fractures on the surface of this spherule (Fig. 1a) was probably caused by cracking. This morphological type revealed a compact holohyaline structure in cross-section (Fig. 1b).

Barred olivine spherules showing few olivine bars (Figs. 2a and b) traversing the compact, glassy matrix. These spherules represent a skeletal type of internal structure. The barred morphology is due to uncovering the internal skeletal structure probably by weathering. A similar process is remarkable in dendrite decorated morphological type (Fig. 3) that also represents a skeletal internal structure. In this case the dendrite decorated spherule has a regular rounded shape and rough surface due to the needle-like, spinels dendrites protruding from the spherule (Fig. 3a). This kind of morphology probably resulted from the leaching of glassy material from between dendrite needles. This is well illustrated in the polished section (Fig. 3b), where skeletal dendrite crystals are developed inside this spherule.

Dendrite decorated spherules revealed an ultrathin vitrophyric internal structure. In this case tiny, mostly submicron, dendritic spinel crystals set in a compact, hyaline matrix.

The octahedron decorated morphological type is represented by a spherule shown on Fig. 4a. Surface of this spherule is covered by spinel octahedrons held together by a rough glaze of Mg, Si, Fe, Ni rich composition. Internally, this morphological type show vesicular vitrophyric structure where spinel crystals of varying size, merge in a hyaline matrix (Fig. 4b). There are no differences in size between spinel crystal inside and on the spherule surface, but they differ in size between different spherules. The spherule on Fig. 4 shows spinel crystals up to 5 μm,

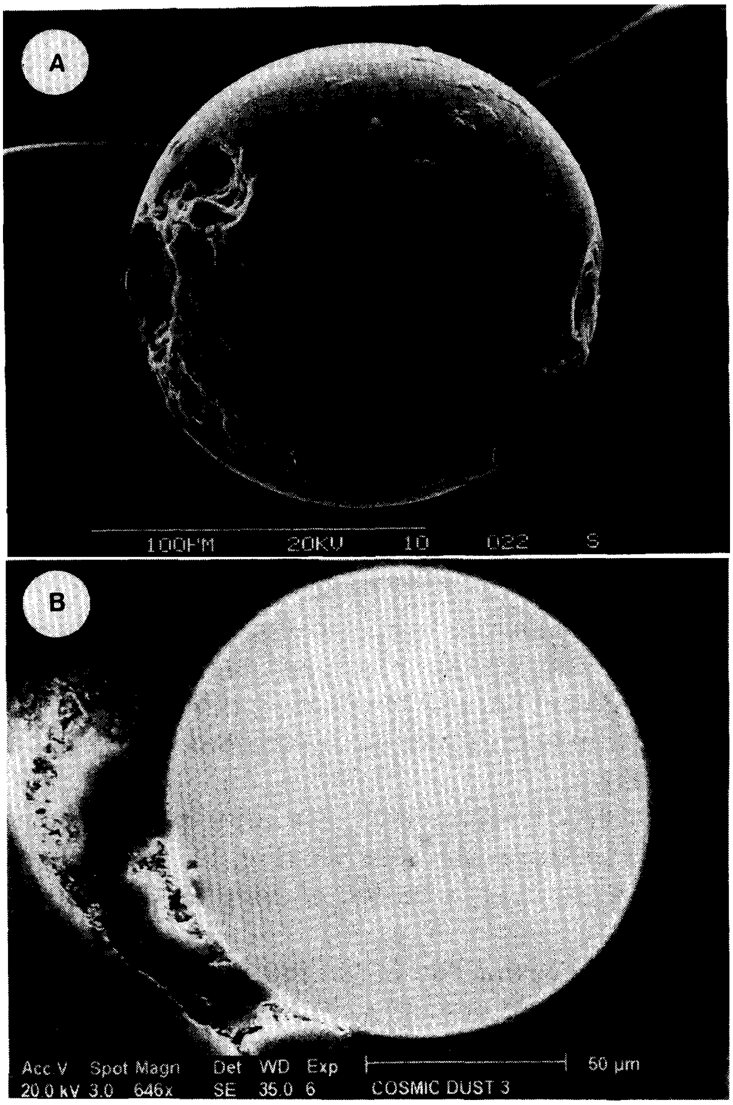

Fig. 1. (a) Spherule [No3] of the smooth glassy morphological type, with conchoidal cracks, (b) compact holohyaline internal structure of this spherule.

that make the surface of this grain very rough. In contrast the spherule that shows tiny spinel crystals up to 1 μm in diameter, is morphologically close to the smooth glassy type, but the presence of vesicles places this in the vesicular vitrophyric type.

The rough glazed morphological type is represented by spherules that are moderately porous with bubbles not exceeding several μm in diameter. They contain FeNi nodules (Figs. 5a and b). Morphologically, spherules often combine the rough glazed and dendrite decorated types. The internal structure of these spherules are also not uniform. Figure 6 shows a spherule with granular structure and with intergranular pores and bubbles, while the vesicular vitrophyric structure combined with dendrite-decorated morphological type is shown on (Fig. 7). The granular spherule demonstrates zoned olivines with dark, magnesium-rich cores and light, iron-rich rims. Small bubbles occur in interstitial glass between the olivines. In some parts of this spherule the intergranular pores are present due to removal of glassy material by weathering. It is noted that a bright, iron-rich rim with spinel crystals and dendrites, covers all the surface of this spherule. These mixed morphological types

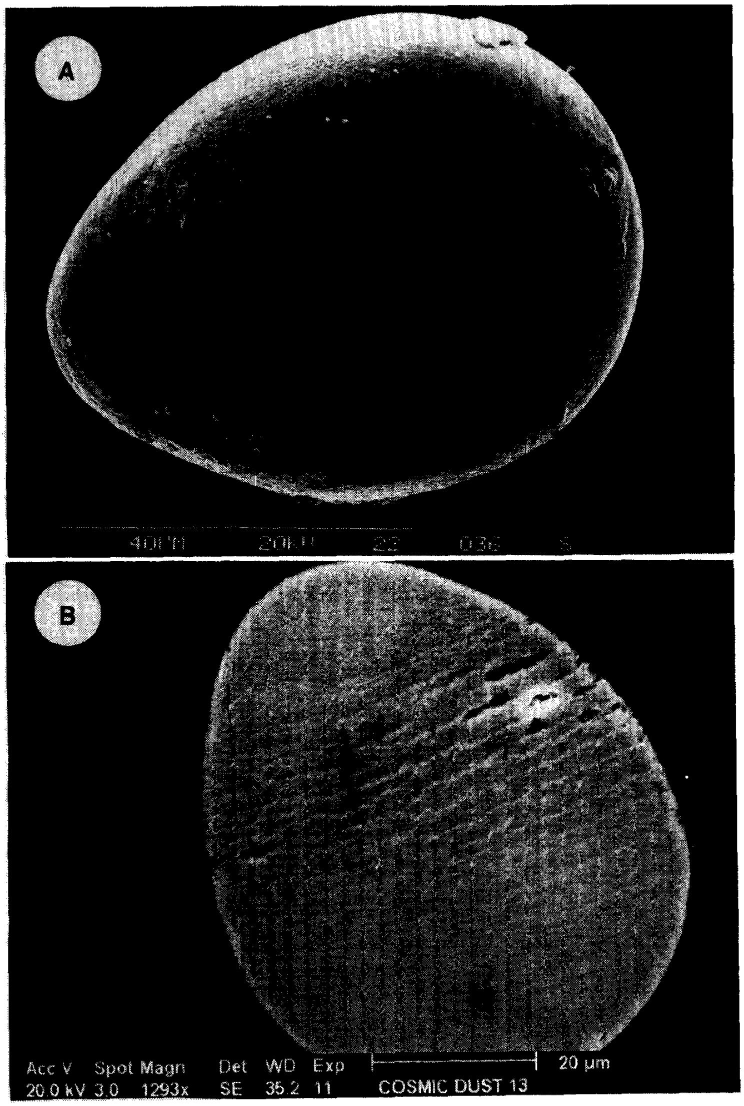

Fig. 2. (a) Spherule [No13] of the barred morphological type, (b) skeletal internal structure build by barred olivine crystal inside this spherule.

have a vesicular vitrophyric structure. The vitrophyric texture of such spherules is often ovoidal, resulting from spinel crystals that encircle dark, iron-poor, glassy ovoids, probable remnants of former olivine grains (Fig. 7b).

3.2. *Structure of meteorite fusion crusts*

The structure of polished sections of the fusion crust of different meteorites was studied under SEM and optical microscope. The crust is macroscopically well-preserved and 300–350 μm thick. It is dull black on the chondrite, glossy black on the eucrite, and turbid gray on the lunar meteorite. There are significant differences between the internal structure of the crust on the chondrites and achondrites (Figs. 8a, b, c,). The chondrite fusion crust (Fig. 8a) revealed a vesicular vitrophyric structure, where dendritic spinel crystals are spread through a hyaline matrix. Both photographs, (Fig. 8b Stannern eucrite, and Fig. 8c lunar meteorite Asuka-881757) show a vesicular holohyaline structure of the outer layer.

The structural features presented in Zbik *et al.* (1989) and in the present study,

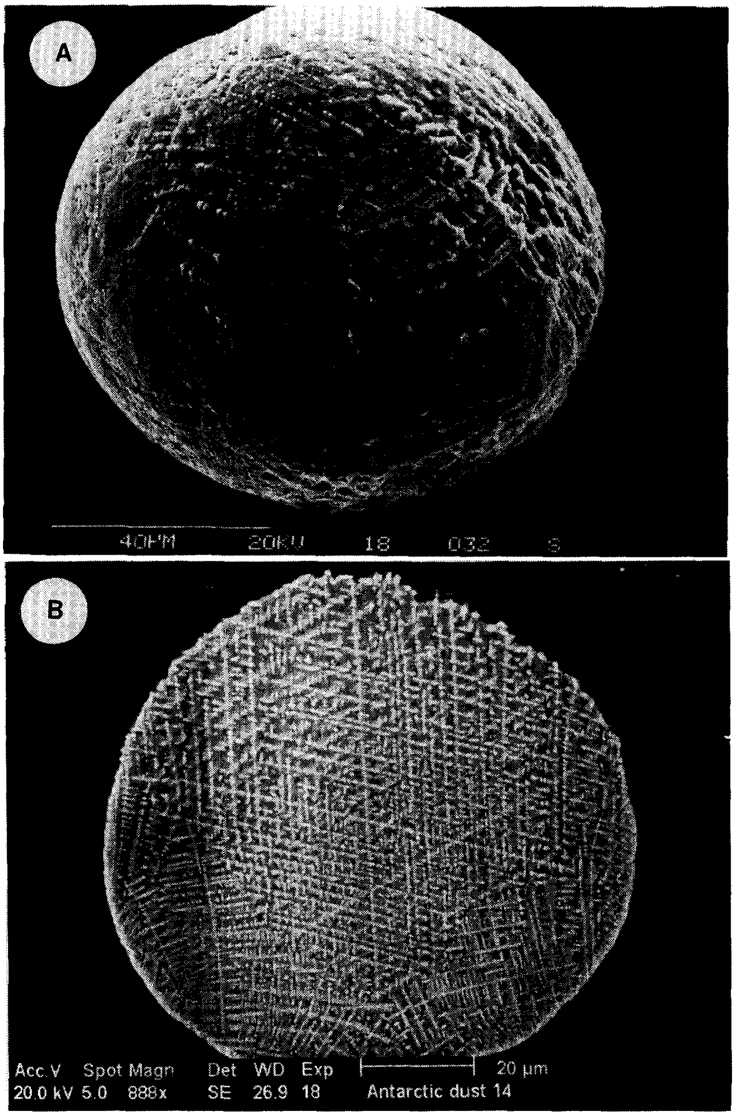

Fig. 3. (a) Spherule [No14] of the dendrite decorated morphological type, (b) skeletal internal structure build by spinel dendrites inside this spherule.

reveal two distinct layers in the fusion crusts. The outer layer, ~100 μm thick, is hyaline with bubbles in achondrites and Lunar meteorite, whereas a vitrophyric structure is characteristic for the outer layer in chondrites. Bubbles are usually spherical in achondrites with mean diameter of 16 μm (the largest one is 60 μm), and amoebous, irregular and varying in size up to 100 μm in the chondrites. At higher magnification, the bubble walls in achondrite and Lunar meteorite are clean, with the hyaline mass showing no crystalline or dendritic forms. In the chondrites, melted minerals are oxidized in the outer zone, and as the glass was quenched, spinel dendrites developed. In both meteorite types, the inner zone does not contain bubbles and is mostly amorphous, perhaps due to an extremely high temperature gradient.

3.3. Chemical features of examined spherules

Microprobe analyses reveal that spherules demonstrate a "chondritic composition" recognized by high SiO_2, MgO, FeO and low Al_2O_3 and CaO content. Main

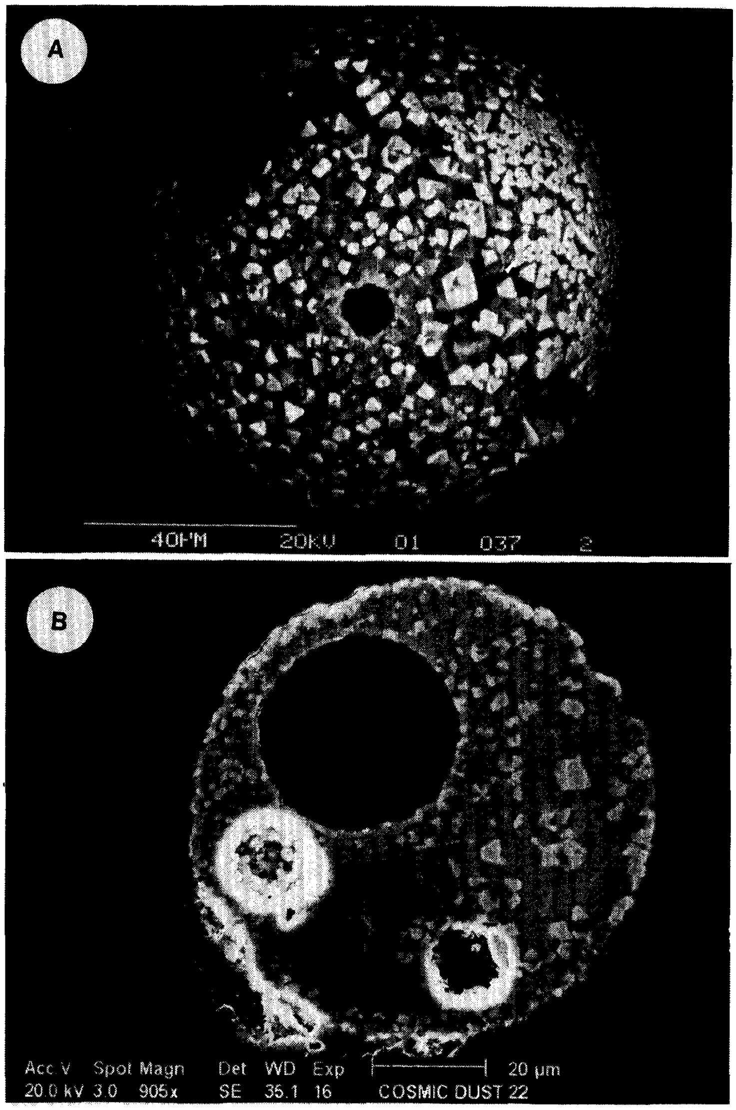

Fig. 4. (a) Spherule [No22] of the octahedron decorated morphological type, (b) vesicular vitrophyric internal structure of this spherule, containing spinel crystals and olivine remnants in glassy matrix.

minerals found are olivine and low calcium pyroxene. The olivine grains are partly melted and there are some remnants of pyroxenes. Dendrites or octahedrons of spinel are present in the dendrite and octahedron decorated morphological types. Similar dendrites occur in fusion crusts of meteorites. Perhaps, during their passage through the atmosphere with cosmic speed, minerals in the fusion crust break down, and iron containing silicates oxidize. After decelerating to aerodynamic speed, quenching occurs, and spinel dendrites grow. The olivines and ghost-olivine glassy ovoidal objects have a low-iron composition $Fa_{<30}$. The FeNi beads were rare, and EDAX analyses of surface layers revealed that some spherules are covered by an FeNi rich film. Such a film could be formed by condensation. Because of the low number of investigated spherules, no statistical investigations were done.

Figure 9 shows that the examined spherules have approximately cosmic Ca/Al ratios, but the octahedron decorated spherules are distinctly different. This could suggest a terrestrial or planetary origin for these objects.

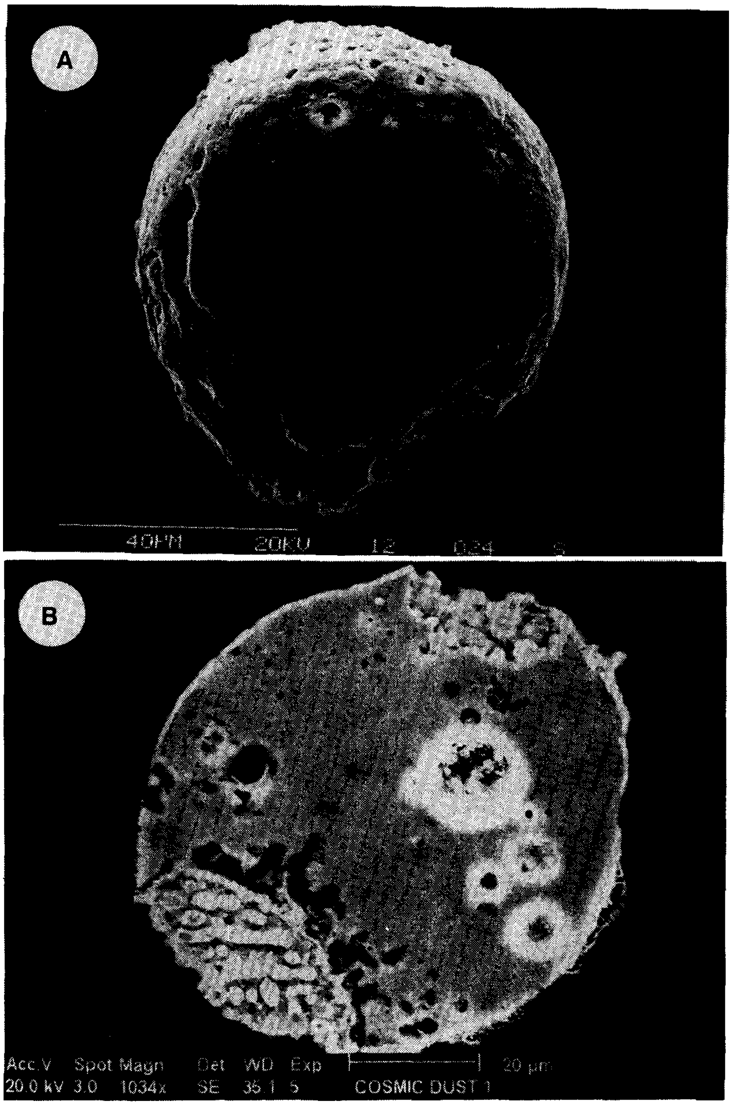

Fig. 5. (a) Spherule [No1] of the rough glazed morphological type, (b) this spherule containing FeNi grains in a vesicular hyaline matrix.

4. Discussion

Most previous studies present links between mineral composition and chemistry of available micrometeorites collected in Greenland, Antarctica and deep sea sediments. Some of them (TAYLOR and BROWNLEE, 1991; BECKERLING, 1992) try to classified the internal structure and establish links between structure and composition. BECKERLING (1992) classified spherules into three types: porphyritic, barred and glassy. TAYLOR and BROWNLEE (1991) review structural types of spherules compiled by different authors as glassy, chain-olivine, radiate-olivine, barred olivine and equant-olivine.

In the present work, perhaps due to the limited numbers of spherules, not all types, quoted above, are represented. Glassy spherules recognized previously, show a compact holohyaline structural type in our study. Such a term more specifically indicates that the amorphous glassy matter forms all the spherule, and that there is no

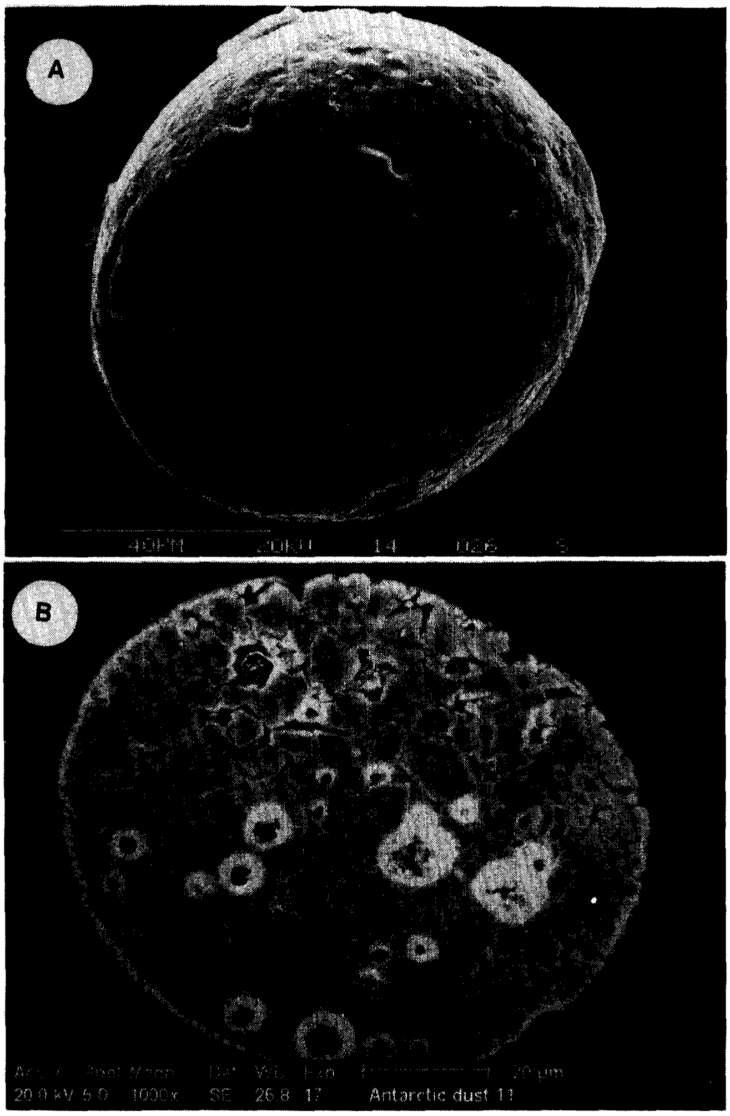

Fig. 6. (a) Another spherule [No 11] of the rough glazed morphological type, (b) porous granular internal structure of this spherule.

evidence of phenocrysts or crystalline parts in that object.

Spherules with a skeletal structure are represented here by barred olivine and spinel-dendrite grains. They are related to the chain-olivine, radiate-olivine, barred olivine and even some G-type (glassy) spherules with distinct dendritic spinel skeletons described by TAYLOR and BROWNLEE (1991). The skeletal structure as we propose is a more general term and does not depend on mineralogical constitution. A range of spherules with different compositions but presenting a distinct crystalline skeleton should be included in this structural type.

The vitrophyric structural type of spherules is characterized by containing crystals and/or crystal remnants embedded in a hyaline or devitrified microcrystaline matrix not previously mentioned in the literature. A spherule like object with similar structure was described by CHRISTOPHE MICHEL-LEVY and BOUROT-DENISE (1992). The above object did not display the basic features of poikilitic or porphyritic structure. In this object ovoid remnants of olivine and small spinel crystals are present, similar to those observed in our spherule, Fig. 7b.

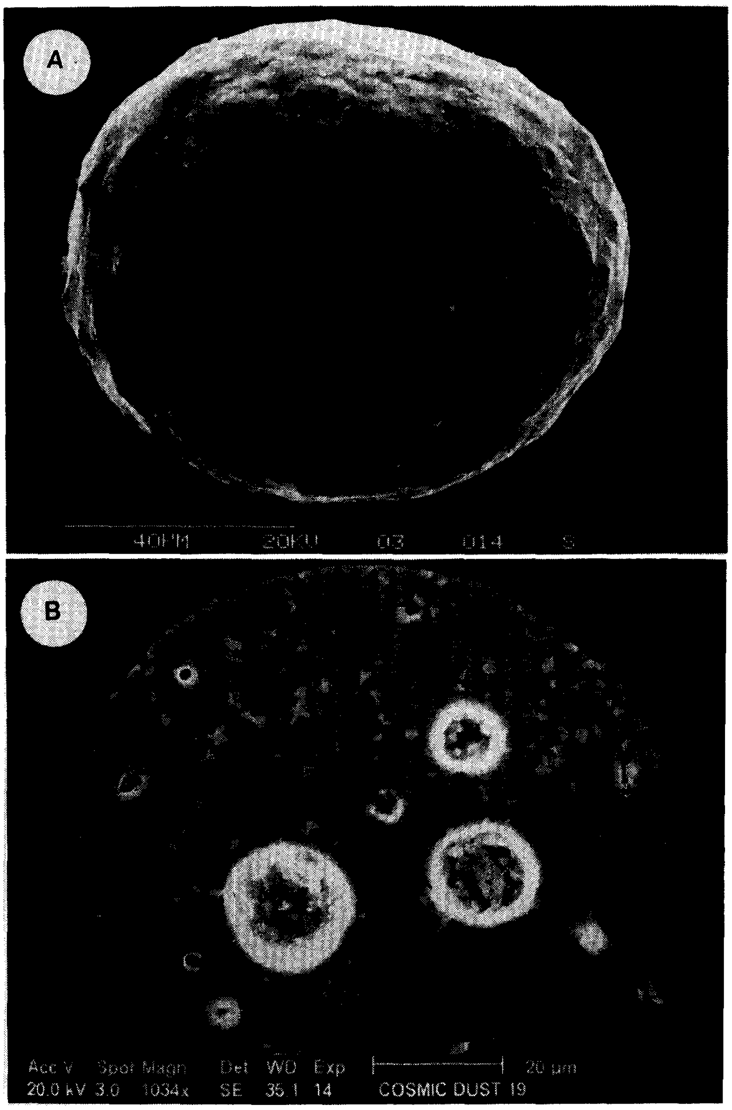

Fig. 7. (a) Spherule [No 19] of mixed morphological type: rough glazed and dendrite decorated, (b) the vesicular vitrophyric structure and ovoidal texture of the interior of this spherule.

An equant-olivine spherule was presented by TAYLOR and BROWNLEE (1991). This spherule contains equidimensional olivine crystals in a glassy matrix, and dendritic spinels in the glassy surface layer. A spherule with similar patterns (Fig. 6b), is described as granular in our study. This was probably formed as a partly melted olivine rich aggregate. The Fe derived from melted olivine crystals form Fe-rich rims on each grain, and small spinel crystals decorating the edges. The interstitial glass is also enriched in iron. Iron rich phyllosilicates filling the intergranular pores are products of interstitial glass weathering. Perhaps vitrophyric spherules with ghost-olivine glassy ovoidal objects decorated by spinel crystals are the transition stage between unmelted micrometeorites and vitrophyric, wholly-melted spherules. Such wholly-melted spherules when cooled slowly could develop a skeletal structure shown in the barred or chain olivine spherules.

A possible range of structural transformations could begin from unmelted cosmic dust of olivine aggregates through granular spherules, to vitrophyric spherules with ghost-olivine glassy ovoidal objects, to vitrophyric, and to skeletal spherules.

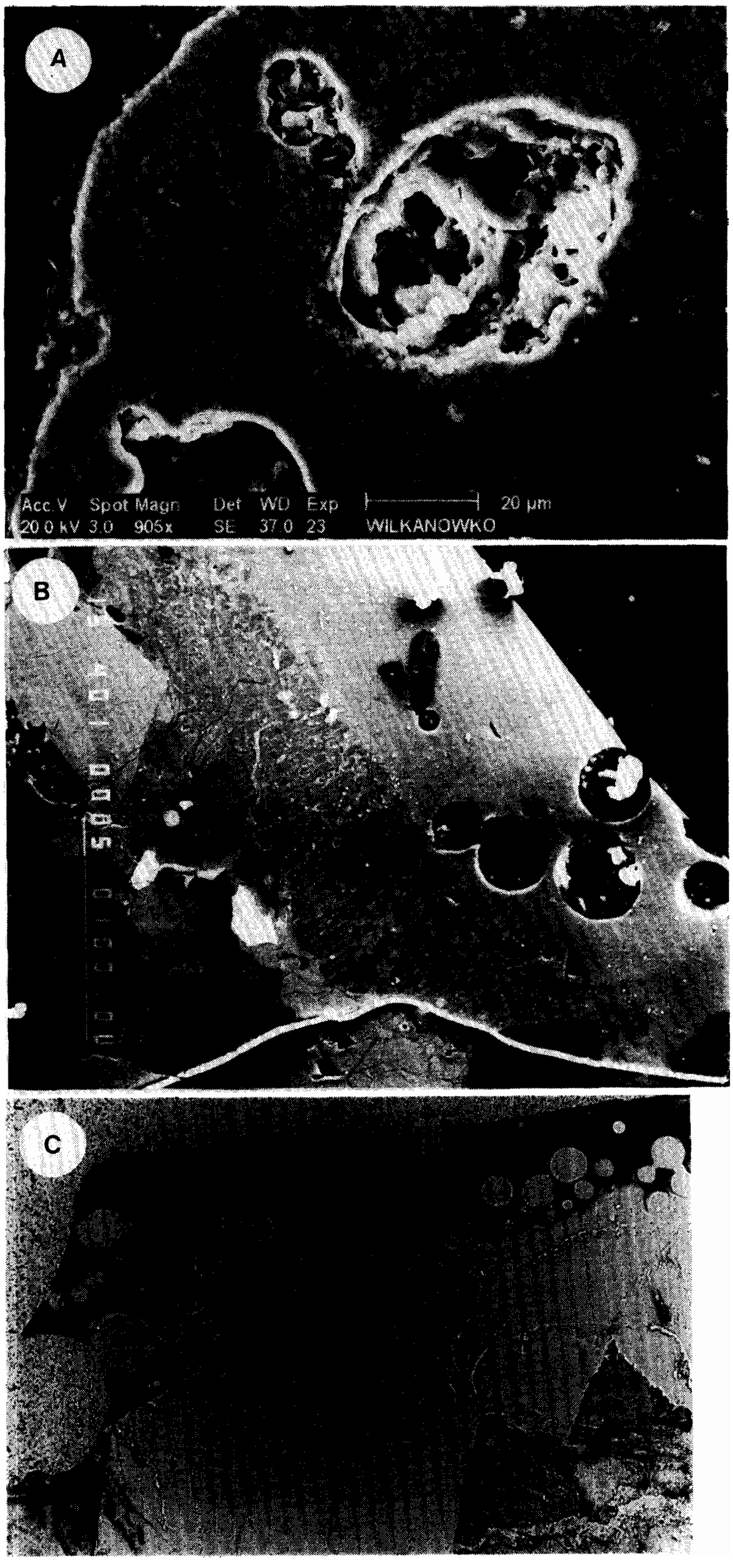

Fig. 8. (a) Fusion crust of the ordinary chondrite Wilkanowko H5, showing a vesicular vitrophyric internal structure of the outermost layer, with distinct spinel dendrites developed in a hyaline matrix, (b) compact holohyaline internal structure of the outermost layer of the Stannern eucrite with several spherical bubbles. The transition zone seen below the surface layer is amorphous and inhomogeneous, (c) holohyaline internal structure with bubbles in the fusion crust of lunar meteorite Asuka-881757.

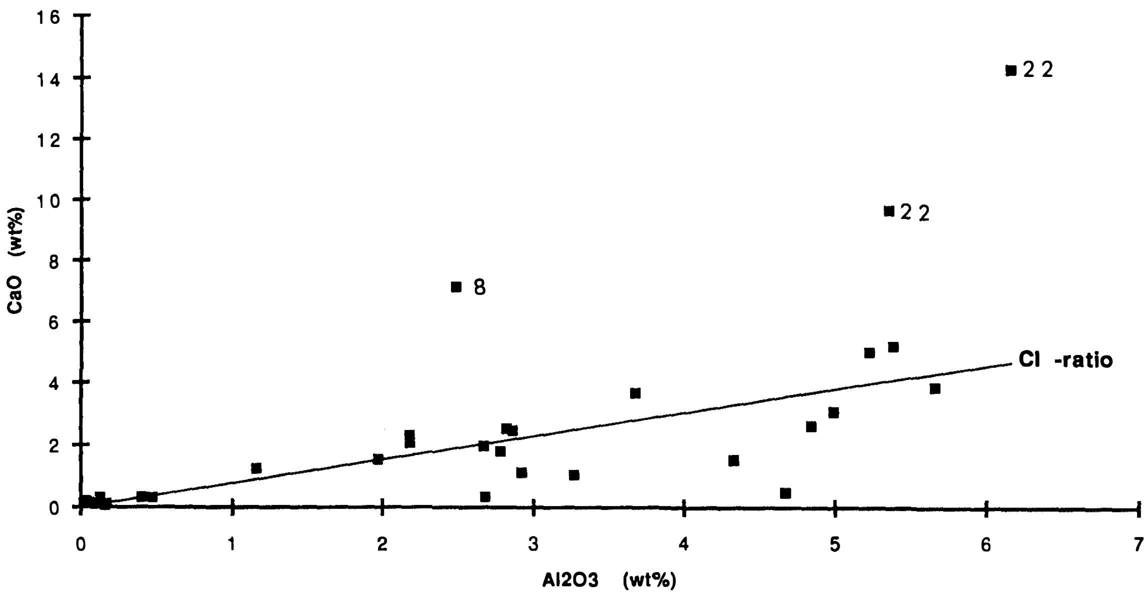

Fig. 9. Relationship of CaO versus Al_2O_3 in examined spherules shows approximately cosmic Ca/Al ratios.

Our study of the morphology and structure of meteorite fusion crusts, indicates that ablation can also produce a variety of spherules. Achondrites could produce glassy smooth, and internally compact holohyaline spherules, whereas chondrites could generate spherules of the rough glazed, dendrite decorated morphological types, with vesicular vitrophyric structure characterized by spinel dendrites in the matrix.

Further research is required to focus on fusion crusts of different meteorites using geochemical and morphostructural criteria so as to distinguish melted micrometeorites from meteorite ablation products.

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