Meteoritics & Planetary Science 38, Nr 3, 329–340 (2003)
Abstract available online at http://meteoritics.org'

Micrometeorites from the northern ice cap of the Novaya Zemlya archipelago, Russia: The first occurrence

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(Received 7 May 2002; revision accepted 28 February 2003)

Abstract–Glacial deposits at the margins of the ice cap of the northern island of the Novaya Zemlya archipelago, Russia, contain numerous spherules and rare scoriaceous particles thought to be extraterrestrial. The 1 Kyr old glacier has decreased in volume and coverage during the last 40 years, leaving the spherules contained in the ice at the margins of the glacier where they can be easily collected.

The spherules are similar in their appearance, texture, and mineralogy to cosmic spherules found in deep-sea sediments in Greenland and Antarctica. Silicate spherules have typical bar-like textures (75%) or porphyritic textures (15%), while other spherules are glassy (7%). The spherules from Novaya Zemlya are altered only slightly. There are spherules consisting of iron oxides, metal cores with iron oxide rims, a continuous network of iron oxide dendrites in a glass matrix, and particles rich in chromite (3%). Some spherules contain metal droplets and relict forsterite and low-Ca pyroxene. Silicate spherule compositions match compositions of other cosmic spherules. Both Nova Zemlya and other cosmic spherules are close to carbonaceous chondrite matrices in patterns of variations for Ca, Mg, Si, and Al, which might suggest that their predecessor was similar to carbonaceous chondrite matrices. Unmelted micrometeorites are generally depleted in Ca and Mg and enriched in Al relative to cosmic spherules. The depletion of the micrometeorites in Ca and Mg can be connected with their terrestrial alteration (Kurat et al. 1994), while the Al enrichment seems to be primary.

INTRODUCTION

Meteorites, which are from a centimeter to a meter in size and from 10^{-2} to 10^6 kg in weight, are an important source of information about asteroids and early planets in the solar system. The flux of these meteorite bodies into Earth was calculated to be ~5×10^4 kg/yr^{-1} (Bland et al. 1996). However, these meteorites contribute only a negligible part of the total mass accreted onto Earth (approximately 30×10^6 kg; estimations by Kyte and Wasson 1986; Love and Brownlee 1993, Peucker-Ehrenbrink and Ravizza 2000), while micrometeoroids in the 10^{-11} to 10^{-5} kg mass range compose 95% of the flux of extraterrestrial matter on Earth (Hughes 1978). Significant progress in the study of these micrometeorite particles has been made in the last 15 years (Brownlee 1985; Maurette et al. 1986, 1991, 1992; Kurat et al. 1994; Brownlee, Bates, and Shramm 1997; Taylor, Lever, and Harvey 2000), despite previous indifference to the role of dust particles as a main constituent of the present day extraterrestrial flux.

Micrometeorites can be found where convenient conditions result in their accumulation and preservation (Taylor and Brownlee 1991). Initially, deep-sea deposits (red clay) were the main source for cosmic spherules (Brownlee 1981, 1985), but now micrometeorites are collected mainly from polar ice in the ablation zone of the Greenland ice cap (Maurette et al. 1986, 1987) and the Antarctic ice sheet (Maurette et al. 1991, 1992; Taylor, Lever, and Harvey 2000; Taylor, Lever, and Govoni 2001; Iwata and Imae 2001). Other polar ice caps can provide specific areas for micrometeorite sampling, too. One such ice cap is located on the northern island of the Novaya Zemlya archipelago, Russia, where the central region of the northern part of the island is covered by a 410 km long and 95 km wide glacier ice sheet (Fig. 1).

The thickness of the ice is not exactly known, and it may vary from 0.3 to 0.7 km (Koryakin 1988). The glacier has existed since at least the late Pleistocene epoch (Forman et al. 1999), and according to calculations of the glacier budget, the oldest ice at the bottom of the glacier is approximately the age of 1 kyr (Koryakin 1990). The Inostrantsev ice valley divides

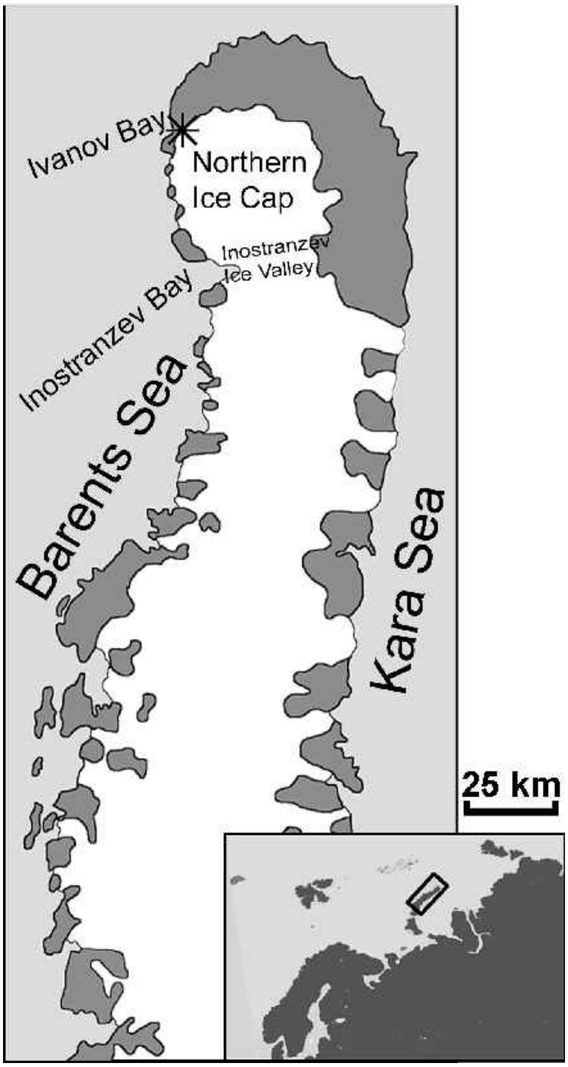

Fig. 1. Map of the northern island of the Novaya Zemlya archipelago. The visited area of the glacier near the Ivanov bay is marked by a star. The rectangle on the inset map shows the northern island.

the glacier into two parts, the main ice sheet and the northern ice cap, which is 80 km in diameter.

Observations and registering of the glacier terminus positions from historical and other sources point to the glacier's retreat for the first half of the past century (Zeeberg and Forman 2001) and a decrease in volume of the glacier. The estimated total loss of ice is from 2.6 to 2.9 km^3 per year (Koryakin 1990). The anomalously warm year 1965 increased the ablation to 11.8 km^3 and resulted in a 7.5 km^3 total negative balance of the glacier during that year (Govorukha 1970). The predominance of ice ablation over accumulation favors the removal of solid particles from within the glacial ice and increases their concentrations in specific areas. The deposits at non-active margins of the glacier should, thus, contain an increased number of extraterrestrial particles. The region is also considered to be a relatively clean environment, free of major contamination sources. The northern ice cap may also provide a productive location for the collection of micrometeorites because it has only a few moving or calfing glacier fingers and, hence, a more widespread area of passive ablation zones.

DEPOSITS DISCOVERED

To explore the possiblity of existing micrometeorite accumulation locations, the margin of the northern ice cap near the Ivanov bay, 1 km to SE from the mouth of the Snezhnaya river, 76°54.4′N, 67°32′E (Figs. 1 and 2), was visited during the August–September 1998 field season as a part of the Marine Arctic Complex Expedition of the Institute of Natural and Cultural Heritage, Moscow. The ice sheet surface at this area has a slope of about 5° and is crossed by numerous drainage channels (Figs. 2a and b). A terminal moraine 100 m wide borders the glacier margin. The moraine deposits consist of crushed terrigenous Lower Proterozoic bedrocks. A zone of "dirty ice" meters to tens of meters wide has developed between the glacier surface and the moraine (Fig. 2b). Rare boulders and pebbles of these rocks and patches of a clayish material ranging in size from a few cm to several tens of cm across are located on the glacier surface close to the "dirty ice" zone (Fig. 2a). Some patches have a spherulitic structure with spherules of a few mm in size. The thickness of these patches ranges from 1–5 mm. These patches seem to be formed due to eolian processes, although their exact origin is questionable. Other silt/sand deposits on the glacier surface above the terminal moraine are accumulated on the floors of the seasonal drainage channels (Fig. 2b). Due to the short time reserved for the field work, only two samples of the clayish material with the spherulitic structure (like the one in Fig. 2a) and one sample of the deposit accumulated in a drainage channel (Fig. 2b) were collected to search for extraterrestrial particles.

ANALYSES

All samples were removed from their plastic bags, washed in water to remove the clay, and sieved using a stack of nylon sieves. Numerous spheres >80 µm in diameter and three scoriaceous particles were recovered from within the 50 to 500 µm fractions. The highest concentrations of spheres were found in samples of the clayish material with a spherulitic structure, where 300 spherules per 1 gram of the sieved material were found. The surface texture of the spherules and preliminary data on their compositions were obtained using a JEOL 6400 analytical scanning electron microscope. Subsequently, the particles were mounted in epoxy and sectioned for optical and electron microprobe studies. Bulk chemistry and mineral analyses were obtained using a JEOL 733 electron microprobe at the Oulu University, Finland. Bulk analyses were made with a broadbeam

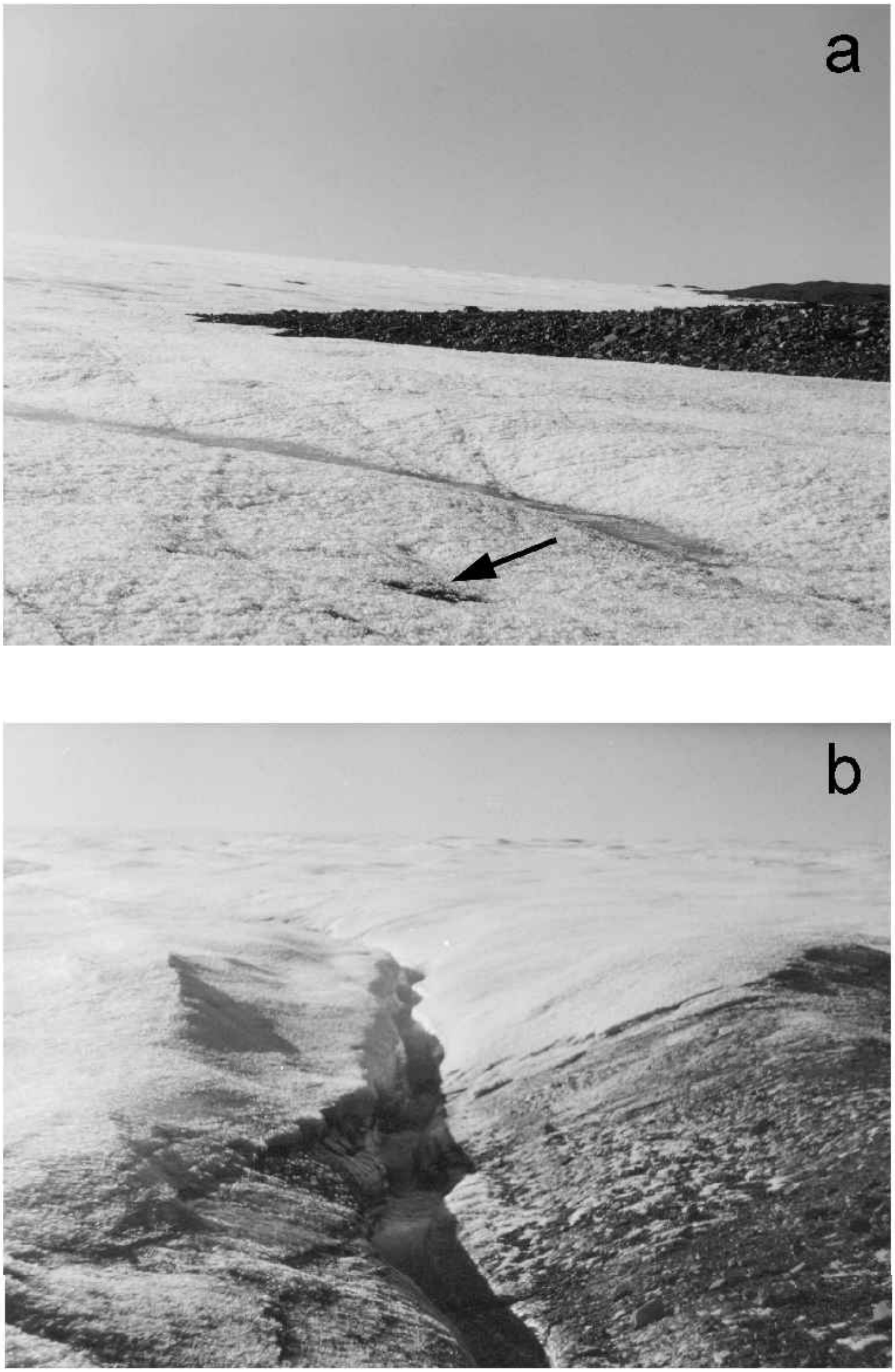

Fig. 2. Areas in which micrometeorite search was conducted: a) a view of the ice margin and the terminal moraine of the northern ice cap near Ivanov bay. The moraine ridge in the background is approximately 20 m long. Seasonal drainage channels and patches of clayish material in the foreground (see the arrow) are situated above the terminal moraine. Some of the patches have a spherulitic structure and can contain cosmic spherules; b) seasonal drainage channel of about 0.5 m in width at the glacier margin. The zone of "dirty ice" is visible in the foreground. One of the spherule-containing samples was collected from a pothole at the icy bottom of the channel above the boundary between the glacier surface and this zone.

technique using either a 30 or 50 µm probe diameter. The total number of analyzed particles was 69.

RESULTS

Spherules

The spherules have variations in their luster, color, and transparency. Optically dark and opaque spherules rich in crystalline phases (olivine and a minor amount of an iron oxide) have either rounded polyhedron (Fig. 3a) or spheroidal shapes (Fig. 3b). The surfaces of the spheres are rough (Figs. 3a and b) or porous due to etching. The altered rim zones consist of glass, iron oxide(s), and, in places, skeleton-like pyroxene. The shapes of the pores seem, in places, to correspond to dissolved euhedral crystals (Fig. 3c), resembling the shape of olivine grains. Transparent or translucent glassy spherules are spheroidal or true spheres with smooth or pitted (Fig. 3d) surfaces. These morphological features reflect combined effects of weathering as well as structural, textural, and mineralogical properties of the spherule interiors.

The most abundant spherules (75%) have a typical "barred" texture (Fig. 4a) and consist of aligned olivine lamellae and of an interstitial glass containing usually dendritic or star-like iron oxide grains and skeletal submicron pyroxene (?) grains. The less common spherules (15%) with porphyritic textures contain relatively large euhedral olivine crystals, tiny crystals of iron oxide, and occasional pyroxene,

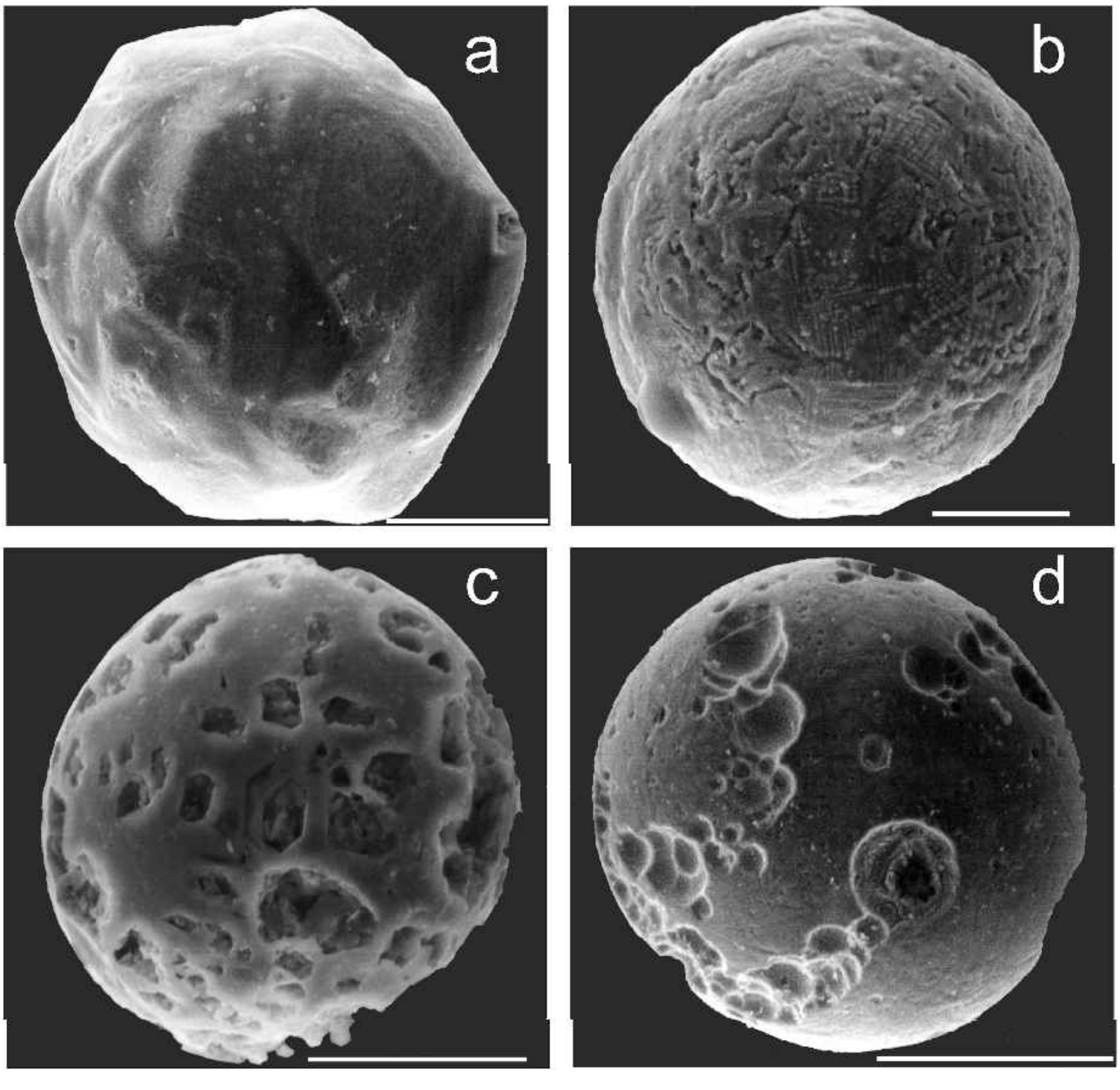

Fig. 3. Secondary electron images of the Novaya Zemlya spherules: a) spherule with a dull polyhedron shape due to a barred olivine texture; b) spherule showing an etched surface and iron oxide dendrites on the surface; c) spherule showing dissolved euhedral olivine crystals; d) glassy spherule with a "pitted" surface. The pits are filled partially by clay. Scale bar is 100 µm.

all of which are embedded in a glassy matrix (Fig. 4b). These spherules contain voids and often relic forsterite grains, recognizable by their euhedral outlines and their compositions. The relic forsterite grains often have thin rims of reformed olivine. Optically transparent or translucent vitreous spherules are more rare (7%). They are poorly crystallized and consist of glass, sometimes with submicron silicate crystals. It should be noted that spherules with intermediate textures between the vitreous and barred ones and between the barred and porphyritic textures were also found. This demonstrates possible genetic relationships between the various types of the stony spherules (Taylor and Brownlee 1991) and indicates that the structures and textures of spherules depend on the thermal history and on their primary chemical composition (Brownlee, Bates, and Beauchamp 1983), including the content of volatiles—especially water. A few spherules display a continuous network of dendritic iron oxide crystals in a glass matrix (Fig. 4c) and can be called G-type (Blanchard et al. 1980). Other spherules (3%) are rich in Fe (I-type). These spherules consist of a magnetite shell around a metal core (Fig. 4d) or of iron oxide(s) with glass (Fig. 4e). One egg-shaped spherule consisting of euhedral chromite crystals and a Ni-rich metal globule, embedded in a glass matrix, was found (Fig. 4f).

The main phases in spherules are olivine, glass, and magnetite, while the more rare minerals are pyroxene, metal, iron sulfide, and chromite. Olivine grains that crystallized from the melt during the passage of the particle through the atmosphere are zoned having Fe-rich rims and Fe-poor cores, and they contain some NiO (Table 1). Reformed euhedral low-Ca pyroxene crystals (Table 1) are more or less homogeneous in their compositions and they can occasionally be found in porphyritic spherules. Porphyritic spherules often contain remains of olivine grains with a forsteritic composition (Fa <5%). The relic grains contain Cr_2O_3 with occasional Al_2O_3 and CaO (Table 1.). The Al and Ca abundances in the latter are similar to the ones found in micrometeorite olivines in Antarctic samples (Steele 1992). Magnetite (?), both in the iron and stony spherules, contains NiO (0.5–1.5 wt%). The stony spherule magnetite (?) crystals large enough to be cleanly analyzed by an electron microprobe contain Al_2O_3 (1.3–5.5 wt%), MgO (2.5–3.5 wt%) and SiO_2 (0.2–0.8 wt%). There may be at least two iron oxide phases in the iron spherule (Fig. 4e) which have different NiO contents (5.4 and 3.3 wt%). CoO contents in the phases are 0.6 and 0.3 wt%, respectively. We assume that the phases might be magnetite and wustite. Chromite crystals were present in three particles (e.g., Figs. 4f and 4h). Chromite has the Cr/(Cr + Al) atom ratio of 0.85–0.90, the Mg/(Mg + Fe) atom ratio of 0.15–0.60, and the TiO_2 and MnO contents of 1–2.5 wt% and 0.4–0.7 wt%, respectively. Metal phases are occasionally present either in the cores of the iron spherules or as small droplet inclusions both in the relic forsterite grains and in the glassy matrix of the stony spherules. The metal cores in iron spheres (e.g., Fig. 4e) have 25–50 wt% Ni and 0.5–1.1 wt% Co, while metal in the relic forsterite grains is kamacite (6.6 wt% Ni and 0.4 wt% Co). Troilite is rare, but, if present, can contain some Ni.

Scoriaceous Particles

Two scoriaceous particles of irregular shape and one scoriaceous spherule are shiny and black. The studied scoriaceous particle and sphere are highly vesicular and consist of olivine in a Fe-rich glassy matrix (Fig. 4g) and of olivine and chromite grains with an interstitial glass (Fig. 4h). Relic olivine grains in the particles are surrounded by newly-formed olivine rims (Fig. 4g), which are Mg-enriched in the immediate vicinity of the contacts with relic grains. The relict olivine grains are richer in FeO relative to the relict olivine grains in the porphyritic spherules (Table 1).

Bulk Chemistry of Stony Spherules

The relatively low totals of chemical compositions from bulk spherule analyses determined by the electron microprobe broad beam technique show that, in many cases, it is impossible to avoid tiny vesicles and cavities. Large variations in analyzed bulk element abundances in the spherules with different textures disable the detailed comparison of their compositions (Table 2). However, transparent vitreous spheres demonstrate distinctively higher SiO_2 and lower FeO and NiO contents than barred and porphyritic olivine spherules (Table 2), and barred olivine spherules have compositions very close to those of porphyritic spherules. Some porphyritic olivine spherules have high MgO (40–50 wt%) and low FeO (7–15 wt%) concentrations, resulting in large standard deviations in the mean concentrations of FeO and MgO. In general, the average compositions of stony spherules (Table 2) are similar to the ones of chondritic meteorites and no spherules were found to differ strongly in composition from the average ones.

DISCUSSION

The Origin of the Novaya Zemlya Spherules

The most direct evidences of an extraterrestrial origin of any particles can be obtained from data on their isotopic compositions (e.g. Olinger et al. 1990). While this data does not exist for the Novaya Zemlya spherules, more general criteria for identifying cosmic spherules (CS) (Blanchard et al. 1980; Brownlee 1981) and a similarity between the Novaya Zemlya spherules and CS with a proven extraterrestrial origin (Papanastassiou, Wasserburg, and Brownlee 1983, 1983; Yiou, Raisbeck, and Brownlee 1985; Raisbeck et al. 1986; Nishiizumi et al. 1992) suggest they are extraterrestrial. The textures, mineralogy, and chemistry of

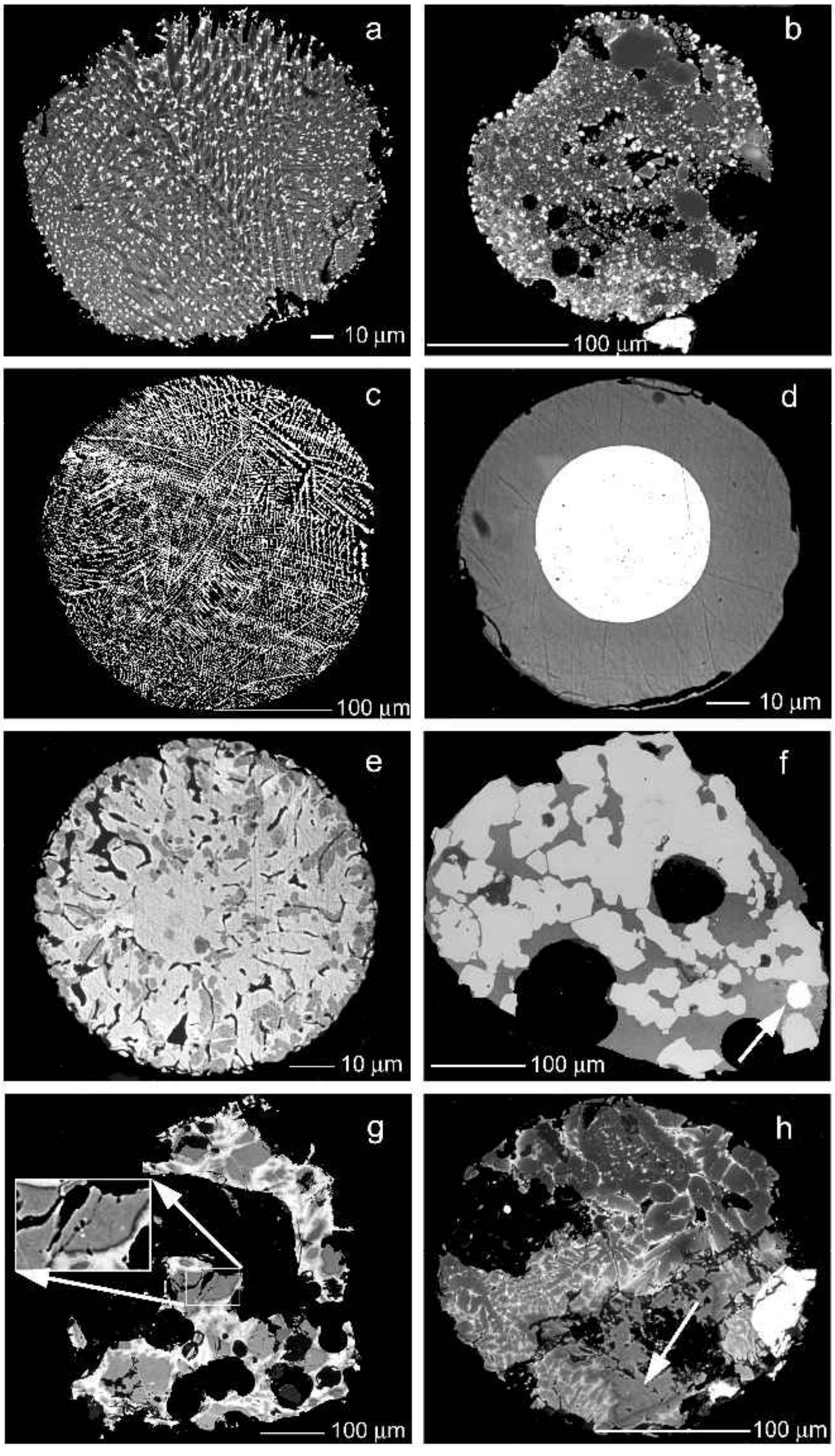

Fig. 4. Backscattered electron images of the Novaya Zemlya spherule sections: a) spherule with a barred olivine texture; b) spherule with a porphiritic texture and rounded voids; large dark gray grains consist of relic forsterite cores with new-formed olivine rims; c) spherule consisting of a continuous network of iron oxide dendrites (light) and a glass matrix (black); d) iron spherule consisting of a high-Ni metal core and an iron oxide rim; e) iron spherule consisting of iron oxides and interstitial glass. The iron oxides are Ni-rich (5.4 wt%, light gray) and Ni-poor (3.3 wt%, gray); interstitial glass is black; f) spherule containing euhedral crystals of chromite (light gray) and a Ni-rich metal droplet (arrow) embedded in a glass matrix (dark gray) with voids; g) scoriaceous particle with relic olivine grains (gray) with newly-formed rims (dark gray); glass is light gray or white. The inset demonstrates the rim surrounding the relic grain; h) rounded scoriaceous particle with chromite (white) and olivine (medium to dark gray) grains; the relic olivine grain (arrow) has a new-formed richer in Mg dark rim.

Table 1. Representative chemical compositions (wt%) of melted and relic silicate grains in micrometeorites.

Sample	NZ4-1[a] melted olivine		NZ2-3[a] melted pyroxene	NZ1-43[b] relic olivine	NZ1-11[b] relic olivine	NZ4-4[c] relic olivine
	core	rim				
SiO_2	39.8	36.4	58.0	42.2	42.6	39.3
Al_2O_3	0.09	b.d.[d]	b.d.	1.19	b.d.	b.d.
Cr_2O_3	0.17	0.23	0.20	0.55	0.53	b.d.
FeO	16.2	31.5	6.50	1.26	0.65	17.4
MnO	0.15	0.25	0.32	0.20	b.d.	0.44
NiO	0.15	0.56	0.17	b.d.	b.d.	b.d.
MgO	43.9	30.4	34.8	54.4	56.3	42.6
CaO	0.10	0.11	0.16	0.94	0.18	b.d.
Total	100.7	99.6	100.1	100.9	100.3	99.6
Fa/Fs	36.2	17.0	9.4	1.2	0.6	19.0

[a]Spherules with barred textures.
[b]Spherules with porphyritic textures.
[c]Scoriaceous micrometeorite.
[d]b.d. = Below detection.

Table 2. Chemical compositions (wt%) of bulk stony spherules, obtained by electron microprobe broad beam technique.

	Barred olivine n = 42 (x ± st. dev.)	Porphiritic olivine n = 10 (x ± st. dev.)	Vitreous n = 5 (x ± st. dev.)
SiO_2	38.5 ± 4.6	37.3 ± 5.5	48.3 ± 3.8
TiO_2	0.13 ± 0.03	0.13 ± 0.05	0.11 ± 0.02
Al_2O_3	2.96 ± 1.13	2.36 ± 0.99	2.42 ± 0.39
Cr_2O_3	0.36 ± 0.15	0.34 ± 0.15	0.53 ± 0.08
FeO	26.3 ± 7.1	26.2 ± 10.7	6.6 ± 1.6
MnO	0.27 ± 0.10	0.25 ± 0.07	0.32 ± 0.14
NiO	0.74 ± 0.55	0.64 ± 0.41	0.13 ± 0.02
MgO	26.2 ± 5.2	28.1 ± 11.7	30.1 ± 2.2
CaO	2.08 ± 0.91	1.71 ± 0.79	1.48 ± 0.31
Total	97.3 ± 1.8	96.9 ± 4.7	99.75 ± 1.43

the Novaya Zemlya spherules are in good agreement with the characteristic properties that have been described for CS collected from different sites (Maurette et al. 1987; Brownlee, Bates, and Shramm 1997; Taylor, Lever, and Harvey 2000). The Novaya Zemlya spherule collection is poor in iron spherules relative to deep-sea CS collections (Brownlee, Bates, and Shramm 1997), just like the CS collected from other ice sheets (Taylor, Lever, and Harvey 2000). The presence of the relict forsterite grains with inclusions of kamacite is further evidence of the cosmic nature of the spherules. The compositions of the Novaya Zemlya spherules, when plotted on a Mg-Si-Fe ternary diagram, correspond well to the compositions of the cosmic spherules from other sources (Fig. 5).

The relative abundances of refractory lithophile elements in stony Novaya Zemlya spherules tend to follow those found in chondritic meteorites. The majority of the spheres have Ti/Si, Al/Si, Ca/Si, and Mg/Si ratios (Fig. 6) very close to the respective ratios for the carbonaceous chondrites. Other elements show various degrees of depletions relative to CI abundances. Na and S abundances are below the detection limit of the microprobe, while the Mn, Fe, Cr, and Ni abundances show more moderate depletions (Fig. 6) like those in the deep-sea and Antarctic CS (Brownlee, Bates, and Shramm 1997; Taylor, Lever, and Harvey 2000). It has been suggested that the depletions of the elements can be due to strong heating of meteoroids by their entry into the atmosphere, which leads to their melting and evaporation (Love and Brownlee 1991; Brownlee, Bates, and Shramm 1997). Calculations show that the evaporation may reduce the pre-atmospheric masses of meteoroids by a factor of 5 (Herzog et al. 1999). Na, S, and in part, Fe and Mn can be lost by the volatilization (Brownlee, Bates, and Shramm 1997; Gerasimov et al. 2001). The proposed reason for the depletions of Ni, Cr, and partly, Fe is the formation of separate

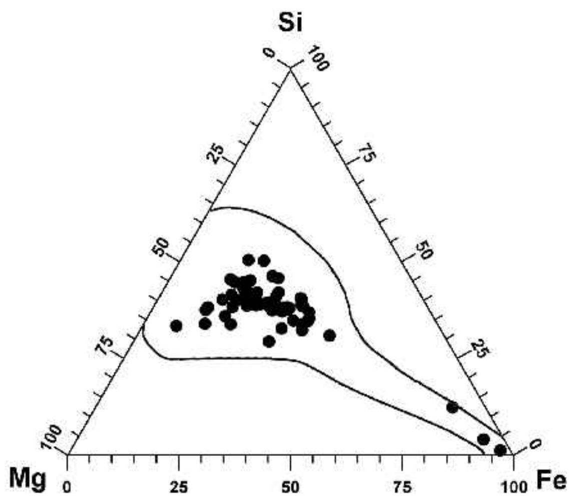

Fig. 5. Mg-Si-Fe (atom) diagram illustrating the location of Novaya Zemlya bulk spherule compositions at the field of other cosmic spherule compositions plotted from data in Taylor et al. (2000) and Koeberl and Hagen (1989).

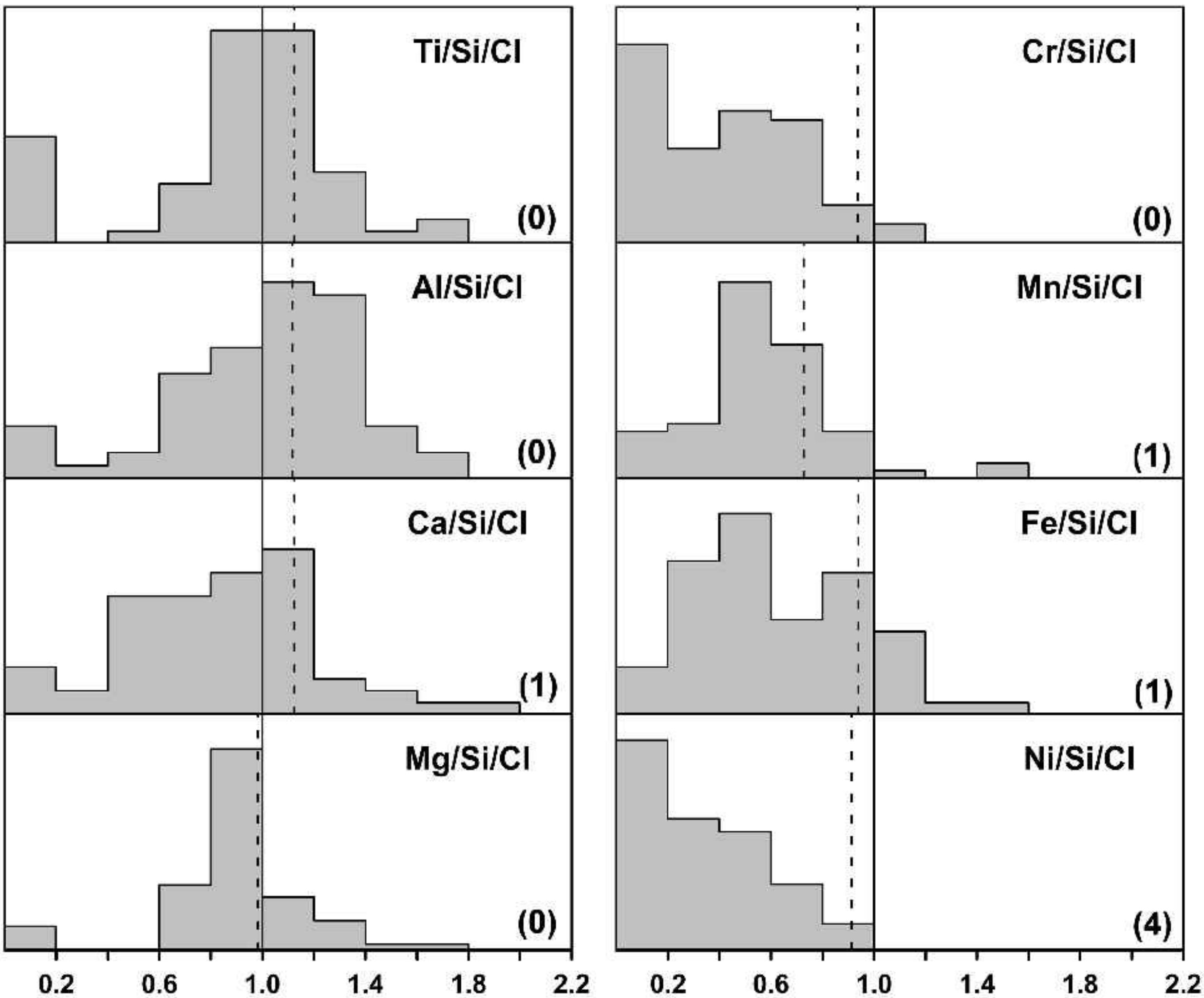

Fig 6. Distributions of element to Si ratios normalized to CI (Anders and Grevesse 1989) for Novaya Zemlya bulk stony spherules. Dashed lines indicate the element ratios for mean CM chondrite composition (Wasson and Kallemeyn 1988). The numbers in parenthesis indicate the number of spheres that have a composition plot outside the range.

immiscible liquid metal or oxide droplet(s) inside a silicate melt during the entry heating. These droplets can be partially lost from molten meteoroids (Brownlee, Bates, and Shramm 1997). The immiscible separation of Fe-Ni-S liquids has been shown to have been a significant process in the case of the Antarctic micrometeorites (Genge and Grady 1998).

Comparing CS with Other Micrometeorites and Carbonaceous Chondrites

Because of the absence or small degree of depletion of such elements as Ca, Mg, Al, and Si in cosmic spherules, their relative abundances should match the abundances of these elements in the precursor material. These elements are also well determined by an electron microprobe technique. On the Ca/Al-Mg/Al diagram (Fig. 7a), the Novaya Zemlya bulk CS correspond well with other CS. Most of CS are plotted within an area occupied by the carbonaceous chondrite matrices and the scattering in the CS compositions matches the scattering in the carbonaceous chondrite matrix compositions, which indicates a possible similarity in their textures and heterogeneity. Unmelted and scoriaceous micrometeorites (MMs) are depleted in Ca and Mg relative to bulk carbonaceous chondrites and their matrices (Fig. 7a). This has been explained by the dissolution of MMs carbonates and sulfates through the terrestrial alteration processes (Presper et al. 1993; Kurat et al. 1994). CS should have Ca and Mg abundances closer to the primary abundances because the carbonate and sulfate most probably reacted with silicates during entry heating (Badjukov et al. 1995) and these non-volatile elements were incorporated in the silicate melts. Hence, the difference of the Ca and Mg abundances between cosmic spherules and MMs is not an evidence for their different original compositions. The Mg/Al-Si/Al diagram

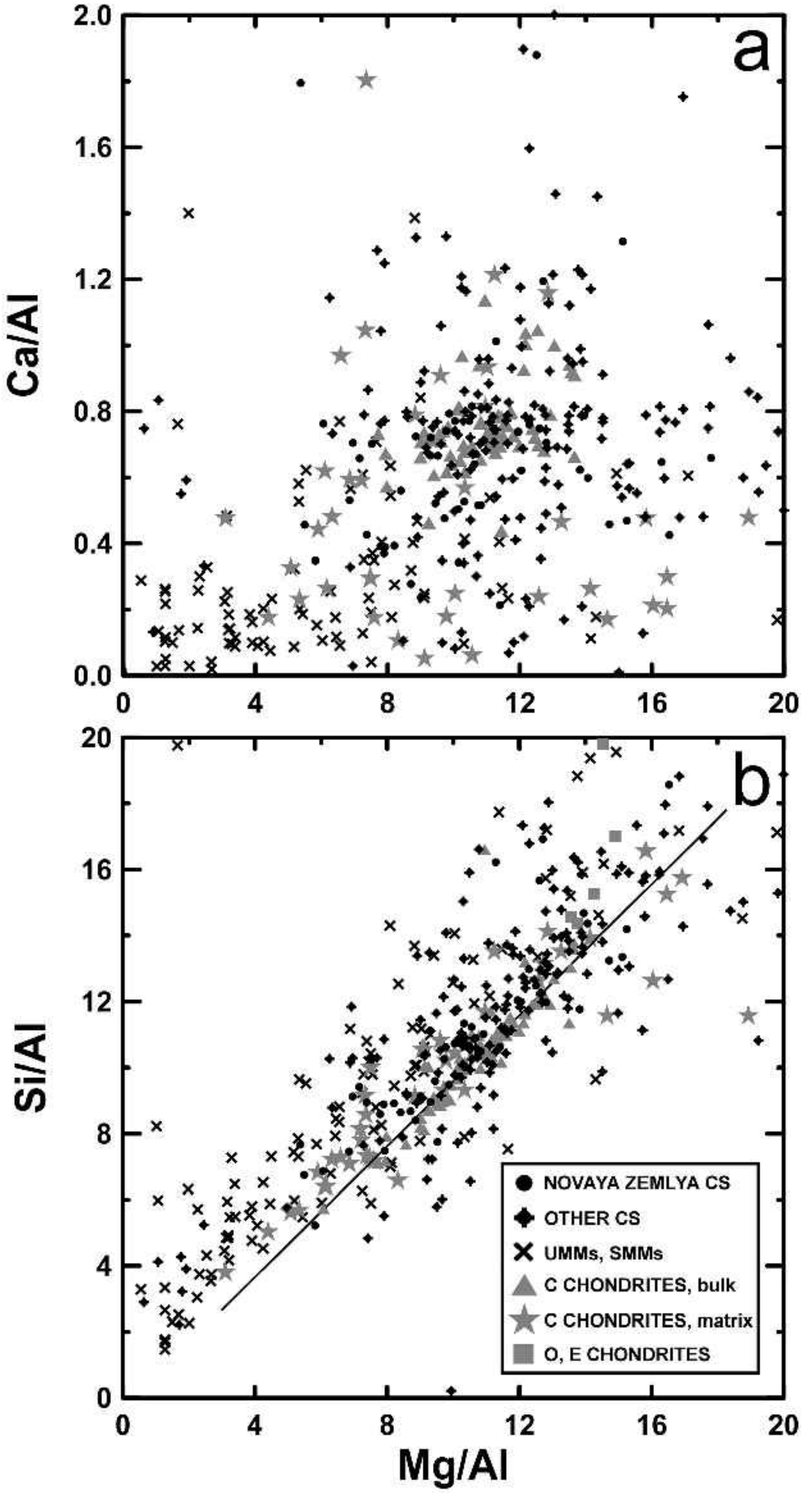

Fig. 7. Comparison of compositions for Novaya Zemlya CS; deep-sea, Antarctic, and Greenland CS; UMMs and scoriaceous MMs (SMMs); ordinary and enstatite chondrites; and bulk and matrix carbonaceous chondrites on Al-normalized Ca-Mg (a) and Si-Mg (b) atom ratio diagrams. The straight line on the Mg/Al versus Si/Al plot fits data on bulk carbonaceous chondrites (r = 0.96). The data on the CS are from Kurat et al. (1993), Papanastassiou et al. (1983), Blanchard et al. (1980), Taylor and Brownlee (1991), Maurette et al. (1986), and Taylor et al. (2000); the data on the UMMs and SMMs are from Kurat et al. (1993, 1994), Robin et al. (1990), and Olinger et al. (1990); the data on the chondrites are from Wasson and Kallemeyn (1988), Jarosewich (1990), McSween and Richardson (1977), and Scott et al. (1988).

(Fig. 7b) demonstrates a deviation of CS and MMs compositions from compositions of bulk carbonaceous chondrites. Individual analyses of bulk carbonaceous chondrites define a straight line on the diagram due to different components rich in Al and poor in Si and Mg (Larimer and Wasson 1988). CS, MMs, and carbonaceous chondrite matrix analyses generally plot higher in the Mg/Al-Si/Al diagram (Fig. 7b) than the bulk carbonaceous chondrites analyses. For the most part, the MMs show a relative enrichment in Al and/or depletion in Si and Mg compared to carbonaceous chondrites and CS. It seems that the Al enrichment and/or Si and Mg depletion in MMs cannot be caused by terrestrial alteration but is primordial and is connected with different precursors for MMs and CS. The component responsible for this difference may have a composition like either CAI or pyroxene.

Proposed Extraterrestrial Particles

The reliable proof of the extraterrestrial origin of a few particles (Figs. 4e–h) is absent, unlike the cases of the other typical Novaya Zemlya spherules (Figs. 4a–d). However, their structures, textures, and compositions may provide constrains on their origin. Spherical shape of the iron oxide particle (Fig. 4e) and the melted metal bead in a glass (Fig 4f) indicate high-temperature events. The composition of this metal bead (48 wt% Ni and 0.5 wt% Co) is consistent with compositions of Ni-rich chondrite metal. Ni-bearing iron oxide(s) in the iron sphere (Fig. 4e) have a Ni/Co weight ratio of 9.0 or 11, which is not contradictory to their origin from kamacite. The scoriaceous particle and spherule show such a sign of high heating and cooling rates as partially melted olivine grains surrounded by zoned olivine rims. The composition of relict olivine (Table 1) is close to the composition of relict olivine from Antarctic scoriaceous MMs (Kurat et al. 1993). Element/Si/CI ratios for Mg, Al, Ca, Fe, and Mn in the bulk scoriaceous particle and spherule are 1–1.3, 0.2–0.6, 0.2–0.4, 0.2–0.4, and 0.9–1.0, respectively. These facts permit us to consider all of the particles as having probable extraterrestrial origins. On the other hand, we can not exclude a man-made origin for these four particles. In that case, the most probable sources are metallurgical plants in Norway or the Kola Peninsula, Russia.

Contamination and Weathering

Because the northern ice cap is close to the Novaya Zemlya nuclear test area, we also tried to look for contamination of the samples by elemental remnants of former nuclear tests. The spheres were checked for spontaneous decay of unstable atomic nuclei by using a polymer film as a detector for the possible resulting decay particles. We found no tracks in these polymer detectors.

The only observed effect of terrestrial alteration in Novaya Zemlya CS is etching of silicates on the spherule surfaces. The surface structures are tiny canals and grooves (Figs. 3b and 4a) and cavities formed due to the removal of olivine (?) crystals (Fig. 3c). Glassy spherules are not etched. It seems that, unlike deep-sea spherules (Callot et al. 1987), olivine was etched faster than glass. The short terrestrial age of these spherules accounts for their insignificant alteration because they can not be older than the oldest part of the glacier ice, which is approximately 1 Kyr (Koryakin 1990). The degree of the spherule weathering as well as the specific feature of the etching resemble the cosmic spherules of Greenland (Maurette et al. 1986, Callot et al. 1987).

CONCLUSIONS

The glaciers of the northern island of the Novaya Zemlya archipelago can be considered a source for micrometeorites. The micrometeorites of the northern ice cap are highly concentrated in well-recognized spots and can be easily recovered. Even the one-day reconnaissance visit to the glacier provided a representative collection of micrometeorites. Some processes at the glacier margin lead to formation of deposits that have a high concentration of extraterrestrial matter. The highest content of extraterrestrial components up to 300 spherules per gram of a 50–500 μm fraction was found in clayish material with a spherulitic structure. According to our observations, these clayish patches are usual deposits on the glacier surface as well as deposits in the seasonal channels where cosmic spheres were also found. However, further field work is required both to obtain new data on formation of the CS-rich material and to collect a larger number of micrometeorites, including samples of the most interesting MMs. In addition, if human made particles are recovered from the Novaya Zemlya glacier ice, they could help to estimate the amount and type of industrial pollutants and their sources in the Barents region.

Acknowledgments–The authors wish to express their appreciation to Dr. P. V. Boyarsky, the chief of the Marine Arctic Complex Expedition, Moscow, for his support. D. Badjukov thanks Dr. David J. Lubinsky (University of Colorado) and Dr. Jaap J. Zeeberg (University of Illinois at Chicago) for help during the visit to the glacier. Academy of Finland is acknowledged for financial support of D. D. Badjukov. The authors thank Dr. Susan Taylor and Dr. Craciela Matrajt for their constructive and helpful reviews and Dr. Donald Brownlee for his editorial handling of our paper.

Editorial Handling—Dr. Donald Brownlee

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