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A consortium study of Antarctic micrometeorites recovered from the Dome Fuji Station

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Abstract: Deposits in the water tank at the Dome Fuji Station were collected by the 37th Japanese Antarctic Research Expedition team in 1996. We recovered 233 micrometeorites from the deposits. A consortium study was started in late 1998 to investigate mineralogy, petrology, bulk chemistry, and isotopic compositions of the micrometeorites. This is the first case of an organized study of micrometeorites in Japan, in order to establish the methods to investigate micrometeorites routinely. Consortium results on mineralogy, petrology, minor and trace element compositions, isotopic compositions of noble gases of the micrometeorites are reported in this volume. We also found a sequence of mineralogical and compositional changes of micrometeorites experienced from frictional heating during atmospheric entry. INAA and ion probe studies are now in progress.

1. Introduction

Micrometeorites (MMs) are extraterrestrial objects whose diameters are smaller than 1 mm (Mason, 1962). Although MMs are distinguished from meteorites only based on their sizes, it becomes clear that MMs are not fine-grained fragments of meteorites. Population of MMs including coarse-grained olivine and pyroxene is about 18% in our consortium study. Most of the MMs resemble CM and/or CI chondrites in bulk chemical compositions (Kurat *et al.*, 1994). However, TEM study of the least heated MMs reveals that their matrix mineralogy are different from those of CM and CI chondrites but rather similar to that of Semarkona chondrite (Klöck and Stadermann, 1994). Carbon/oxygen ratios of MMs are higher than meteorites and MMs are depleted in chondrules (Engrand and Maurette, 1998). These data suggest that most of the MMs are materials that have not been found among meteorites. There is a possibility that interplanetary dust particles and MMs are representative samples of minor planets in the asteroid belt (Zook and McKay, 1986). On the other hand, meteorites fall onto the earth with ellipsoidal orbits from the asteroid belt with a strong preference for derivation from near 2.5 AU where objects in circular orbit have a 3 : 1 resonance with Jupiter (Brownlee, 1994). Therefore, it is plausible that MMs are more unbiased samples from the asteroid belt than meteorites. Moreover, some MMs may come from comets. Due to these characteristics, a consortium study on MMs has been started.

In the next decade, there will be some opportunities to get fine-grained materials directly from a comet (Stardust) and an asteroid (MUSES-C), and meteoroids on low earth orbit (International space station). Therefore, the consortium study of MMs gives us an opportunity to improve analytical techniques of such fine-grained extraterrestrial materials prior to these missions.

Until this work, MMs were recovered only from two locations in Antarctica: blue ice field near Cap Prudhomme (1987–1994) (Maurette *et al.*, 1992a, b, 1994) and the South Polar water well at the Scott-Amundsen Station (1995) (Taylor *et al.*, 1998). The Japanese Antarctic Research Expedition (JARE) team has started to collect MM samples since 1996.

Approximately 50 g of deposits was recovered in the melt water tank for daily life at the Dome Fuji Station by the JARE-37 (1995–1996) team (Nakamura *et al.*, 1999a). The Dome Fuji Station stands on the top of the Queen Maud Land (77° 19″ 01′ S, 39° 42″ 12′ E, 3810 m altitude). The deposits were recovered by melting of approximately 100 t of snow. They were exposed to water in the tank for less than 3 months before recovery. However, they were severely contaminated by the products of human activities at the station. Most of the deposits are composed of pieces of wood and paint flakes, fibers of clothes, spherules formed during welding, and even human hairs (Nakamura *et al.*, 1999a). The authors of this paper found MMs from the deposits of the water tank. From the depth (about 3–5 m) of the melted snow layer from the surface and the rate of snowfall around the station, it was estimated that the snow melted at the station fell during 1950s to 1970s. About 5 MMs were found per 1 g of the deposit (Nakamura *et al.*, 1999a). Total mass of the collected MMs was estimated as 640 μg assuming all MMs are spherical with a diameter which is an average of the longest and the shortest axes and that the density is 3 g/cm^3. As a result, the estimated accretion rate of MMs is about 1200 t/yr. Our consortium study to investigate MMs recovered from the deposits collected by the JARE-36 has been started from the end of 1998. Here we give a general description of the collected MMs, purposes of this consortium and analytical methods, and summarize the results briefly.

From the deposits recovered in 1996 (JARE-37 samples), 233 MMs with chondritic bulk chemical composition were identified. Identification and characterization were based on scanning electron microscope (SEM) observation of their morphology, and the pattern of energy dispersive system (EDS) spectra attached on SEM.

2. Curatorial processing of MMs used in this consortium

2.1. *Processing of deposits*

Before the selection of MM candidates, two procedures to increase the concentration of micrometeorites in precipitation were performed. As Nakamura *et al.* (1999a) reported the procedures in detail, we describe the outline briefly. The first procedure is a combination of three separation processes: filtration, separation by differences of sedimentation rates and grain sizes, and magnetic separation. The precipitation was separated into eight fractions. During the characterization of each fraction, it was revealed that MMs were concentrated in a magnetic and rapidly-sedimentated fraction. MMs with sample numbers F96C-series were collected from the precipitation of the F3 fraction. Nomenclature of the sample number is described in Table 1. In the second procedure, the precipitation was separated only by filtration. F96D-series MMs were concentrated in a fraction with the fastest sedimentation rates, again the F3 fraction.

Because magnetite is more abundant in the MMs that experienced higher temperatures during atmospheric entry, it is expected that severely heated (magnetite-rich) ones are more concentrated in F96C-series samples than in F96 D-series samples. However, severely heated MMs were not concentrated in the F96 C-series samples very much. On the contrary, no phyllosilicate-bearing MMs were found from the F96D-series samples but were found only in the F96C-series samples, although the F96D-series samples are about three times more abundant than the F96C-series samples.

The F3 fractions contain 16 wt% of total spherules. Total number of the spherules were estimated to be about 2×10^5 in 2531 μg of the F3 fractions. In this estimate, the average diameter of 314 spherules was 67 μm and the density of magnetite was employed. Two hundred iron-oxide rich spherules were investigated by SEM-EDS. Nickel was never detected from the surfaces of these spherules (Nakamura *et al.*, 1999a). Twenty-six spherules were randomly selected among them and polished to investigate their interiors by EDS. Nickel was not detected from the interiors either. Therefore, the ratio of I-type spherules/artificial spherules (*i.e.* metal welding droplets) is probably much lower than 0.5%. This idea is supported by the fact that gamma rays from ^{26}Al formed by an interaction between cosmic rays and elements in spherules were not detected after a continuous measurement for 51 days. Because only 26 S-type spherules were found among all the spherules in F3 fractions, the lower limit of the ratio of S-type spherules/

artificial spherules is 0.01%.

Then, MM candidates were handpicked from the F3 fractions in deposits recovered in 1996 (96023-1 and 2, and 960901) by the authors. By the end of 1998, initial characterization of the MMs was almost completed and data of their initial characterization including optical properties, SEM photomicrographs, and EDS spectra were open on the web (Murakami *et al.*, 1998). Low-vacuum (LV-) SEM was used during the curatorial processing and the consortium study, because it does not require any carbon coating, which may affect analysis by various methods. Therefore, LV-SEM was suitable for this consortium study.

2.2. *Nomenclature of MMs recovered from the Dome Fuji Station*

A systematic nomenclature of investigated MMs was determined by the AMM working group. Sample ID for each MM is consisted of three letters and five numbers (Table 1). Sample IDs for MMs collected from the Dome Fuji Station start from a letter "F" representing "Fuji". Two numbers that follow the letter "F" is the last two digits of the year the MMs were collected. In the case of the MMs investigated in this consortium, the numerals are "96", which means that they were collected in 1996. One more letter follows these two digits. It indicates the fraction from which the MM was recovered. The letter "A" was allocated for MMs that were recovered from the F3 fraction (magnetic, the fastest sedimentation rate in water) in 960423-1 (the first deposit collected on April 23rd, 1996). The letter "C" was allocated for MMs recovered from the F3 fraction in 960423-2 (the second deposit collected on April 23rd, 1996). The letter "D" was allocated for MMs recovered from the F3 fraction in 960901 (the deposit collected on September 1st, 1996). The next letter following indicates the name of the university where the MM was selected. The letter "D" means Dokkyo University, School of Medicine. The letter "H" means Hiroshima University. The letter "I" means Ibaraki University. The letter "K" means Kyushu University. The last three-digit serial numbers (001–999) of MM follow this. This nomenclature system will be followed in future.

Table 1. Nomenclature of AMMs in this consortium study.

Example	F96[a][b]001
F : Dome Fuji	
96 : The year when the deposit including MMs was recovered (1996 in this case).	
[a] : The name of Fraction in the initial processing of the deposit (A, C, D, etc).	
[b] : The name of university where the sample was selected.	
K: Kyushu University	
I: Ibaraki University	
H: Hiroshima University	
D: Dokkyo University, School of Medicine	
001 : Serial No. of MM samples at each university.	

3. The collected MM samples

3.1. Morphology, surface feature, and inner structure of the MM samples

The inner structure of 83 MMs was investigated by SEM and EPMA. About 62% MMs were composed of fine-grained (sub-μm sized) aggregates of anhydrous minerals, and about 18% MMs were composed of coarse-grained ($>5\ \mu$m across) anhydrous minerals. The former is thought to have been mainly composed of phyllosilicates. Morphology and surface features of the MMs are related to the degrees of melting of the MMs by heating during atmospheric entry.

Figure 1 shows backscattered electron images (BEIs) of MMs with various morphological features on their surfaces and BEIs of their cross sections. Figures 1a and 1b show the only MM containing abundant phyllosilicates found during this consortium study. Compared with other MMs in this figure, a large portion of the surface of this MM seems not to be covered with iron-rich crusts. Figure 1b displays that this particular MM has a discontinuous, slightly brighter rim with $<2\ \mu$m in thickness. TEM observation shows that the rim is composed of fine-grained (<50 nm across) anhydrous minerals. The texture of the rim suggests that the rim is not a fusion crust but that it was formed by dehydration of phyllosilicates.

The other 7 MMs in Fig. 1 are composed of anhydrous minerals but for those formed by terrestrial weathering. Figures 1c and 1d, Figs. 1e and 1f, Figs. 1g and 1h show three MMs which were heated slightly to weakly. The MM in Figs. 1c and 1d has a continuous, bright rim with $<2\ \mu$m in thickness. TEM observation shows that the rim contains abundant iron-rich fibrous materials and magnetite. The cross section of this MM indicates that its matrix is compact although hydrous minerals have been dehydrated. Dark patches in Fig. 1d are more magnesian than brighter areas. The dark patches are composed of finer anhydrous minerals than the brighter areas (Noguchi and Nakamura, 2000). On the contrary, the MM in Figs. 1e and 1f is composed of a loose aggregate of fine-grained (<50 nm) anhydrous minerals and coarse ($>1\ \mu$m) angular olivine and kamacite (Noguchi and Nakamura, 2000). Structure of this MM suggests that this was originally a loose aggregate of fine-grained phyllosilicate and coarse minerals. The MM in Figs. 1g and 1h has a compact matrix. However, grain sizes of anhydrous minerals formed by dehydration of phyllosilicates are larger than that in Figs. 1c and 1d, which can be deduced from Fig. 1h because brighter spots in bright areas in the cross section of the MM are magnetite formed by dehydration of phyllosilicates.

In the case of MMs having received more heating than the MMs in Figs. 1c to 1h, their cross sections are rounded (Figs. 1i and 1j). Surfaces of such MMs are covered by fusion crusts. The surface of the crusts is often granular (Fig. 1j). The fusion crusts contain abundant small ($<3\ \mu$m) voids formed during melting (Fig. 1j). Interior of this MM contains less abundant vesicles than its periphery. Cracks are also often observed on the crusts (Fig. 1i).

Two MMs shown in Figs. 1k and 1l and Figs. 1m and 1n are ones heated moderately to severely. They have more rounded shapes than the MM in Fig. 1i.

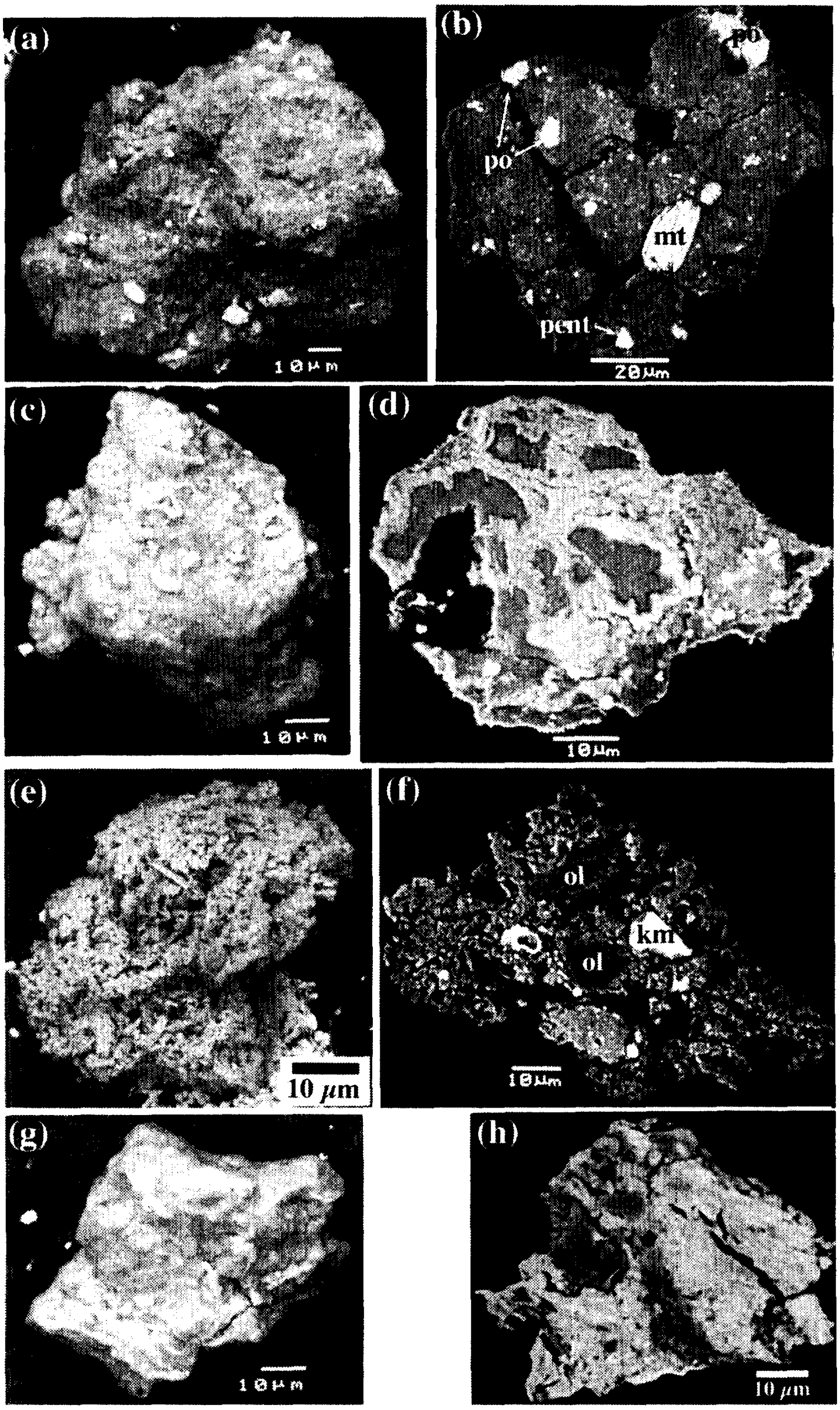

Fig. 1. MMs investigated in the consortium study. In these hackscattered electron images (BEIs), shapes, surface texture, and internal structure of MMs which experienced various degrees of heating or melting are shown. In these figures, fine-grained MMs, some of which contain a few relict coarse minerals, are displayed. (a) and (b): Exterior and interior of a least heated MM in our consortium study. (c) and (d): A slightly heated MM. This MM has a compact matrix. (e) and (f): A slightly heated MM. This is a rare MM. It is composed of a loose aggregate of fine-grained minerals with some coarse relict minerals. (g) and (h): A weakly heated MM. This MM contains coarse (<1 μm) of anhydrous minerals which were formed by dehydration of phyllosilicates.

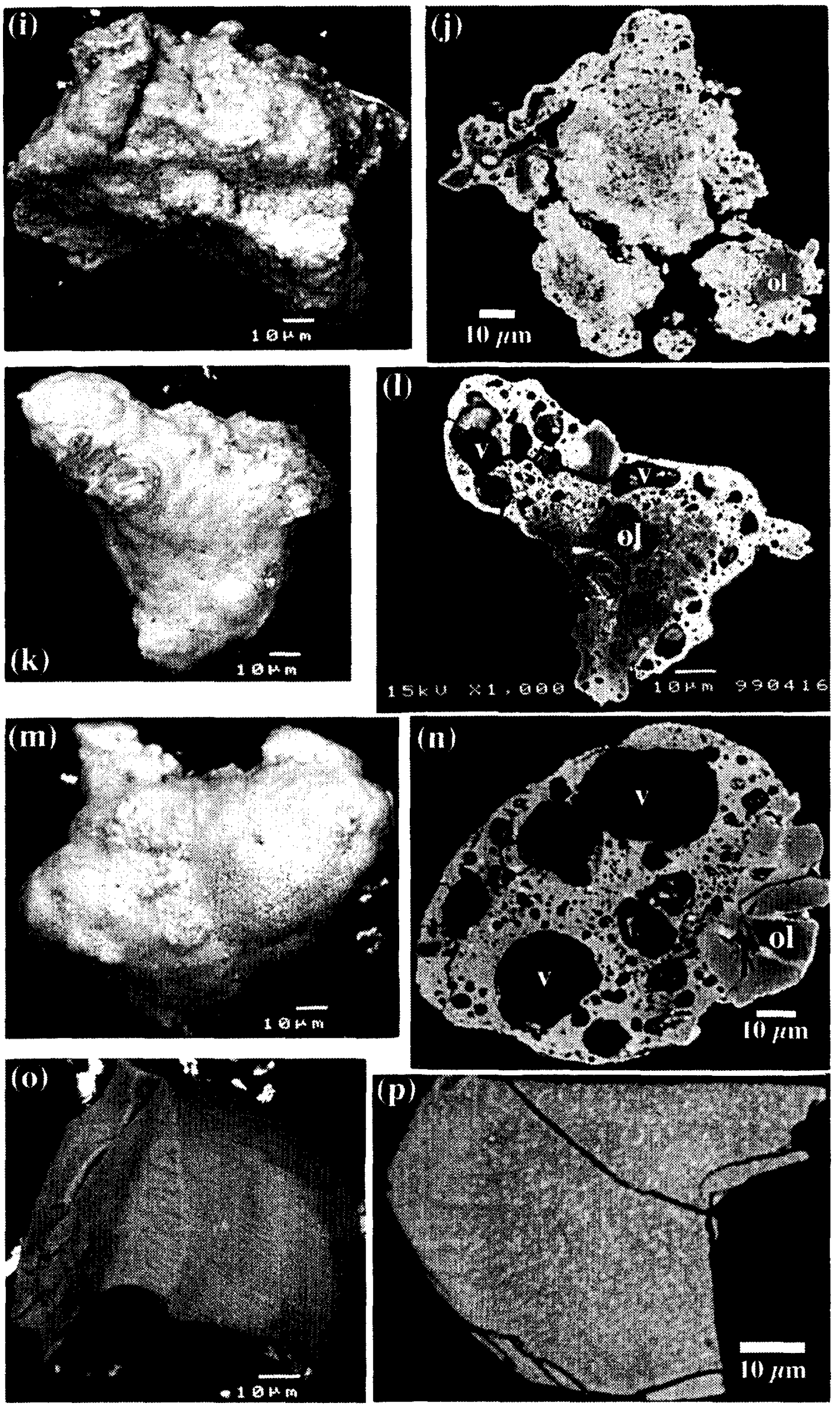

Fig. 1 (continued).
(i) and (j): A weakly melted MM. There are tiny vesicles near its surface. (k) and (l): A moderately heated MM. It is partially melted and contains vesicles near its surface. (m) and (n): A severely heated MM. It is heavily melted and contains large vesicles near its surface. (m) and (n): A severely heated MM. It is heavily melted and contains large vesicles in it. (o) and (p): A fragment of a cosmic spherule. It is composed of glass and quenched crystals. Because these photomicrographs were taken by low-vacuum (LV)-SEM, no carbon coating was needed to take photographs. Abbreviations: ol: olivine, mt: magnetite, po: pyrrhotite, pt: pentlandite, km: kamacite, v: vesicle.

Granular texture is also observed on their surfaces. They contain large vesicles formed during melting. In the MM shown in Figs. 1k and 1l, about half of it was melted. On the other hand, the MM shown in Figs. 1m and 1n was totally melted except for a large relict olivine grain. Swells on the surface in Fig. 1m correspond to large vesicles in Fig. 1n underneath the swells.

Figures 1o and 1p show a fragment of totally melted MM (a fragment of S-type spherule). Its cross section shows that it is composed of glass embedding quenched crystals. Dendritic crystals develop near the surface of the MM. Sub-parallel grooves on the surface of the MM correspond to the dendrites. Because this MM was melted and degassed totally, it contains no vesicles. However, some S-type spherules contain vesicles.

3.2. *Size distribution of the MM samples*

Since there are no quantitative parameters reflecting degree of melting, 233 collected MMs were divided into 4 groups reflecting the degree of melting, by comparing their BEI photomicrographs shown in Figs. 1a, 1c, 1e, 1g, 1i, 1k, 1m, and 1o. MMs that have similar texture to that of Fig. 1a were regarded as MMs being heated very weakly. There were, however, no MMs classified into this group except for the MM in Fig. 1a. This fine-grained hydrous MM comprises 0.4% of those 233 MMs in the F3 fraction. MMs that have similar surface texture to Figs. 1c, 1e, 1g, and 1i were regarded as slightly to weakly heated. One hundred and thirty six MMs were classified into this group (58%). MMs with similar texture to Figs. 1k and 1m were regarded as moderately to severely heated MMs. Sixty five MMs were classified into this group (28%). "Scoriaceous" MMs correspond to those shown in Figs. 1c, 1e, 1g, 1I, 1k, and 1m. MMs with similar texture to that of Fig. 1o are totally melted MMs (spherules or fragments of spherule). 26 MMs were classified into this group (11%). As stated above, population of spherules is underestimated due to the difficulty to find cosmic spherules among artificial spherules.

Grain size distribution of MMs collected at the Dome Fuji Station in 1996 is shown in Fig. 2a. The longest and the shortest axes of each MM were measured from projected images of the BEI photomicrograph. The length of the axes of each MM was measured according to the way explained in the Cosmic Dust Catalog (http://www-curator.jsc.nasa.gov/). Average length of long and short axes of the 233 MMs are 131 and 102 μm, respectively. These size ranges are 40 to 340 and 20 to 300 μm, respectively. Average aspect ratio of "slightly-to-weakly" heated MMs is very similar to that of "moderately-to-severely" heated ones: 0.76 and 0.77, respectively. On the other hand, the aspect ratio of totally melted MMs, 0.90, is larger than them. This implies that original shapes of MMs may well be irregular.

Although the least heated MM group contains only one MM, the other three groups contain 26 to 136 MMs. Therefore, the relationship between grain size and degrees of heating during atmospheric entry can be investigated among the three groups of MMs. These three groups include MMs with similar size ranges (Table 2). However, the average grain sizes of those MMs increase as the degrees of melting during atmospheric entry increase. In other words, the average grain size

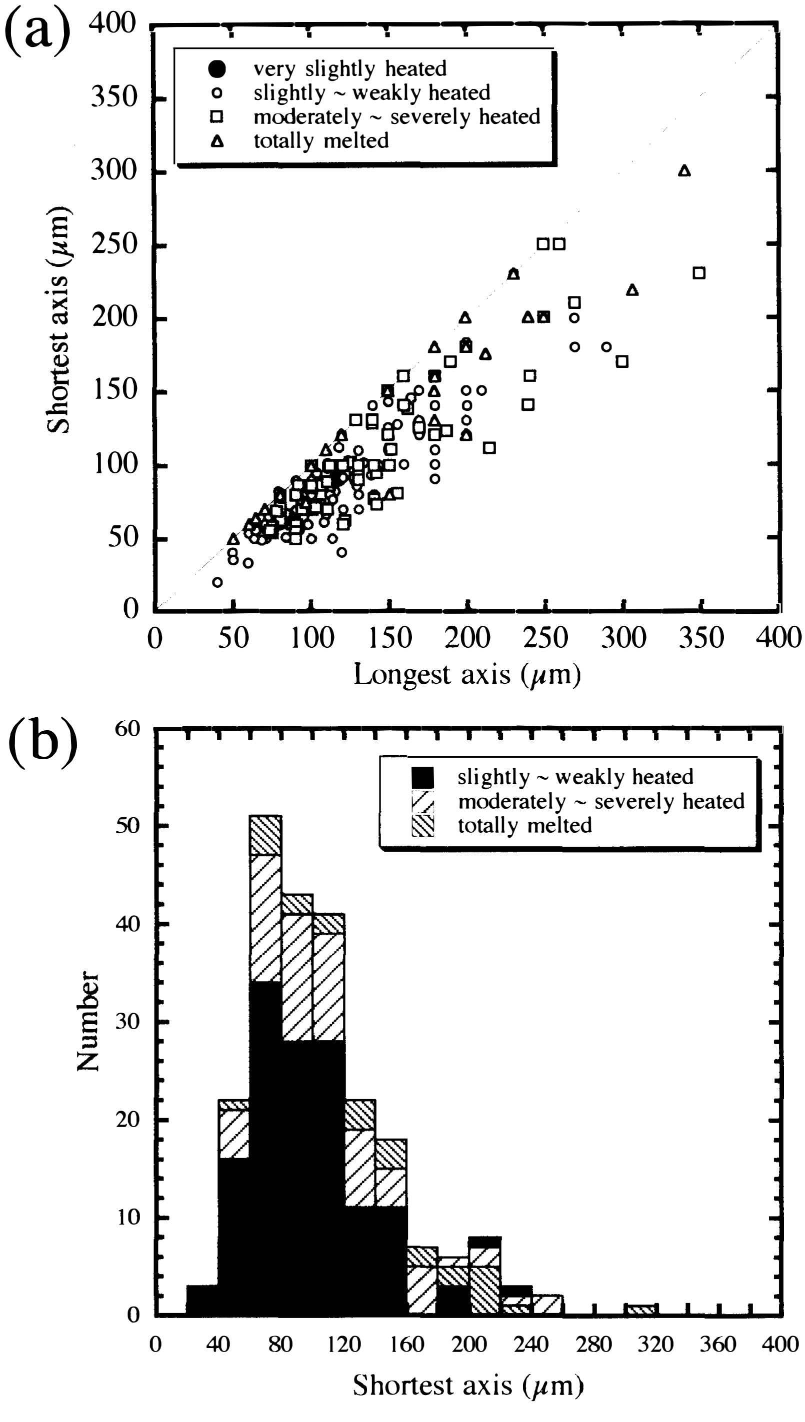

Fig. 2. (a) Grain size distribution of the MMs collected at the Dome Fuji Station in 1996. (b) A histogram of size distribution of them. There are only a few MMs with short axes less than 45 μm. MMs with surface features similar to Figs. 1c, 1e, 1g, and 1i are classified as "slightly-to-weakly" heated MMs, MMs similar to Figs. 1k and 1m as "moderately-to-severely" heated MMs, and spherules as completely melted MMs.

Table 2. Averages and size ranges of longest and shortest axes of the MMs collected at the Dome Fuji Station in 1996.

	No.	Average length (μm)		Size range (μm)	
		Long axis	Short axis	Long axis	Short axis
All data	233	131	102	40–350	20–300
Very slightly heated	1	112	92	—	—
Slightly~weakly heated	136	122	91	40–290	20–230
Moderately~severely heated	65	143	110	73–350	50–250
Totally melted	26	166	144	50–340	50–300

of more heated MMs is larger than that of less heated ones.

There are only five MMs that have the shortest axes with $<45\,\mu$m among the 233 collected MMs (Fig. 2a). A histogram of the short axes of those MMs displays that the number of MMs with $<60\,\mu$m short axes decreases abruptly (Fig. 1b). This abrupt decrease is obvious among the "slightly-to-weakly" heated MMs and the moderately to heavily melted ones.

4. Consortium study of the MMs

4.1. Purposes of this consortium

This is the first case of a nation-wide, organized study of micrometeorites in Japan. Therefore, the primary purposes of the consortium study on MMs are to organize researchers who wish to investigate MMs (cosmic dust) in Japan and to establish routine procedures to investigate MMs. Because of the first reason, this consortium study was restricted to members of the consortium study. In contrast, the JARE-37 and JARE-39 samples are open to researchers who request samples from NIPR (JARE-37 sample has been allocated to other researchers already). JARE-39 samples are open to overseas researchers.

After the SEM/EDS initial characterization, each MM should be fully investigated and analyzed by as many methods as possible. In this consortium study, MMs were first investigated by non-destructive methods such as synchrotron radiation XRF, then investigated by destructive methods such as mass spectrometry of noble gases. During investigation of the MMs, we tried to establish the way to investigate small samples by several different methods. We also tried to investigate the effects of heat during atmospheric entry and to clarify the variation of petrography, mineralogy, and chemistry of these MMs, and to look for samples preserving pristine mineralogy and chemistry. We did not dissect each MM into a few fragments to spread to several methods because the entire MM was needed for the investigation of noble gases by mass spectrometry and that of trace elements by INAA.

4.2. Organization of researchers

Table 3 shows the members of this consortium study. When the consortium study on the MMs recovered from the Dome Fuji Station started, some additional researchers participated in this effort, to investigate mineralogy, petrology, major and trace element compositions, and isotopic compositions of MMs.

As described above, we started to investigate MMs by non-destructive methods. Qualitative to semi-quantitative analysis of each MM by synchrotron radiation XRF analysis was performed first. However, not all the MMs could be analyzed by synchrotron radiation XRF due to the lack of enough machine time. Synchrotron radiation XRF was performed for major and trace element analyses by I. Nakai and his coworkers (Table 3). Ninety-four MMs which suffered from various degrees of frictional heating (from a phyllosilicate-bearing MM to S-type spherules) were investigated at the High Energy Accelerator Research Organization (KEK). Relative abundance of Ca, Ti, Cr, Mn, Cu, Rb, Sr, Y, Zr, Mo, Ni, Ge, and Pb was compared with those of Murchison. Non-volatile elements such as Ti and Cr tend to be enriched with increasing degree of frictional heating during atmospheric entry (Nakamura *et al.*, 1999b).

After synchrotron radiation XRF, 29 MMs were analyzed by the Gandolfi X-ray camera to investigate bulk mineralogy of each MM by T. Nakamura. It was found that the relative abundance of anhydrous minerals formed from phyllosilicates during atmospheric entry change with the degree of heating (Nakamura *et al.*, 1999b).

Forty one MMs with XRF data, and 42 MMs with no XRF data were observed by SEM and analyzed by EPMA to investigate their internal textures and chemical compositions of the constituents of each MM. EPMA of these MMs were performed

Table 3. Members of the consortium study on Antarctic micrometeorites in Japan.

investigator	institution	type of investigation	co-investigators
Fukuoka, T.*	Rissho Univ.	INAA	
Imae, N.*	NIPR	EPMA	
Murakami, T.*	Gakushuin Univ.	Web catalog	
Nakai, I.*	Tokyo Sci. Uiv.	Synchrotron XRF	Kondo, N.*, Sasaki, M.*, Itabashi, M.
Nakamura, T.*	Kyushu Univ.	Sample picking, Gandolfi X-ray camera, SEM/EDS, EPMA, and Noble gas analysis	Nozaki, W.*, N. Takaoka
Nogami, K.*	Dokkyo Univ., Sch. Medicine	Sample picking, X-ray microscopy, SEM/EDS	Ohmori, R.*
Noguchi, T.*	Ibaraki Univ.	Sample picking, SEM/EDS, EPMA, and TEM	
Ohashi, H.*	Tokyo Uiv. Fish.	AMS	
Terada, K.*	Hiroshima Univ.	Sample picking, X-ray microscopy, Ion microprobe	Mori. T.*
Kojima, H.	NIPR	Curation of AMM samples	
Yada, T.	Kyushu Univ.	Sample picking and SEM/EDS	
Yano, H.	ISAS	Sample picking and SEM/EDS	
Hiyagon, H.	Univ. Tokyo	O isotopes (Ion microprobe)	
Sugiura, N.	Univ. Tokyo	N isotopes (Ion microprobe)	
Nagao, K.	Univ. Tokyo	Noble gas analysis	Osawa, T.

*: authors of this work

by T. Nakamura, N. Imae, and T. Noguchi (Table 3). Imae *et al.* (1999) shows that textural variations of MMs are related to both difference in primary petrography (composed of anhydrous coarse-grained minerals or fine-grained hydrous minerals) and degree of melting by frictional heating.

Six MMs regarded as "very slightly-to-weakly" heated ones by X-ray analysis were observed by TEM in order to investigate electron petrography by T. Noguchi (Table 3). TEM samples were made by ultramicrotomy, which is a typical sample preparation technique for IDPs and MMs. Noguchi and Nakamura (2000) reported that electron petrography of a phyllosilicate-bearing MM and effects of terrestrial weathering on MMs.

Isotopic compositions of noble gases in 20 MMs with XRF data, 22 Group 3 MMs with no XRF data were analyzed by T. Nakamura and N. Takaoka (stepped pyrolysis technique) and T. Osawa and K. Nagao (laser gas-extraction system) (Table 3). Nakamura and Takaoka (2000) and Osawa *et al.* (2000) report that the MMs contain solarwind derived noble gases and that they contain a very minor amount of cosmogenic gases. These data suggest that they were exposed to cosmic rays for <2 Ma and thus they were not very fine fragments of meteorites formed during atmospheric abrasion on the basis of isotopic compositions of noble gases.

The following studies are now in progress. The first is ion microprobe studies by SHRIMP (super-high resolution ion microprobe) and SIMS (secondary ion mass spectrometry). Some polished sections are used for the ion microprobe studies. Improvement of preparation of polished sections of MMs for ion microprobe (especially SIMS) analysis is still required. K. Terada and his colleagues are measuring rare earth abundance and isotopic compositions of Pb, etc (Table 3). N. Sugiura, H. Hiyagon and their coworkers are measuring isotopic compositions of light elements, such as N and O. The second is the INAA study. T. Fukuoka is measuring trace element abundance in each MM. About 10 grains of large MMs were used for this analysis until now.

5. Discussion

5.1. *Existence of a "threshold" value for size of the collected MMs*

It is expected that the number of MMs would become larger as their grain sizes decrease if MMs had been formed by fragmentation of their precursor materials. However, the number of collected MMs decreases as the short axes of MMs become shorter than $60\,\mu$m, and there are only five MMs having short axes $<45\,\mu$m. Because the MMs were hand-picked by eight individuals, it is thought that the smallest size of collected MMs are different among each individual. Therefore, it is difficult to regard this "threshold" value for the size of the MMs as a collection bias. Therefore, it is thought that the MMs with $<45\,\mu$m shortest axes were lacking in the deposit of the water tank and/or that they were deficient in the F3 fraction. The F3 fraction is composed of particles which deposited onto the bottom of a beaker within 10 s after the water in the beaker was stirred (Nakamura *et al.*, 1999a). Particles suspended in the water constitute the F4 fraction. MMs were rarely found among the particles in the F4 fraction. Therefore, MMs having short axes with $<45\,\mu m$ were lacking in the deposit of the water tank.

Water in the tank was circulated by a gentle current made by a motor, in order to prevent freezing. Fine-grained materials embedded in snow were released from snow during melting, and were deposited across a gentle current onto the bottom of the water tank. It is thought that there were fine-grained particles whose sedimentation rates were too slow to deposit onto the bottom of the tank. This is a plausible idea for the cause of the deficiency of MMs having short axes with $<45\,\mu m$. However, it is not possible to reconfirm this idea quantitatively because there are no data on the speed of the current in the tank and on the mode of flow. The deficiency of phyllosilicate-bearing MMs among the collected samples may be also due to this slow sedimentation rate, because phyllosilicate-bearing MMs often have a lower density (fluffy) than that of heated ones.

5.2. Relationship among shape, grain size, and degrees of melting

MMs entering the earth's atmosphere at higher velocitites and/or having larger grain sizes will be heated to higher temperatures by frictional heating and experience higher degrees of melting than smaller and slower grains. Therefore, it is expected that the average grain sizes of more heated and melted MMs are larger than those of less heated and melted ones. This is consistent with the grain size distribution of the collected MMs (Table 2, Fig. 2). The average aspect ratio of MMs decreases only in the case of totally melted ones (cosmic spherules). This means that melted MMs become spherical after most degassing vesicles have been released.

6. Concluding remarks

Two hundred and thirty-three MMs were collected from sediments in a water tank at the Dome Fuji Station by the AMM working group. Most of them are unmelted to partially melted MMs. On the other hand, only 26 MMs are "spherules", because it is very difficult to find "cosmic spherules" among artificial spherules, most of which were made during welding at the station. The MMs were (and are) studied by various techniques: synchrotron radiation XRF, Gandolfi X-ray camera, SEM, EPMA, TEM, noble gas analysis, ion microprobes, and INAA. Because each MM has various characteristics of texture, chemical composition, mineralogy, and petrography, most of the MMs were (and are) investigated by at least two methods or more. Relationship among chemistry, mineralogy, petrology, and degree of heating by atmospheric abrasion become more clearly understood in this consortium study. The other major results in this consortium are about the information of the sizes and exposure ages of MMs before entering the earth's atmosphere, electron petrography of a phyllosilicate-bearing MM, and clues of terrestrial weathering in these MMs. Ion microprobe and INAA studies are now in progress and will give insights on origins of MMs.

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