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Search for Antarctic meteorites in the bare ice field around the Yamato Mountains by JARE-41

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Abstract: The wintering party (November 14, 1999–March 28, 2001) of the 41st Japanese Antarctic Research Expedition (JARE-41) conducted a meteorite search in the bare ice field around the Yamato Mountains. The period of the travel was 89 days. Departure from Syowa Station was on October 27, 2000, entrance into the bare ice field on November 17, 2000, leaving the bare ice field on January 10, 2001, and arrival at Syowa Station on January 23, 2001. The 6 men party (field leader: Y. Shimoda, and sub-leader: N. Imae) of JARE-41 collected about 3500 meteorites. The total sample weight was about 196 kg. The average meteorite weight was 55 g. The most frequent weight was in the bin of 3.2–10 g of the weight histogram. The heaviest meteorite collected on the present expedition was an iron meteorite of 50.5 kg. This is also the heaviest meteorite among the Yamato bare ice region since the first expedition in 1969 (JARE-10). The iron meteorite was found on the northwest region of JARE IV Nunataks. Compared with other areas, relatively large meteorites were found here. The number of meteorites on the bare ice region around Minami-Yamato Nunataks, which is the most famous meteorite concentration area, was large but the weight of each meteorite was lighter compared with other areas.

Sublimation rate, which must be one of the most important factors for the concentration of meteorites, was measured at the near YM175 (71°44.4′S, 35°54.7′E, 2138 m) using two independent methods. Both the stake method and the empirical formula method gave nearly comparable values in average; 50–80 and 130.8 mg cm^{-2} d^{-1}, respectively, which are larger than that at Mizuho Station. Sublimation using the stake method was measured at 8 points. Precise GPS measurements for 20 days at YM175 showed that the bare ice is moving 3 cm to the west and 2 cm upward. This suggests that the upward movement is nearly balanced with the sublimation of ice. However, in order to consider the annual balance, longer measurements are needed.

1. Introduction

Antarctic meteorites have been abundantly collected from bare ice regions accompanied by mountains or nunataks (Cassidy *et al.*, 1992). Bare ice fields only occupy about 1% of Antarctica (Cassidy *et al.*, 1992). About 10000 meteorites (*c.* 700 kg as total) have been found from the huge bare ice area around the Yamato Mountains (Kojima *et al.*, 2000) located to the east of Droning Maud Land in Antarctica. The Yamato bare ice area has been estimated to be *c.* 3250 km^2 including an ice-free rocky area of *c.* 50 km^2 (Nishio and Mae, 1979). Yanai (1978) estimates the Yamato bare area as 4000 km^2. Our estimation is that Yamato bare ice field occupies *c.* 2900 km^2 and the moraine, mountains, and nunataks occupy *c.* 180 km^2 from the map of the Yamato and Belgica bare ice area of 1: 500000 (Yanai and Kojima, 1981). The bare ice field around the Yamato Mountains was where meteorite concentrations were place recognized for the first time. The area potentially still has new meteorites because it has not been completely searched.

The concentration mechanism of meteorites in such a bare ice field has been explained by an approximate balance of the ablation of ice and the upwelling of ice (Nagata, 1978; Yanai *et al.*, 1981; Cassidy *et al.*, 1992). The upwelling motion of ice is driven by the presence of the Yamato Mountains. The ablation of ice is controlled by the catabatic winds, relative humidity, and temperature. Based on this representative concentration model of meteorites, in the bare ice fields in the Transantarctic Mountains and the Sør Rondane Mountains as well as Yamato bare ice field the meteorites searches have been conducted (Cassidy *et al.*, 1992).

If it is assumed that (1) meteorite concentration in Yamato bare ice field has been occurring for 0.3 Ma, based on the fall age variation being <0.3 Ma (Nishiizumi *et al.*, 1989; Jull *et al.*, 1999), that (2) the number of meteorites was initially 20000 in the Yamato bare ice area, and that (3) the number of meteorites linearly accumulates, and the annual accumulation number for the Yamato meteorites is $20000/(0.3\times10^6)$ (= 0.07), that is, one new meteorite in Yamato bare ice area every 15 years interval newly appears. Thus newly appearing meteorites from ice are considered to be few after the previous search, that is, the estimation is less than one meteorite for 20 years on the bare ice of *c.* 2900 km^2. Still the fact that a lot of meteorites have been recovered from the Yamato bare ice area implies that perfect search has not been carried out yet.

The wintering party of the 41st Japanese Antarctic Research Expedition (JARE-41) from November 14, 1999 to March 28, 2001 conducted meteorite searches in the bare ice field around the Yamato Mountains. Rock sampling of the Yamato Mountains was also carried out. And in the bare ice field, we obtained precise global positioning system (GPS) observations and the data on sublimation of ice.

2. Field Work

2.1. Research contents

We planned researches in the Yamato bare ice field including (1) the meteorite search, (2) the rock sampling on the Yamato Mountains and (3) the measurement of weather by an automatic weather station, ice movement observations by the precise GPS and measurements of ice sublimation rate using stakes.

2.2. Periods

The period of the meteorite search was 89 days. We departed from Syowa Station on October 27, 2000, and arrived at the bare ice field (YM 168) in November 17, 2000. After we stayed for 55 days in Yamato bare ice field, we left on January 10, 2001, and returned to the Syowa Station on January 23, 2001. The return to the station was 4 days earlier than the schedule.

2.3. Routes

The traverse route on the snow between Syowa Station and the Yamato Mountains was used from Syowa Station to Tottuki Point (Tottuki route, 14 km), Tottuki Point to S16 (Tottuki–S16 route, 17 km), S 16 to Mizuho Station (Mizuho route, 255 km), and Mizuho Station to YM 175 (YM route, 352 km) (Fig. 1).

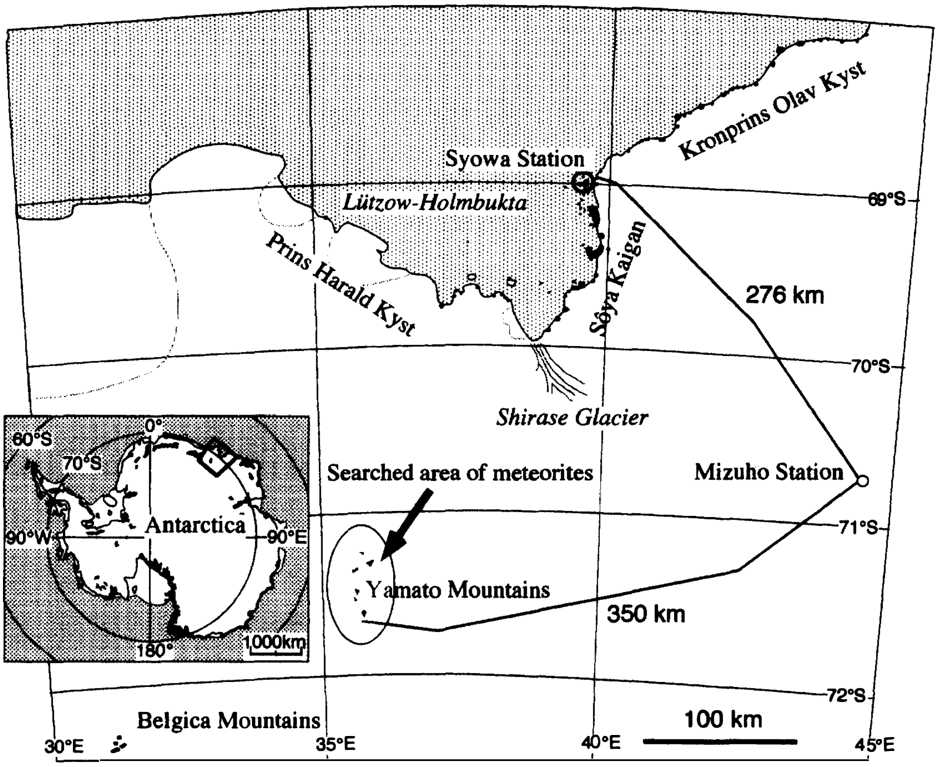

Fig. 1. Route map between Syowa Station and the Yamato Mountains.

2.4. Member

The team consisted of 6 men, including a surgion and two engineers; Yasuyoshi Shimoda (leader and field assistant), Naoya Imae (sub-leader and navigator), Naoyoshi Iwata (meals and rock-sampling), Mitsuaki Sakai (surgion and daily weather measurement), Taku Kondo (radio engineer), and Shintaro Nomoto (engineer for vehicles).

2.5. Surveyed area

Figure 2 shows the schematic Yamato bare ice field, the route of meteorite search and searched area in detail. Counterclockwisely around the Yamato Mountains, the bare ice area was divided into 9 regions (I~IX) for convenience as shown in Roman numerals. The bare ice region around JARE IV Nunataks and one around Minami Yamato Nunataks were selected as important search areas. Thus we planned to visit regions in the order of II, VIII, VII, and VI. As scheduled, we visited II, VIII, and VII, but could not go to the area VI due to a change of the schedule brought by the bad weather (Table 1).

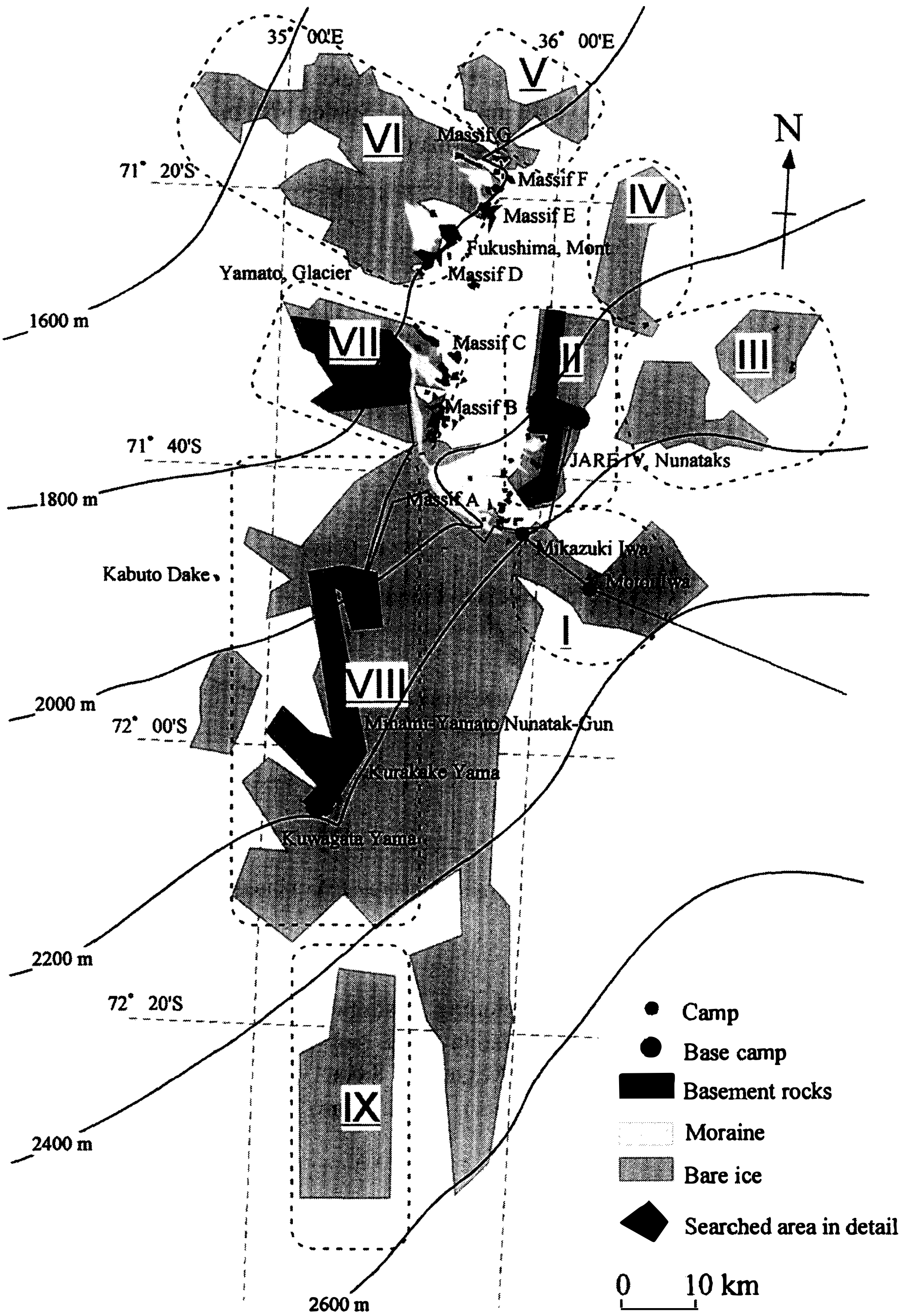

Fig. 2. Yamato bare ice field and meteorite searched area in detail. The Yamato Mountains mainly consisting of Massif A to G, JARE IV Nunataks, and Minami Yamato Nunataks are shown. Moraine areas around the mountains are also shown. Bare ice area was divided into nine (I–IX areas shown as dotted line) for convenience. Three base camps are shown as larger closed symbols, and five camps as smaller closed symbols.

Table 1. Period of the each surveyed area.

Area	Period	Number of days	Searched days	Stagnation
I	17 Nov. '00 and 10 Jan. '01	Moving		
II	21 Nov. '00-11 Dec. '00	21	10	11
VIII	14 Dec. '00- 2 Jan. '01	20	9	11
VII	2 Jan. '01- 7 Jan. '01	6	6	0
Total days		47	25	22

Maintenace of apparatus and vehicles 12-13 Dec. and 8-9 Jan.

2.6. *Preparations for the meteorite search*

Large snow vehicles

Three large snow vehicles (SM107, SM109 and SM111) were prepared: SM100 OHARA with weight of 11 ton per snow vehicle. These were used for the transportation between Syowa Station and the Yamato Mountains.

Fuels

We prepared one hundred and fifty 200-liter drums of fuel (30 k*l*). Residual fuel was 54 drums (10.8 k*l*). Two 200-liter drums of fuel for a Cessna aircraft from Syowa Station were also prepared for emergencies.

Snowmobiles

Five snowmobiles [YAMAHA CS340 (8BE)] and the twenty 200-liter drums (4 k*l*) of gasoline for these were also prepared. Snowmobiles have been reformed for use on the ice surface, the main points being ice spikes, single seat and box; except ski same as that of JARE-39. Gasoline was mixed with engine oil by the volume ratio of 20:1 in advance.

Food

Weight of prepared foods was *c.* 1700 kg including canned beer *c.* 400 kg and rations for dinner *c.* 300 kg. Foods including rations, separately vacuum-packed and frozen of grilled foods, were prepared by a chef and a member in charge in JARE-41 at the Syowa Station. Dinner had five kinds of rations with a unit of a week (35 types for dinner). Three round rations were thus used in the expedition. One cycle of a week was packed into corrugated carton $56\times39\times29$ cm^3 in size. Abundant rice, breads and drinks were also prepared. Drinks such as the canned beer, juice, and tea were kept in snow vehicles. Frozen fried rice, frozen spaghetti, or Japanese or Chinese noodles were used for lunch. Breakfast was rice or bread. Japanese pickles, packed fermented soybeans, toasted and seasoned laver and abundant canned foods were also prepared. Residual meals were *c.* 400 kg.

Radio/medical/vehicles/equipment

Each person prepared radio, medical parts, vehicles and equipment for daily life.

Sledges

Almost everything such as fuels, meals and snowmobiles except clothes, sleeping bags and drinks are set in sledges. The contents of sledges were as follows: 15 sledges for fuels, a sledge for equipment, a sledge for meals, a tented sledge for meteorites storage, a tented sledge for parts for vehicles, a tented sledge for toilet and garbage, and 2 sledges for snowmobiles. Each vehicle could pull 7 sledges. And each sledge was capable of carrying 2 tons.

2.7. *Meteorite search method*

We carried out the meteorite search according to the traditional method carried out by JARE for thirty years. Figure 3 is a typical scene during the meteorite search. One snow vehicle (SM107) for guides of the route and 4 to 5 snowmobiles went side by side over a distance of about 30–100 m. All vehicles run slowly (4–8 km/h) in the same direction. Because dirt bands were useful for determing position, a search along dirt bands at the bare ice was also carried out in the search northwest of the JARE IV Nunataks. The navigator in SM107 always used GPS for a guide. Three 20-liter gasoline tanks (total 60 *l*) for snowmobiles were prepared in SM107 during the meteorite search from base camp. Snowmobiles run in the field of view from the snow vehicle for safety. Each driver of snow vehicles always carries a handy UHF radio (1 W). When a meteorite is found, we write the field number and collection time using an oily magic ink on a sealed polyethylene bag with a zip fastener (10 cm × 6 cm), and store it in the bag. The field number is a tentative name for the meteorite and is written as S00122607, for example. The first letter (S) means the first name of a finder (Shintaro), 00 the last two-digit number of the Christian Era (2000), 1226 December 26, 07 the seventh meteorite of the day by the person. Photography of meteorites by camera (digital camera, still camera or video camera) was sometimes carried out.

Fig. 3. A scene showing the typical meteorite search method in the Yamato bare ice field (area VII). The red vehicle besides the mountain is a snowvehicle (SM107), and four small vehicles of the side are snowmobiles. The distance between vehicles during searches is about 30–50 m.

2.8. *Daily routine*

The daily routine is shown on Table 2. There was a slight difference between the daily routine during camp moves and during the meteorite searches. Thus these are shown separately.

Table 2. Daily routine during the trip.

Local time	During the moving between camp	Base camp (during meteorite search)
0700	Getting up	Getting up
	Key on for snow vehicles	Key on for snow vehicles
	Preparation for meals	Preparation for meals
0740	Breakfast	Breakfast
0810	Warming up driving for snow vehicles	Warming up driving for one snow vehicle
	Connection between snow vehcle and sledges	Key on for 4 ~ 5 snowmobiles
	Check of sledges	
0900	Departure the camp site	Departure the camp site
	Driving	Meteorite search
1200	Fuel supply for snow vehicles	Preparation for meals
	Preparation for meals	Lunch
	Lunch	
1300	Departure the site	Departure the site
	Driving	Meteorite search
1500	Break time (20min)	Break time (20min)
	Driving	Meteorite search
1800	Camp in	Camp in
	Fuel supply for snow vehicles	Fuel supply for snow vehicle and snowmobiles
	Preparation for meals	Preparation for meals
	Dinner	Dinner
2200	Key off for snow vehicles	Key off for snow vehicles

2.9. *Typical equipment on snowmobile*

The expedition clothing included a pair of goggles with face mask, boots, grip cover, a pair of gloves with inner wool and outer leather, coyote fur around the face, ski cap, sunglasses, woolen face mask, and double woolen socks.

2.10. *In situ weighting and descriptions of meteorites*

Sample weights and descriptions were obtained in a little wider tented sledge (area: 2.4×4.5 m^2) than usual ones mainly for the sample storage at low temperature with no air conditioning. That is, during the stay in the Yamato bare ice field, we did rough classification, sample descriptions and weighting of collected meteorites by an electric balance (Sartorius; BP2100S, 0.01 g accuracy). Each meteorite was weighed with the polyethylene bag for storage and it was corrected for estimating real weight. An optical microscope was used for the sample description. The simple field classifications into chondrite, achondrite, or iron were carried out. The shape of complete, half, or fragment, and interior luster, interior stiffness (rough or smooth) were also examined. If more precise classification is possible, eucrite, carbonaceous chondrite, or lunar meteorite etc. was recorded. Still more precise weighing and sample descriptions will be done at the NIPR and will be crosschecked.

2.11. *Additional researches in the Yamato bare ice area*

In addition to the meteorite recovery, rock sampling of the Yamato Mountains, the measuring of ice ablation length by the stake method, ice flow measurement by precise GPS at YM175, weather measurement by an automatic weather station (MAWS) at

YM175 were carried out.

Rock sampling: Rock sampling was carried out at 4 points; (1) 2513 m Nunatak in JARE IV Nunataks, (2) Mt. Kuwagata in Minami Yamato Nunataks, (3) the Massif C, and (4) the Massif A. Collected weight was 200 kg.

Stake method: We buried a stake of 28 mm in diameter and 2 m length made of wood or aluminium into the ice using an electrically-driven ice drill (*c.* 40 mm in diameter) at 8 measured points among set 16 points (Table 3). In order to glue it to the ice, we poured water liquid of several hundreds cm^3 into the space between the ice and the pole. In order to measure the change, we marked the interface between the ice surface and the pole using a knife. We measured the surface change after 17–28 days at 8 points.

Table 3. Results of ice sublimation experiments.

Site name	Latitude	Longitude	Height (m)	Period	Run duration (days)	Sublimation length (cm)	Sublimation rate (cm/day)
YM175	71°44.355'S	35°54.726'E	2138	11 Dec.- 7 Jan.	28	2	0.07
N1	71°43.025'S	35°58.868'E	2149	21 Nov.-11 Dec.	21	2	0.10
N2	71°41.029'S	36°01.594'E	2139	21 Nov.-11 Dec.	21	1.75	0.09
N3	71°39.044'S	36°04.200'E	2120	21 Nov.-11 Dec.	21	2	0.10
N4	71°37.065'S	36°04.568'E	2056	21 Nov.-11 Dec.	21	1	0.05
S1	71°44.051'S	35°47.095'E	1982	14 Dec.- 7 Jan.	25	3.75	0.16
S2	71°41.257'S	35°37.249'E	1876	14 Dec.- 7 Jan.	25	2.75	0.11
S7	71°59.928'S	35°16.262'E	2034	15 Dec.-31 Dec.	17	1	0.06

GPS: Precise GPS observations by an Ashtech Z-Surveyer were conducted at a bare ice (YM175) from November 21 to December 15, 2000. The period from November 21 to December 15 was missed due to a low battery. In order to accurately detect ice movement position and avoid the sublimation effect of ice, we buried the tripod into ice to a depth of 30 cm. The position of Syowa Station was used as a reference point. Two storage batteries (YUASA; 170F51, 12V 120Ah) connected in parallel were used for the operation.

Weather: Temperature, relative humidity, dew point, air pressure, wind speed, and wind direction, were automatically measured by MAWS; VAISALA and every 10 min the averaged data for these values were recorded into a data logger. However, the period from November 23 to December 11, 2000 was missed due to a low battery. The measured period was from November 20, 2000 to January 7, 2001 at YM175. A 45° angle deviation in the area was corrected in advance. A storage battery (YUASA; 170F51, 12V 120Ah) was used for the operation. The obtained data was applied in order to estimate the ice sublimation rate using the empirical formula method (Fujii and Kusunoki, 1982).

3. Results

3.1. Collected meteorites and these features

We worked for 25 days on the meteorite search in the Yamato bare ice field, but we also experienced 22 heavy weather days such as whiteout, snowstorm, and blizzard, when we could not work and stayed in snowvehicles (Appendix).

We describe the characteristics of each surveyed area, II, VIII and VII (Table 4). In area II, located on the eastern side of the Yamato Mountains, relatively large meteorites were found compared with other areas (number=1320; average weight=80 g). Part of this area has been searched previously, however, the northern part of the area had not been completed. In the insufficiently searched area, we found two large meteorites. One of these is an iron of 50.5 kg (Field number: M00112930) free from Widmanstätten structure on the surface (Fig. 4). It is the heaviest meteorite recovered from the Yamato Mountains area since the first expedition in 1969 (JARE-10). It was found in the northwest region of JARE IV Nunataks (Fig. 2). This specimen has the surface feature of beautiful regmaglypts. The other large meteorite is an achondrite (Y00112922) of *c.* 13.5 kg (Fig. 5), making it the heaviest achondrite from Antarctica. The specimen is fragile, and is covered with black fusion crust. The interior of the specimen is greenish colored.

Table 4. Summary of collected meteorites.

Area	Numbers of meteorites	Total weight (kg)	Average weight (g)
I	6	0.07	11.7
II	1324	107	80.8
VIII	1800	50.5	28.1
VII	424	38.5	90.8
Total	3554	196.1	55.2

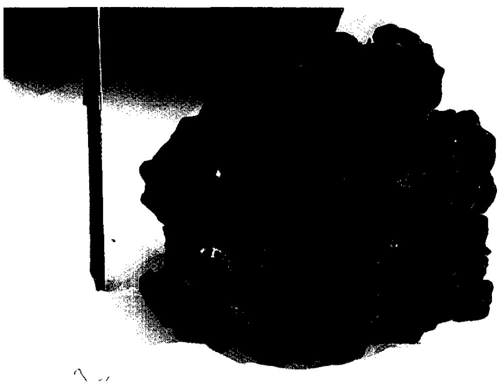

Fig. 4. The field occurrence of the heaviest meteorite (50.5 kg) in the Yamato meteorites. The specimen is an iron meteorite found in area II.

Fig. 5. The specimen of 13.5 kg found in area II. It is the largest achondrite ever found in Antarctica. The specimen is covered with black fusion crust, and the interior shows greenish color.

Area VIII is the famous area from which a large amount of meteorites have been collected (Yanai, 1978; Kojima *et al.*, 2000). Especially, remarkably abundant meteorites have been collected from the bare ice region around Minami-Yamato Nunataks (area VIII) (Yanai, 1981; Kojima *et al.*, 2000). In the present search, an abundant number of meteorites (1800) were also found (Table 4). However, the average weight of meteorites in this area was small (28 g) compared with that of other areas. This is

Fig. 6. An achondrite found in area VIII with the weight of c. 12 kg.

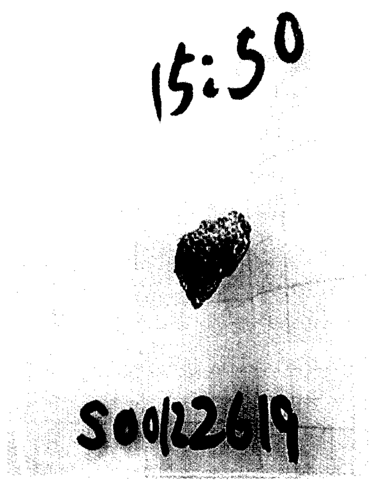

Fig. 7. An achondrite (3 g) found in area VIII has the character of a lunar anorthositic regolith breccia.

Fig. 8. Sampling of 322 fragmented ordinary chondrites found in area VII. The field number is N01010501.

probably because the southern part of the area VIII had previously been searched well. Also in this search, the number of collected meteorites was abundant, but the weight of each meteorite was lighter compared with other areas. Nevertheless, we found an achondrite (N00121800) of *c.* 12 kg (Fig. 6). The specimen consists of green colored transparent crystal and is coarse grained. Samples of it were first collected by JARE-39 and entirely consists of Mg-rich clino-pyroxene showing polysynthetic twinning (Kojima, personal commun.). They also collected the specimen from the area VIII. Another unique meteorite recovered from area VIII is a lunar anorthositic regolith breccia (S00122619; 3 g), which is covered with greenish fusion crust and in the interior white

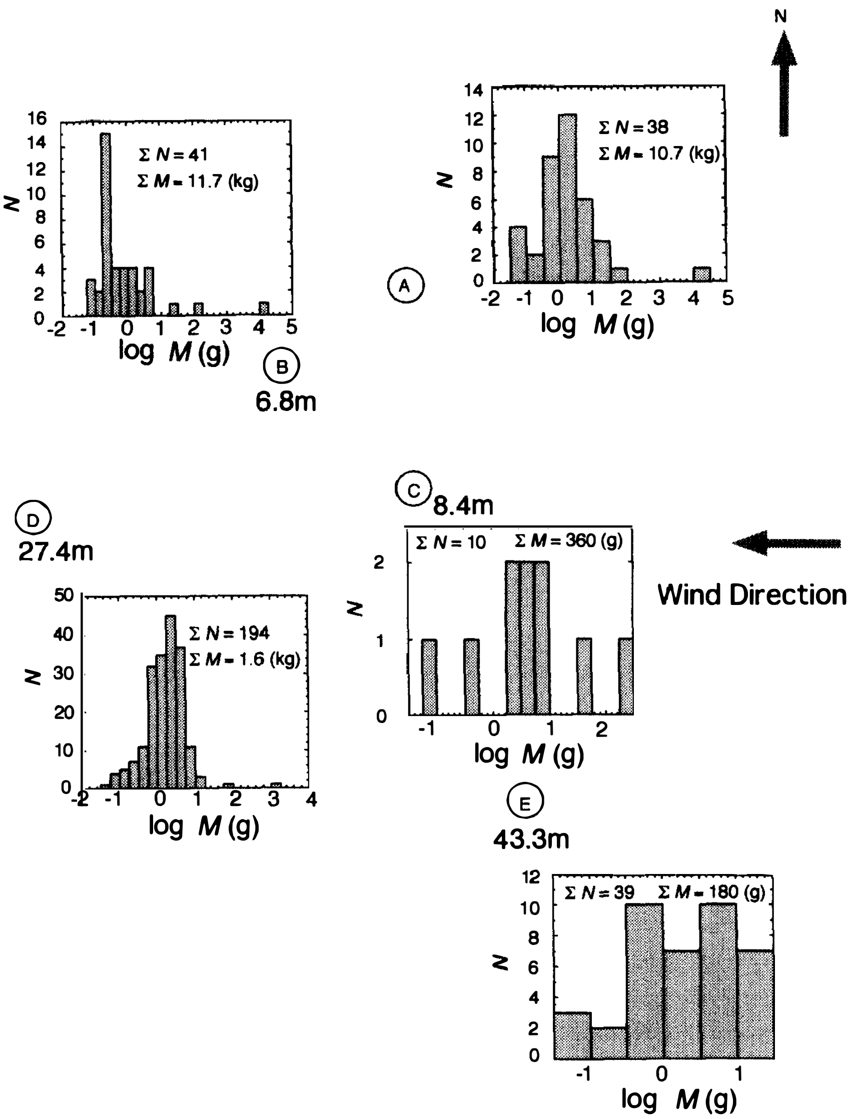

Fig. 9. A schematic illustration of 322 fragments of an ordinary chondrite. The location of the meteorite is 71°32.641′S and 35°13.112′E, and the altitude is 1734 m. The distribution was broadly divided into five areas (A–E). The distance from position A is also shown in the figure. Figures of the number of fragments (N) versus weight (M) within each area were incorporated into the figure.

crystals of plagioclase can be seen (Fig. 7).

It has been known that area VII, the western side of the Yamato Mountains, has a meteorite concentration down by a factor of 10 compared with areas VIII and II. It is true that meteorites are not abundant, nevertheless, several characteristic meteorites were found. 322 fragments, mainly from two large broken stones of 11.5 and 10.5 kg were found within a diameter of about 100 m (Field number: N01010501) in area VII, the western side of the Massif C (Fig. 8). The specimen is a weathered ordinary chondrite. Such a large number of meteorites were formed by the fragmentation of a single meteorite by Antarctic weathering not by a shower. The distribution of fragments is reproduced in Fig. 9. The weight histogram and the cumulative plot of N01010501 is shown in

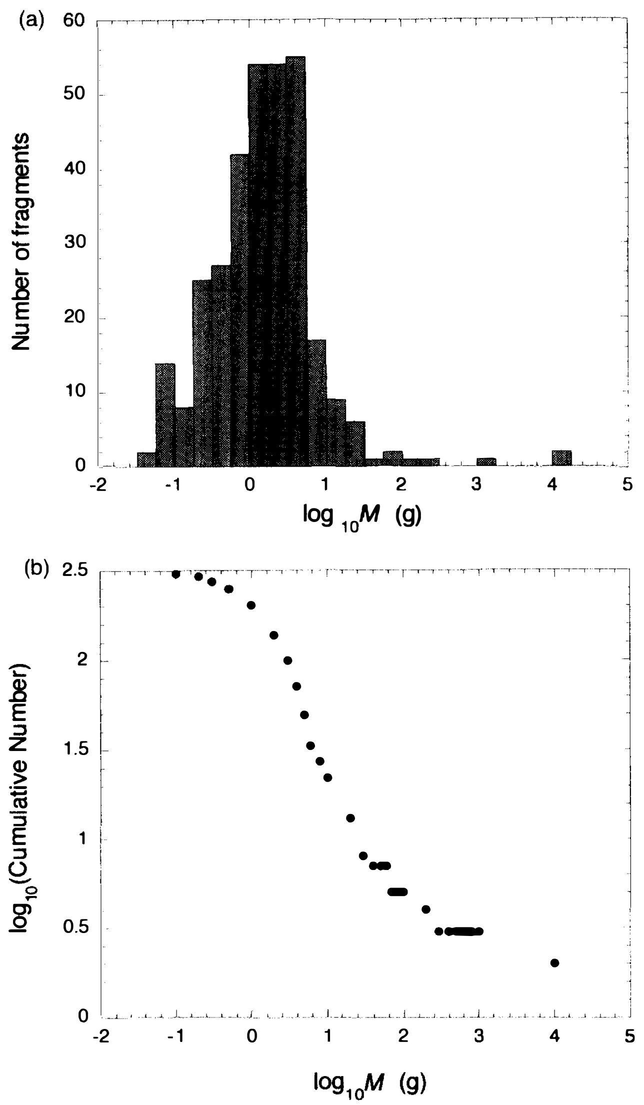

Fig. 10. (a) The weight histogram of 322 fragmented ordinary chondrites (N01010501). (b) The cumulative number plot versus log M (g). The distribution in the range of 1–100 g shows a power law type distribution and the power exponent is nearly 2.

Fig. 10a and b, respectively. In this area VII, we found an iron of 11 kg (Y01010203; Fig. 11a) and a small stony-iron meteorite of 14.5 g (K01010304; Fig. 11b).

In Fig. 12, the mass variation of meteorites recovered by the present expedition is shown. We collected more than 3500 meteorites. The total weight of recovered meteorites is 196 kg. Then average weight is 55 g. The most frequent weight was in the bin of 3.2–10 g (Fig. 12). Meteorites more than 10 kg were 6 in number and those more than 1 kg were 14. We compared the collected meteorites by the present search with the previous Yamato meteorites (Fig. 13). Hatched lines are the present collection and solid lines are the previous one. We can see that though the most frequent weight range is the same, the fraction of light meteorites in the latter collection is relatively

(a) (b)

Fig. 11. (a) An iron meteorite with elongated shape (c. 20 × 10 cm) of 11 kg found in area VII. In the surroundings, a small pond was observed. (b) A tiny stony-iron meteorite of 14.5 g. The specimen may be pallasite.

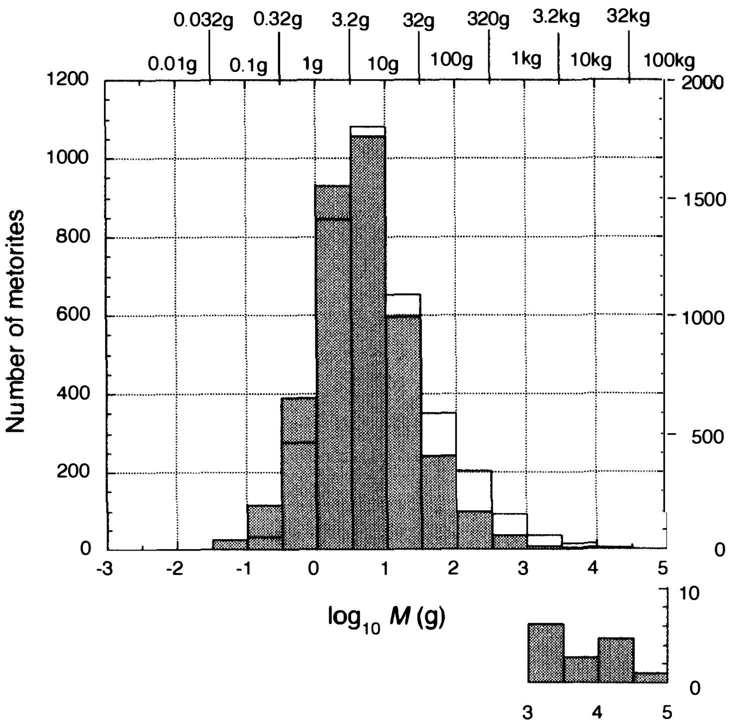

Fig. 12. Mass variation of the Yamato meteorites collected by JARE-41 comparing with previous Yamato meteorites before the 1995 collection. Hatched bars show the present collection, and solid bars show the previously collected Yamato meteorites. Both peaks are in the bin 3.2–10 g. Previously collected Yamato meteorites are abundant in the size range greater than 3.2 g compared with those of JARE-41. Meteorites in the mass range less than 3.2 g are abundant for JARE-41 compared with those of previously collected Yamato meteorites.

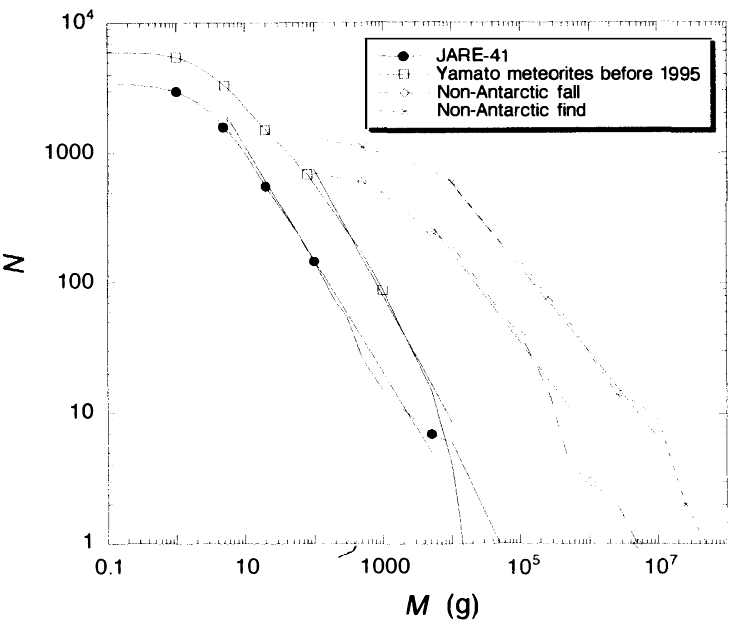

Fig. 13. Cumulative number (N) plots of meteorites from JARE-41 plotted against M (g). N is nearly proportionate to $M^{-0.7}$ in the range in which a straight line is drawn. For comparison, cumulative number plots of the previously collected Yamato meteorites before 1995, non-Antarctic falls, and non-Antarctic finds are also shown. These are nearly proportion to $M^{0.68}$, $M^{-0.99}$, and $M^{0.87}$ at the range approximated as straight lines.

higher. A similar feature is seen from the cumulative number plot against M (g) (Fig. 13). When we compare the present collection including all meteorites with the previously collected Yamato meteorites, the slopes of the meteorites between the two distributions are similar, and the two graphs largely show a straight line meaning that the meteorite distribution obeys a power law. However, for the present data the deviation from the line starts from less than ten grams. On the other hand, the previous data deviates from the straight line at weights above one hundred gram. This means that the present collection includes more abundant lighter meteorites compared with previous Yamato collections.

The frequency of meteorite types, that is, chondrites, achondrites, iron, or stony-iron in the field, was 94.7, 4.9, 0.3 and 0.03%, respectively. The stony-iron was only one small fragment. The frequencies of chondrites and achondrites are nearly consistent with those of previous Antarctic finds, however, those of irons and stony-irons are both less than those of previous Antarctic finds (Harvey and Cassidy, 1989).

We defined the shape of meteorites as "complete", "half" and "fragment". "Complete" means that the meteorite is not fragmented or completely covered with fusion crust (15.4%), "half" is one complete meteorite fragmented into two pieces (13.0%), and "fragment" is a small fragmented chip usually without fusion crust or with fusion crust nearly absent (71.6%). The fragmentation could have taken place at the time of fall of a meteorite and/or due to weathering on or in the ice. The fraction of each shape was examined as a function of bin of mass (g). Figure 14 shows that "complete" and "half" have a negative linear correlation and "fragment" has a positive linear correlation with bin

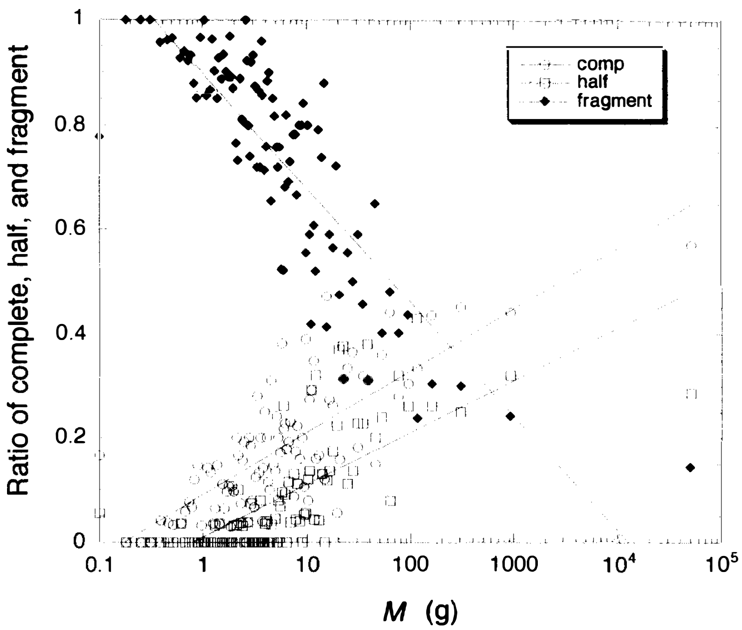

Fig. 14. Fraction of "complete", "half" and "fragment" in the present collection. Both "complete" and "half" are correlated versus the logarithm of M with positive slopes, on the other hand, "fragment" is nearly linearly correlated with a negative slope. Equations of three least square fitting lines are $R=0.09 + 0.119 \log M$ (correlation factor $r=0.77$), $0.011 + 0.1 \log M$ (g) ($r=0.73$), and $0.897 - 0.22 \log M$ (g) ($r=0.84$), for complete, half, and fragment, respectively.

of log M (g) (the number of each bin is 38). This feature suggests that larger meteorite (more than 100 g) occupies the largest fraction of complete and half, on the other hand smaller meteorites (less than 10 g) are mainly fragments. We did a similar plot for the previously collected Yamato meteorites before 1995 using the description by Kojima and Imae (1998, 2000) (Fig. 15). Note that in the descriptions by Kojima and Imae (1998, 2000) meteorites less than a few gram are not included. When we compare Fig. 14 with Fig. 15, we do not find any substantial differences. Thus we can say that in the present search, we found a lot of small sized meteorites compared with the previous collection, and the fractions of three kinds of shape in such small meteorites are along extrapolation of the previous distribution (Fig. 15). Since the fraction of fragments increases at low mass, the fraction of each shape must be considered in estimates of the small sized meteorite flux.

3.2. *Recording of sampling sites*

The GPS recording for each meteorite location has not been carried out due to its difficulty in the face of strong winds and the time necessary to receive the position. Instead, we recorded the track using the GPS (Fig. 16) and waystations for a guide (SM 107), and drivers of snowmobiles recorded the collection time for each meteorites. These data can reproduce sampling sites. Results of the calculation will be reported elsewhere.

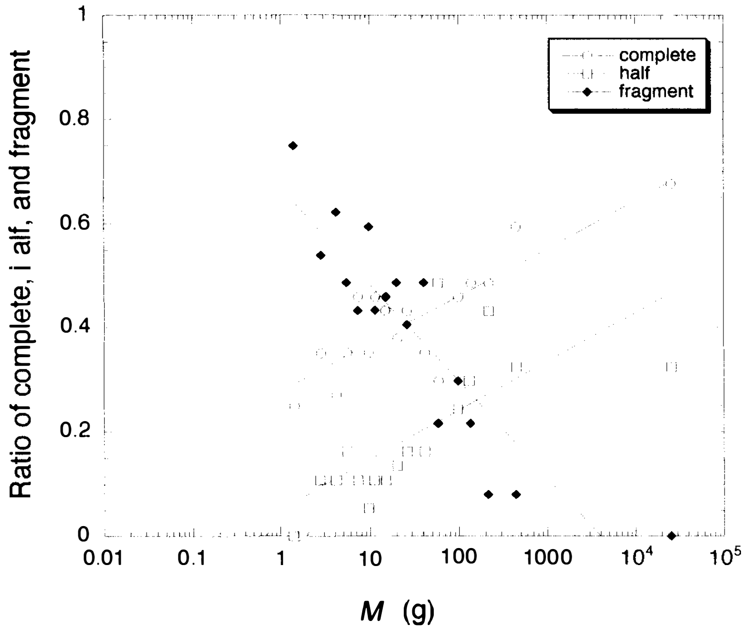

Fig. 15. Fraction of "complete", "half" and "fragment" of the previous Yamato meteorite collection. Similar to Fig. 14, both "complete" and "half" are positively correlated and "fragment" is negatively correlated versus M (g), respectively. Each of the fraction distributions overlap. In Fig. 15, meteorites less than a few grams are not included. Equations of three least square fitting lines are $R=0.28 + 0.09 \log M$ (correlation factor $r=0.8$), $0.054 + 0.094 \log M$ (g) ($r=0.7$), and $0.67-0.185 \log M$ (g) ($r=0.9$), for "complete", "half", and "fragment", respectively.

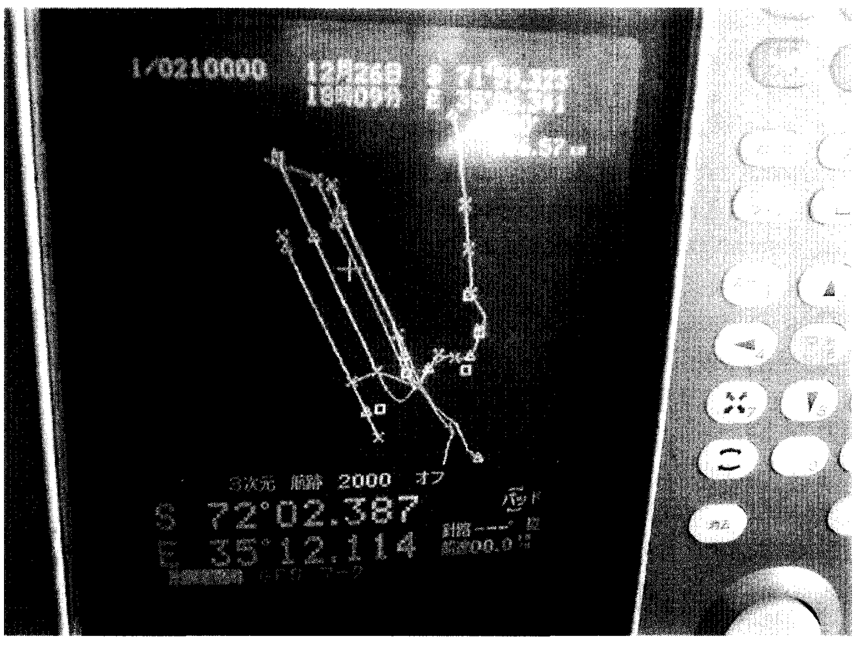

Fig. 16. The GPS monitor showing the track for the meteorite search in SM107. The monitor includes the track of four days of searches as four nearly parallel straights lines. Turning points (cross), lunch time or tea time points (triangle) and initially planned points (square) are shown with the track.

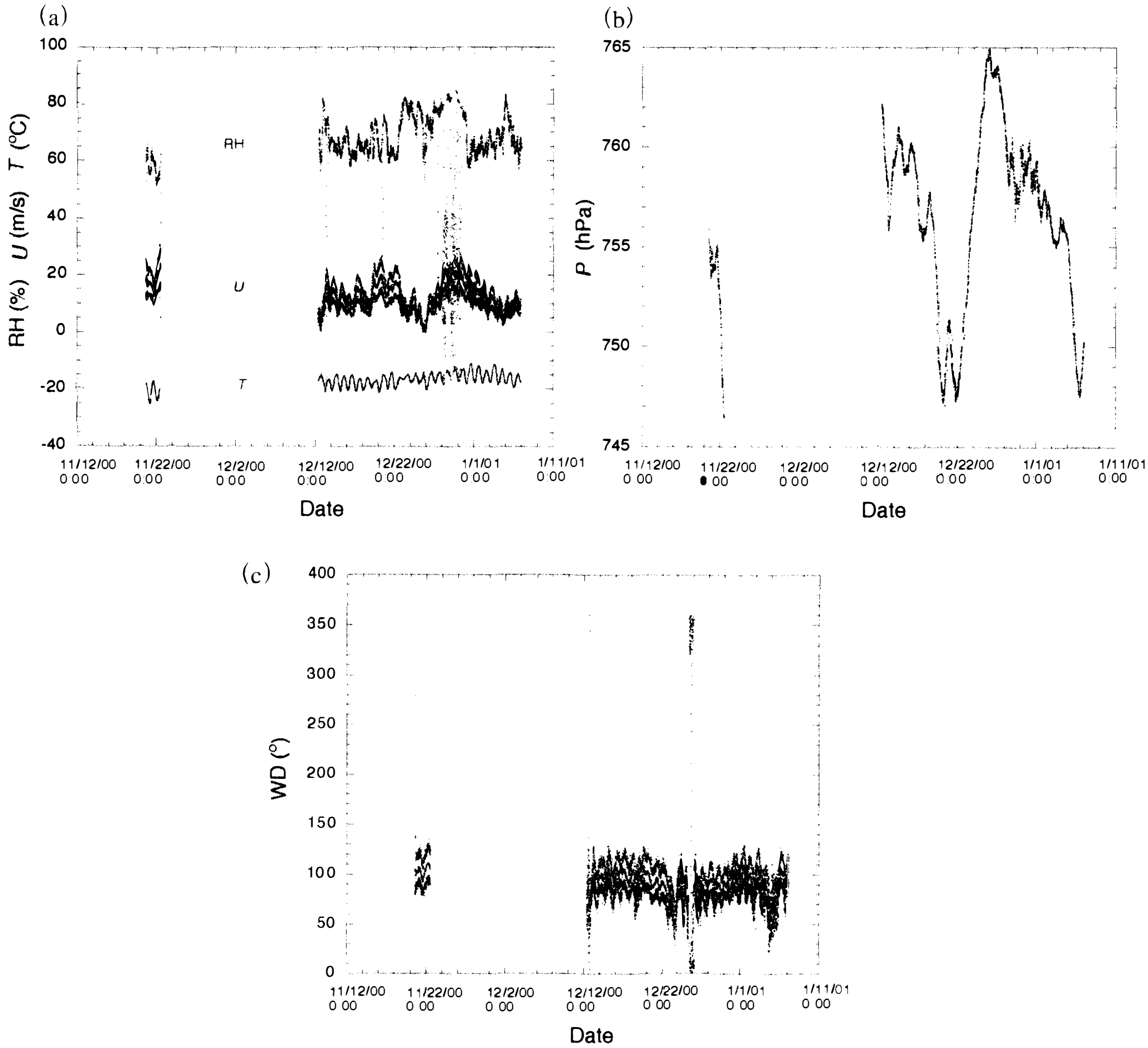

Fig. 17. Measured weather on a bare ice at YM175. The interval for the data record was 10 min. (a) Relative humidity, RH (%), wind speed (maximum, average and minimum), U (m/s) at z = 1.76 m and temperature, T (°C), (b) air pressure, P (hPa), and (c) wind direction (maximum, average and minimum), WD (°). There is a period lacking data due to a low battery.

3.3. Weather

An automatic weather station was set in YM175 in line with GPS measurement. Temperature, wind speed, wind direction (corrected), relative humidity, and total pressure were monitored. Figure 17 shows that eastern winds predominate suggesting a strong katabatic wind.

3.4. Ice sublimation rate

The ice sublimation from the ice surface in the Yamato bare ice areas was measured at 8 sites (Table 3). The measuring method is schematically shown in Fig. 18. We found that 1–4 cm of ice ablated from the bare ice surface (Table 3; Fig. 19). It seems that the rate of sublimation is correlated with elevation above sea level (Fig. 20). If this is the case, the difference of the sublimation rate in the Yamato bare ice field is mainly

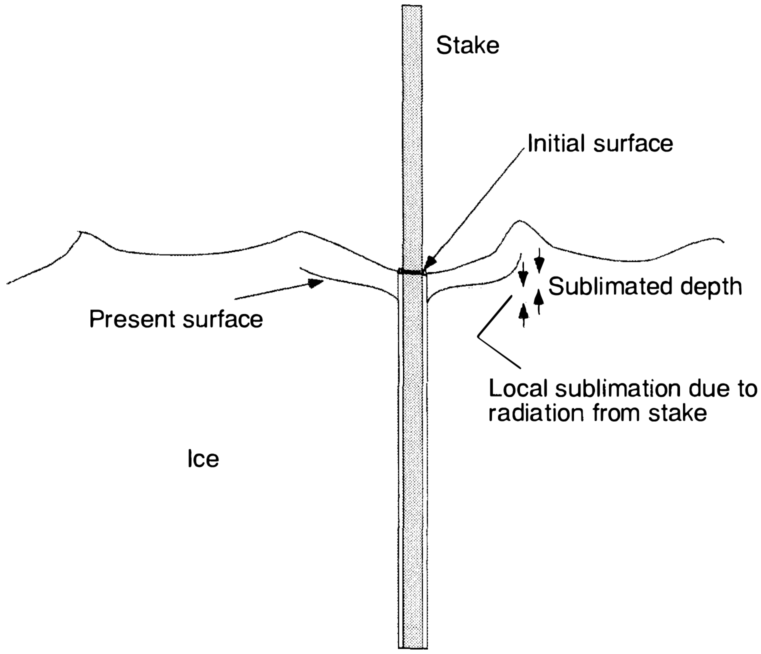

Fig. 18. Schematically shown stake method. As shown in the figure, the sublimation length was measured.

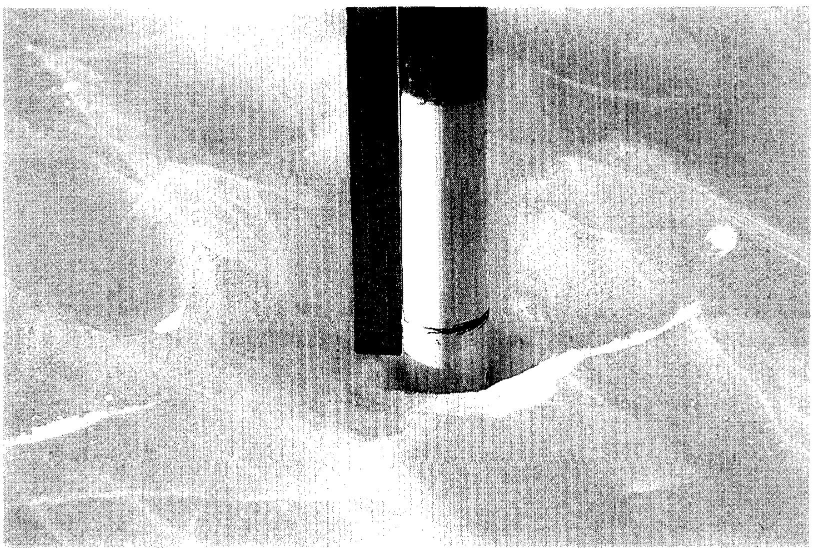

Fig. 19. The stake for ice sublimation measurement at S7. Initial ice surface is marked by a knife. The difference of about 1 cm between the observed ice surface after about 17 days and the mark means that surface ice sublimated.

due to air temperature difference. This also implies that the spacial variation of wind speed is small in this area.

When we focus on the each region, the sublimation of area II is clearly lower than that of the western side (S1 and S2 in Table 3) of the Massif A. It has been known that the meteorite accumulation density of area II is much higher than that of the western side

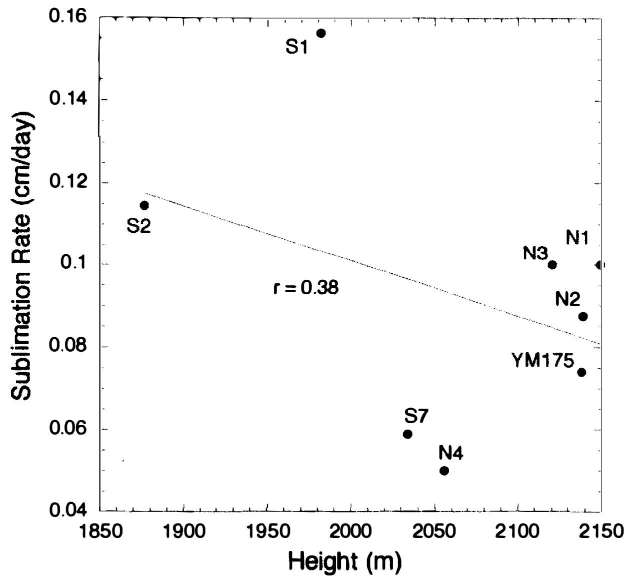

Fig. 20. The ice sublimation rate vs. the height from sea level at 8 sites. It seems that there is a negative correlation between them. The correlation factor r is low to be 0.38.

of the Massif A. Generally it is expected that if the sublimation rate is larger, more meteorites may accumulate. However, the reality is different. This inconsistency may be due to the presence of the accumulation barrier of the Yamato Mountains. Therefore the present data is not inconsistent with the previously proposed meteorite accumulation mechanism (Nagata, 1978; Yanai, 1978).

In addition, the ice sublimation rate at YM175 was independently analyzed using automatically measured weather data and was compared with the stake method. According to the empirical formula method (Fujii and Kusunoki, 1982; Houghton, 1986), the sublimation rate F (mg cm^{-2} d^{-1}) is given by

$$F = C_d\, \rho\, (q_s - q_z)\, U_z,$$

where C_d is an empirical transfer coefficient for latent heat or the drag coefficient, ρ the density of air, q_s the specific humidity at the surface, q_z the specific humidity at height z m (z=1.76 m), and U_z the mean wind speed. ρ and q are expressed in the following equations:

$$\rho = 348.8\, P\ 10^{-6} / (273.15 + t)$$

$$q = 0.623\, p/P,$$

where P the atmospheric pressure, and p the water vapor pressure, and t (°C) the air temperature (Fujii and Kusunoki, 1982). Since the wind speed was measured at the height of 2.72 m, it was corrected to that of 1.76 m taking into account of U_z having a linear relationship with ln z (*e.g.*, Houghton, 1986). While C_d is defined as

$$C_d = (k/\ln\, (z/z_0))^2,$$

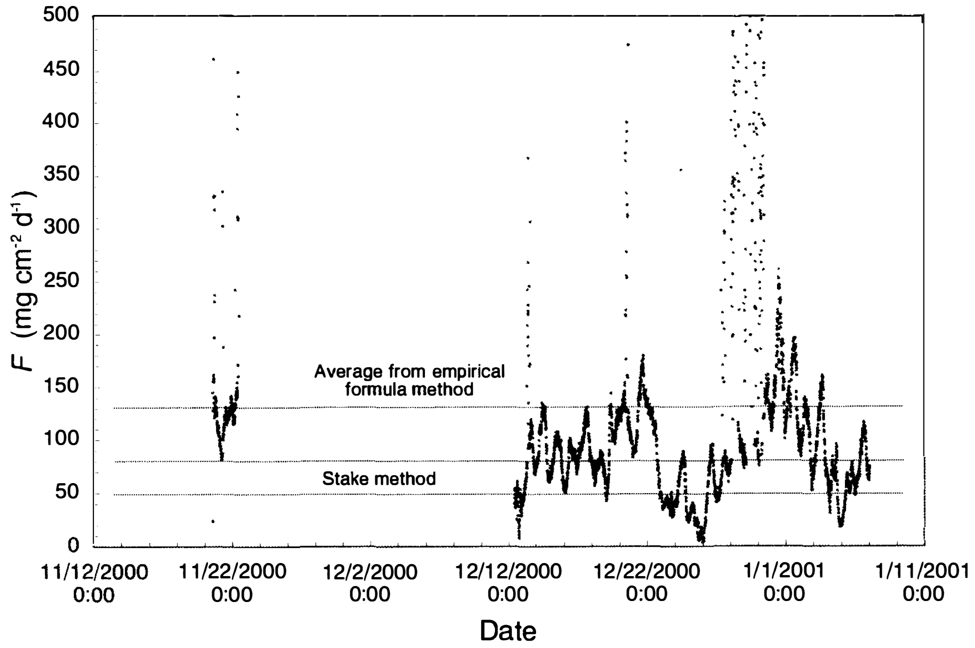

Fig. 21. The sublimation rate calculated from temperature, humidity, and wind speed using the empirical formula method (Fujii and Kusunoki, 1982). The average gives 130.8 mg cm^{-2} d^{-1}. The ice sublimation rate by the stake method gives 50–80 mg cm^{-2} d^{-1} at YM175. The independent two methods yield consistent results.

where k is the von Kármán constant (=0.4), z_0 the roughness parameter, 0.085 cm at the Yamato bare ice field (the west of the Massif F) (Kobayashi, 1979). Then F (mg cm^{-2} d^{-1}) is expressed as

$$F = 5 \times 10^3\ U_z\ (\mathrm{m/s})\ (p_s - p)\ (\mathrm{mbar})\ /\ (273.15 + t).$$

The water vapor pressure at the surface, p_s was calculated assuming that the ice surface temperature equals the air temperature and at the surface water vapor is saturated to the surface temperature. Substituting weather data for this equation, F was calculated. Figure 21 shows the calculated value of the sublimation rate F and the average is 130.8 mg cm^{-2} d^{-1}. On the other hand, the value at YM 175 using the stake method during the same duration as that of meteological observation gives $50-80$ (= 2 ($\pm$0.5) cm/28 days $\times 0.917 \times 10^3$ mg/cm^3) mg cm^{-2} d^{-1} and is nearly consistent with the empirical formula method (Fig. 21). These values are slightly higher than those at Mizuho Station (Fujii and Kusunoki, 1982). Ice sublimation of 6–10 cm/yr has been obtained at the bare ice area around the Yamato mountains using the stake method (*e.g.*, Yokoyama, 1975; Fujii *et al.*, 1986). The sublimation rate measured by us using the stake method at the Yamato bare ice field in the summer season can not be directly compared with those from such a long period.

3.5. Global positioning system

As a result of the detailed analyses of the precise GPS observation at YM175, the derived ice movements are about 3 cm (corresponding to 60 cm/yr) roughly to the west and the upward movement was found to be a maximum about 2 cm (corresponding to 40 cm/yr).

The degree of upward movement is comparable with the sublimation length mentioned above. The result implies that at least during this duration the upward motion is nearly balanced with the sublimation of ice. It is suggested that the upward motion is constant irrespective of seasons, on the other hand sublimation of ice must increase in the austral summer. This might lead to the result that annually bare ice surface at YM175 is slightly rising, but we will need longer observations in order to conclude this. Detailed analytical results of the GPS observations will be reported in another paper.

Naruse (1975) has measured 30 cm/yr ice movement to the northwest, and upward movement to be 8 cm/yr at bare ice area near Motoi-iwa, which have been obtained by measuring over 4 years period. Nevertheless our short period data seems to be consistent with those values. Nishio and Annexstad (1980) suggested that ice sublimation was nearly balanced by the upward motion of ice based on observations at the Allan Hills bare ice field (Nishio and Annexstad, 1980). This result is also consistent with our observations.

3.6. Accidents

We met several accidents during the expedition but fortunately these were not serious. The main accidents are: (1) Just in front of Yamato bare ice on snow surface, meal sledge fell into a hidden crevasse on the YM-route. This was at the entrance to the Yamato bare ice region, corresponding to the transitional region. We were able to recover it after 3 hours and we successfully entered into the Yamato bare ice field. The route around here within several km changed from snow surface to glazed snow surface and eventually bare ice and such areas often feature abundant huge crevasses. (2) On the bare ice region in Yamato, a sledge rolled over twice due to the sharply ridged hard sastrugi and a steep slope.

Acknowledgments

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Appendix. Daily log of the journey.

Date	Staying	Movement (km)	Collected meteorites	T (°C)[1]	Weather	WS (m/s)[2]	Visual field (km)	Comments
27 Oct '00	S16	18.4		-15.5	Cloudy	0	10	Connection of sledges at N16
28 Oct '00	H100	67.4		-20.7	Snow	4	0.8	Lunch at H1
29 Oct '00	H250	79.6		-36.5	Fine	4	30	Lunch at H170/Whiteout
30 Oct '00	Z30	59.4		-25	Snow	14	0.1	Lunch at Z10, 1600 Camp/View 100m/Z20~Z30 second moving
31 Oct '00	Z30	0		-23	Cloudy	4	30	Waiting for departure
1 Nov '00	Mizuho	59.2		-30.2	Fine	6	30	Lunch at Z78'/1600 camp in
2 Nov '00	Mizuho	0		-33.1	Fine	11	0.2	Waiting for departure
3 Nov '00	Mizuho	0		-31.6	Fine	13	0.1	Waiting for departure
4 Nov '00	YM10	24.8		-31	Fine	4	30	Departure at 1530
5 Nov '00	YM40	66.4		-25.2	Cloudy	8	0.1	Route finding of YM40→YM41
6 Nov '00	YM40	0		-22	Cloudy	10	0.1	Waiting for departure
7 Nov '00	YM62	43.9		-25	Slightly cloudy	8	30	
8 Nov '00	YM78	32.3		-19.5	Cloudy	12	2	Afternoon, waiting for departure due to bad weather/Lunch at YM76
9 Nov '00	YM102	48.5		-22	Fair	5	30	Lunch at YM90/Bad surface/Good weather
10 Nov '00	YM128	53.7		-20	Slightly cloudy	6	30	Waiting for departure
11 Nov '00	YM128	0		-23	Cloudy	8	10	Waiting for departure
12 Nov '00	YM128	0		-21.5	Snow	7	2	Waiting for departure
13 Nov '00	YM146	36.4		-25	Cloudy	7	0.2	
14 Nov '00	YM146	0		-20	Snow	7	0.1	Waiting for departure
15 Nov '00	YM146	0		-24	Fine	5	30	Waiting for departure
16 Nov '00	YM146	0		-23	Fine	7	30	Waiting for departure (since noon better weather)
17 Nov '00	C1 (YM168)	47.2	1	-20.5	Fine	11	20	Good weather/Lunch at YM155/An accident in front of YM162
18 Nov '00	C1	0		-20.7	Fair	17	20	Waiting for departure
19 Nov '00	C2 (YM175)	14.4		-18	Fair	16	30	Waiting for departure
20 Nov '00	C2	0		-19	Fine	17	5	Set up of MAWS/GPS
21 Nov '00	C3	23.2	4	-18.8	Fine	12	30	Same position as C13 by JARE-39
22 Nov '00	C3	0		-18.6	Fine	25	0.4	Afternoon, strong and high blizzard/Waiting for departure
23 Nov '00	C3	0		-18.9	Cloudy	18	0.4	From morning strong and high blizzard, waiting for departure
24 Nov '00	C3	0	2	-16.1	Cloudy	18	10	Strong wind/Waiting for departure
25 Nov '00	C3	0		-14.8	Fair	10	10	Strong wind/Waiting for departure
26 Nov '00	C3	22.1	62	-15.3	Cloudy	16	10	Search in north and north west in II
27 Nov '00	C3	12.7	58	-16	Slightly cloudy	9	10	Search in north west in II (afternoon)
28 Nov '00	C3	25	115	-17	Fine	11	30	Search in north west in II [afternoon (1045~)]
29 Nov '00	C3	27	353	-14	Fair	8	20	Search in north west in II
30 Nov '00	C3	0		-13	Cloudy	14	20	Waiting for departure
1 Dec '00	C3	0		-14.7	Cloudy	10	0.2	Waiting for departure
2 Dec '00	C3	0		-16	Fair	12	20	Waiting for departure
3 Dec '00	C3	30.3	349	-15	Fair	9	20	North in north-west part in II (1030~)
4 Dec '00	C3	26.3	75	-16.1	Fair	12	20	North in north-west part in II (1030~1250)
5 Dec '00	C3	0		-15.9	Snow	6	5	Waiting for departure
6 Dec '00	C3	0		-15.5	Snow	8	0.8	Waiting for departure
7 Dec '00	C3	0		-16.5	Fine	12	10	Waiting for departure
8 Dec '00	C3	0		-15.2	Fine	12	30	Waiting for departure
9 Dec '00	C3	45.5	250	-15	Fair	9	30	To north end in north-west in II

[1]Temperature (T) measured by a handy thermometer
[2]Wind speed (WS) measured by a handy anemometer

Appendix. Daily log of the journey (continued).

Date	Staying	Movement (km)	Collected meteorites	T (°C)[1]	Weather	WS (m/s)[2]	Visual field (km)	Comments
10 Dec '00	C3	25.7	15	-16.4	Fine	8	30	To north end through the center of north-west in II (~1230)
11 Dec '00	C4 (YM175)	33.8	38	-16.8	Snow	8	0.8	Connection of sledges/Route finding to the south
12 Dec '00	C4	0		-14.4	Snow	0	5	Battery charging
13 Dec '00	C4	0		-16.6	Fair	12	5	Waiting for departure
14 Dec '00	C5	47.4	32	-12.3	Fine	7	30	Windward of Karigane sunken place
15 Dec '00	C6	35.4	393	-14.4	Fine	11	30	Moraine area of Mt. Kurakake
16 Dec '00	C7	28.6	284	-15	Fine	8	30	Westside of Mt. Kuwagata
17 Dec '00	C7	24.5	262	-15.5	Fine	10	30	North-west end in south of Mt. Kurakake
18 Dec '00	C7	27.3	265	-16	Fair	9	30	South end in south of Mt. Kurakake
19 Dec '00	C7	0		-16	Fine	16	30	Holiday
20 Dec '00	C7	0	2	-14.3	Cloudy	17	5	Waiting for departure
21 Dec '00	C7	26.6	118	-12.8	Slightly cloudy	14	20	South-west end in south of Mt. Kurakake
22 Dec '00	C7	0		-15	Cloudy	10	30	Waiting for departure
23 Dec '00	C7	0	2	-13.3	Cloudy	4	2	Waiting for departure
24 Dec '00	C7	0	1	-13.3	Snow	6	2	Holiday
25 Dec '00	C7	0	1	-11	Snow	3	2	Waiting for departure
26 Dec '00	C7	28.6	149	-13.8	Cloudy	9	10	South of Mt. Kurakake
27 Dec '00	C7	0	5	-13.1	Cloudy	10	0.8	Waiting for departure
28 Dec '00	C7	0		-12.9	Snow	10	0.1	Waiting for departure
29 Dec '00	C7	0		-12.9	Fair	24	0.2	Waiting for departure
30 Dec '00	C7	0	35	-11.7	Fair	10	10	Waiting for departure
31 Dec '00	C8	33.1	253	-9.2	Fine	13	30	
1 Jan '01	C8	0	2	-9.8	Fine	11	30	Holiday
2 Jan '01	C9	33.2	50	-10	Fine	8	30	
3 Jan '01	C9	30.5	23	-8.8	Fine	4	30	Center in north of VII
4 Jan '01	C9	28.5	11	-10.9	Fair	4	30	Center in south of VII
5 Jan '01	C9	18	334	-10.3	Fair	8	30	West of C9/2-Snowmobiles withdrawal on sledge
6 Jan '01	C9	41	5	-10.2	Snow	7	20	Tuitate-rock in Massif C/Rock sampling in Mimi-rock
7 Jan '01	C10 (YM175)	32.6	4	-13.7	Cloudy	8	5	Withdrawal of GPS and MAWS/Rock sampling in Massif A/Snowmobiles withdrawal
8 Jan '01	C10	2.2	0	-13.3	Cloudy	13	0.4	Maintenaince of snowmobiles
9 Jan '01	C10	0	0	-12.6	Cloudy	14	0.1	Waiting for departure
10 Jan '01	YM146	58	1	-15.5	Cloudy	9	0.8	Whiteout
11 Jan '01	YM117	58.7		-15	Fine	7	20	Turning over of a sledge
12 Jan '01	YM99	40.6		-16	Cloudy	7	20	SM107 engine trouble
13 Jan '01	YM68	59.4		-16.1	Slightly cloudy	9	1	Whiteout for a while
14 Jan '01	YM31	77.6		-17.2	Fair	6	20	SM107 engine trouble
15 Jan '01	Z87	80.8		-19.1	Fair	3	30	SM107 recovered
16 Jan '01	Z87	0		-16.9	Fair	2	30	
17 Jan '01	H284	82.9		-15	Fine	8	30	
18 Jan '01	H116	88.6		-7	Fair	4	30	
19 Jan '01	S16	76		-4	Slightly cloudy	5	30	Arrival at 1617
20 Jan '01	S16	0		-3.5	Fine	3	30	Arrangement/First helicopter flight by JARE-42
21 Jan '01	S16	3		-6	Fine	2	30	Deposit of sledges
22 Jan '01	S16	3		-6.6	Fine	4	30	Deposit of sledges
23 Jan '01		0		-11.8	Fine	10	30	Pick up to Syowa Station
Total of collected meteorites			3554					

[1]Temperature (T) measured by a handy thermometer
[2]Wind speed (WS) measured by a handy anemometer