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Review

Antarctic meteorites

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Abstract: Antarctica is currently the most productive region of the Earth for the recovery of meteorites and over 9800 specimens have been found there, most of these since 1969. This material consists of meteoritic fragments representing a much smaller, but unknown, number of distinct meteorites. The particular climatic and environmental conditions of Antarctica result in the recovery of a much larger fraction of the extra-terrestrial material that falls to Earth than would be the case in other regions. Remarkable concentrations of meteorites are found in some 'blue ice' areas resulting from the movement and ablation of the ice. Most meteorites are believed to have been derived from asteroids less then 200 km in diameter. The discovery in Antarctica of meteorites of lunar material proved that other sources are possible. Indeed two meteorites from Antarctica may have come from the planet Mars. Antarctic meteorites have much older terrestrial ages than non-Antarctic specimens and may be used to obtain information on the movement of the ice sheets in the past.

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Introduction

Meteorites are our main source of information about the early history of the solar system; most of them were formed 4.6×10^9 years ago, at about the same time as the Earth. Antarctica provides a large surface area (14×10^6 km^2) for potential meteorite impact and acts as a huge collector, concentrator and preserver of meteorites. The moving ice sheets transport the meteorites that fall upon them to zones of concentration and the cold climate inhibits the terrestrial weathering of the specimens. Only four meteorites had been recovered from this continent before 1969 due, in the main, to the restricted human activity. The first meteorite recovered from Antarctica, the Adélie Land stone, was found on 5 December 1912 by the western sledging party of the Australasian Antarctic Expedition of 1911–14 (Mawson 1915, p. 11, Bayly & Stillwell 1923). It was not until 1961, however, that a further meteorite recovery was made: the Lazarev meteorite was found by a Soviet expedition at the edge of a nunatak at the southern fringe of the Humboldt Mountains (Krinov 1961, Ravich & Revnov 1965). Following this the Thiel Mountains and Neptune Mountains meteorites (Krinov 1962, 1965) were found by American field parties in 1962 and 1964 respectively. These finds seemed to be fortuitous and random and, at that time, no suggestion was made that it might be possible to recover numerous meteorites by systematic searching of pre-assessed areas. The first indication that this was possible came in 1969 when a glaciological field party from the Japanese Antarctic Research Expedition (JARE 10, 1969–70 at Syowa base) recovered nine meteorites in the Yamato Mountains (Queen Fabiola Mountains) area, Yamato 6901 to Yamato 6909 (Yoshida *et al.* 1971, Kusunoki 1975). These stony meteorites were found on a blue ice surface some distance from moraines and rock outcrops and represented five different meteorite types. Clearly these specimens were not the fragments of a single fall and their close proximity suggested that some concentration mechanism was operating. Twelve further meteorite specimens were found in the same area in 1973, eight of these on the same icefield as the 1969 finds. It became clear that certain areas were more suitable than others for the recovery of meteorites and, in 1974, a Japanese field party was organized specifically to collect meteorites. This expedition recovered 663 meteorite specimens, of which 200 were found on the same icefield as the 1969 recoveries. The following year, 1975, a further 308 specimens were recovered, again on the icefield close to the Yamato Mountains. There then followed three seasons of joint Japanese/American expeditions, this time to the Allan Hills area of Victoria Land (Cassidy *et al.* 1977, Yanai 1978; Fig. 1). In this area the three seasons' tally of specimens was 581. During the 1976–77 field season a 407-kg specimen was found, the largest meteorite recovered to date from Antarctica. The specimens found during the joint expeditions were distributed approximately equally between the National Institute of Polar Research in Tokyo and the National Science Foundation of the USA which houses the material in Houston, Texas.

There is now a wealth of experience in analysing satellite

Fig. 1. Recovery of a meteorite specimen during the 1978–79 field season in the Allan Hills region. Dr W.A. Cassidy is holding the field identification counter beside the meteorite. (Photograph by J.O. Annexstad.)

images and aerial photographs of Antarctica to identify surface areas likely to yield meteorites (Fig. 2). Only field activity, however, can determine whether or not the potential source region actually contains meteorites for collection. A significant advantage that the recovery of meteorites in Antarctica has over similar activities elsewhere is that it is possible to collect a much larger proportion of the meteorites that are available over a given area. Perhaps more importantly, some specimens not immediately recognized as meteoritic may be collected and, being unusual, greatly extend the chemical variation seen in meteorites. Further, the ease of recognizing an object quite distinct from the ice facilitates the collection of much smaller specimens than would be the case in non-Antarctic environments (Fig. 3). One exception to this was the recovery of the Revelstoke, Canada, meteorite (Folinsbee *et al.* 1967). The recovery of fragments of this fall totalling about 1 g in weight was only possible because the meteorite fell onto the surface of a frozen lake. It was collected as a dark patch of snow, which, on melting, was proved to contain meteoritic fragments. Although most meteorite recoveries in Antarctica are from ice surfaces there is an increasing awareness that moraines are also a source, but it is much more difficult to distinguish meteorite fragments in this situation. The recovery of meteorites from Antarctica has provided a number of remarkable specimens for study. Not only are the meteorites interesting in their own right but, as it is possible to determine their terrestrial residence time (terrestrial age), they may also provide new information on the age and movement of the ice sheets.

Meteorite recovery localities

Table I lists all of the meteorite recovery sites presently known in Antarctica; most are plotted in Fig. 4. Meteorites are named after the nearest geographical place of fall or find. Obviously, the number of place names available in Antarc-

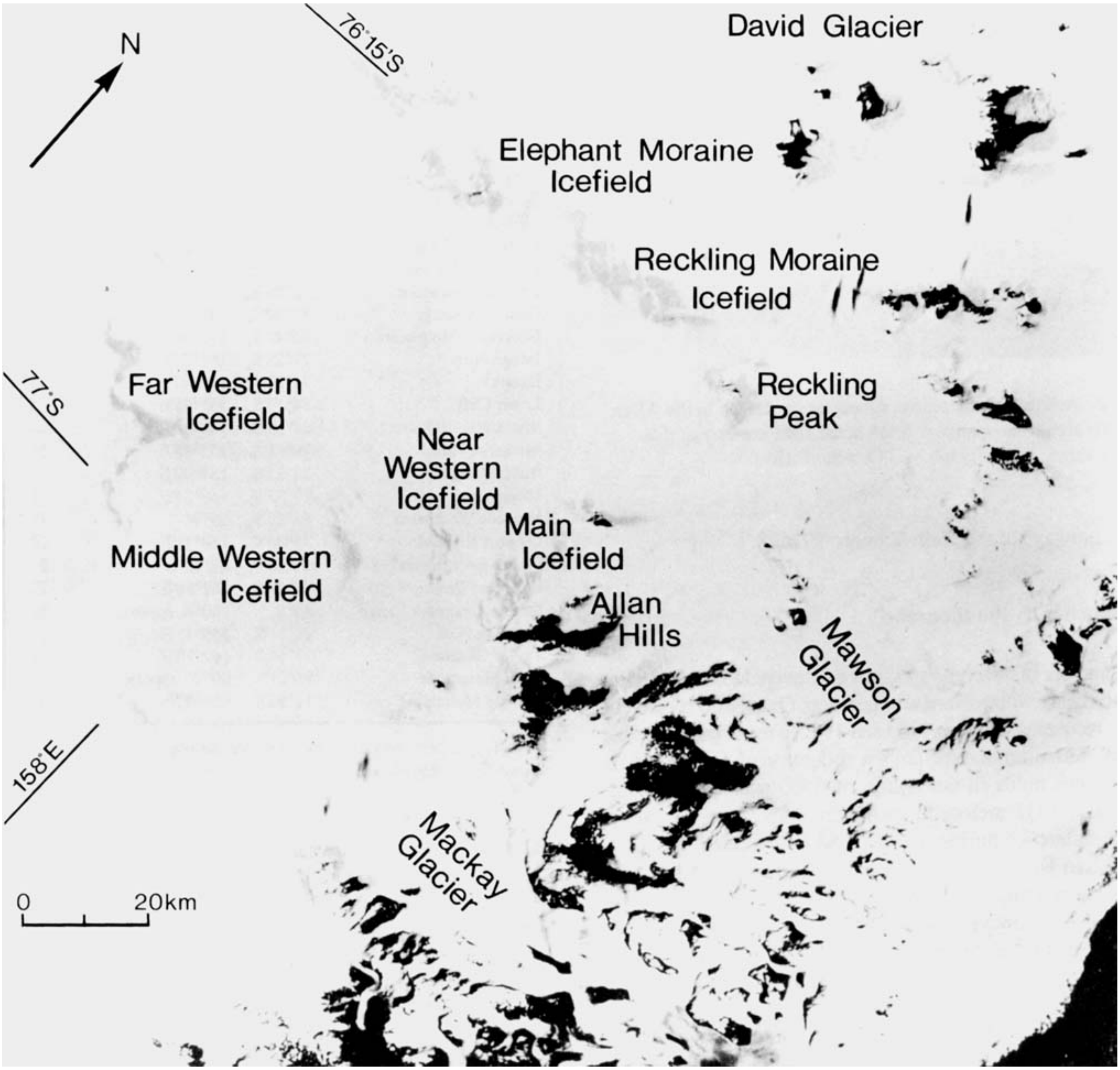

Fig. 2. Satellite image of the Allan Hills region showing meteorite recovery ice sheets. The blue ice areas appear slightly darker than the surrounding snow cover. (Photograph from enhanced image courtesy of the US Geological Survey.)

tica (Alberts 1981) could not possibly allow for each find to be given a unique geographical name, so a different naming system was required. The Meteorite Nomenclature Committee of the Meteoritical Society devised the following system for uniquely identifying the recovered meteorite specimens (Graham 1980). A meteorite name consists of a locality name followed by an expedition letter and then a number, the first two digits of which refer to the December year of the expedition season during which the specimen was collected, thus Allan Hills A77308 is a specimen collected in the Allan Hills area during the 1977–78 field season. A77308 is the 'number' specific to that specimen. The letter A preceding the numbers is to distinguish between the collections of different field parties collecting in the same area in the same year. As it turned out, this complication did not arise so the naming system was modified for the 1982–83 and subsequent field seasons and this letter is now omitted. The name of a specimen from the 1982–83 field season is of the form Allan Hills 82100. The numbering system used for the Yamato specimens never included the field party letter

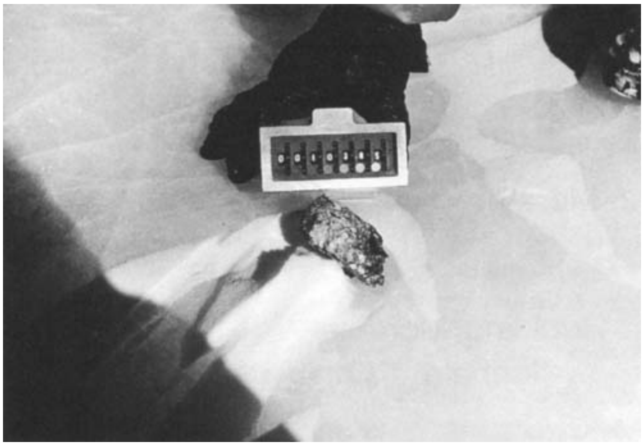

Fig. 3. Achondritic meteorite specimen on the ice in the Allan Hills area. The number 10385 is the field number of this specimen. (Photograph by J.O. Annexstad.)

and is always of the form Yamato 791438.

Table I. Antarctic meteorite recovery localities.

Name	Lat.	Long.	Locality no.
Adélie Land	67°11'S,	142°23'E	1
Allan Hills	76°43'S,	159°40'E	2
Asuka	72°S,	26°E, approx.	3
Bates Nunataks	80°15'S,	153°30'E	4
Belgica Mountains	72°35'S,	31°15'E	5
Bowden Névé	80°05'S,	165°00'E	6
Derrick Peak	80°04'S,	156°26'E	7
Dominion Range	85°20'S,	166°30'E	8
Elephant Moraine	76°15'S,	156°30'E	9
Frontier Mountains	72°59'S,	160°20'E	10
Geologist Range	82°20'S,	155°30'E	11
Grosvenor Mountains	85°40'S,	175°00'E	12
Inland Forts	77°38'S,	161°00'E	13
Lazarev	71°57'S,	11°30'E	14
Lewis Cliff	84°17'S,	161°05'E	15
MacAlpine Hills	84°13'S,	160°30'E	—
Meteorite Hills	79°41'S,	155°45'E	16
Miller Range	83°15'S,	157°00'E	17
Mount Baldr	77°35'S,	160°34'E	18
Neptune Mountains	83°15'S,	55°W	19
Outpost Nunatak	75°50'S,	158°12'E	20
Pecora Escarpment	85°38'S,	68°42'W	21
Purgatory Peak	77°20'S,	162°18'E	22
Queen Alexandra Range	84°S,	160°E, approx.	23
Reckling Peak	76°16'S,	159°15'E	24
Taylor Glacier	77°44'S,	162°10'E	25
Thiel Mountains	85°27'S,	90°W, approx.	26
Yamato Mountains	71°30'S,	35°40'E	27

Locality numbers correspond to the numbered sites in Fig. 4. Not all the localities listed in this table have been plotted on Fig. 4.

Meteorites by the thousand

The number of meteorite specimens recovered from Antarctica is increasing with each new expedition. Over 8800 specimens were recovered between 1969 and 1987, a remarkable number bearing in mind that the largest collection of non-Antarctic meteorites holds in the region of 3500 specimens. Most recently, 1032 meteorite specimens have been recovered from Antarctica during the 1987–88 field season, 692 from the Allan Hills region of Victoria Land and 338 from the Balchen and Nansen areas near the Queen Fabiola (Yamato) Mountains (Yanai *et al.* 1988).

Meteorites that have been seen to fall are distinguished carefully from those that have been found because entry into the terrestrial atmosphere begins a weathering process which, given sufficient time, would ultimately destroy the meteorite. As the specimens are used for chemical studies and represent early solar system materials, it is important to know whether the specimen was seen to fall for, if so, it should have suffered minimal alteration by terrestrial weathering processes. All meteorites from Antarctica are finds and the majority have been affected by weathering to some degree. A surprising number, however, are relatively unweathered and much of the research is concentrated on these samples.

A major difficulty with the assessment of the number of individual meteorite falls represented in the collections from Antarctica is the problem of multiple falls from a single mass which fragmented during passage through the atmosphere. Non-Antarctic meteorites, named after the place of fall or find, can reasonably be distinguished one from another. Thus the Wold Cottage meteorite, which fell in 1795 in Yorkshire, England is quite distinct from the Middlesborough meteorite which fell in 1881 also in Yorkshire, although they are chemically similar. On the other hand a single meteorite fall may be represented by many stones. For example, the L'Aigle meteorite fell in France in 1803 as a shower of 2000–3000 individual stones. Each one of these is part of the L'Aigle meteorite and has the same name. Had this fall occurred in Antarctica, the present system of nomenclature would give each stone a 'name', even though, on entry into the atmosphere, they were all part of the same meteorite. While this is an excellent arrangement for research purposes, because each and every specimen is uniquely identified, it should not be thought that each numbered specimen necessarily represents a single and unique meteorite. There is a wide range in the estimates of the number of distinct falls represented in the Antarctic collections and numbers in the region of 300 to 2000 have been suggested (Scott 1985). One method of estimating the number of distinct meteorite falls represented in the Antarctic collections is to compare the population of non-Antarctic meteorites with that from Antarctica.

The population of non-Antarctic meteorite falls consists of 5% irons, 2% stony-irons and 93% stones (from data in

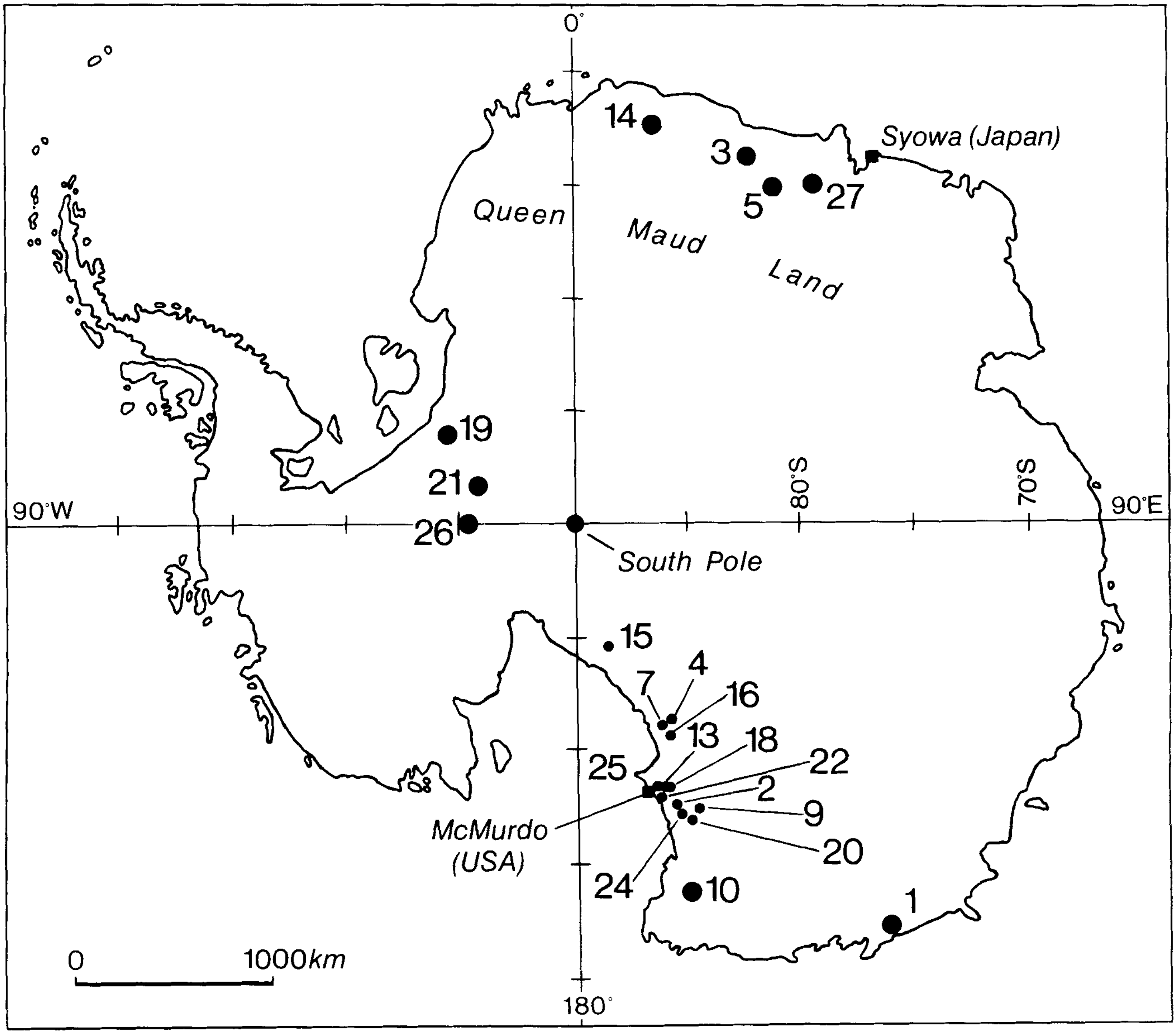

Fig. 4. Map of Antarctica showing meteorite recovery localities. The numbers correspond to the localities listed in Table I; not all the localities listed in this table are plotted.

Graham *et al.* 1985). Twenty-eight distinct irons and 11 distinct stony-irons have been recovered from Antarctica. It is remarkable that the ratio of the number of irons to that of stony-irons from Antarctica (28 : 11) is essentially the same as that for non-Antarctic falls (5 : 2). As these proportions are the same, then 28 irons (5% of the population) should represent 5% of the total number of distinct falls; similarly, 11 stony-irons should represent 2% of the same number. The total number of falls works out at 560 from the irons and 550 from the stony-irons. The possible error in these numbers can be quantified. If, for some reason, seven irons have not been collected, that is instead of 28 irons we should have 35, this would be equivalent to a total number of individual meteorite falls of 700. Similarly, for the stony-irons, if 15 had been recovered rather than 11 this would give a total of 750 individual falls. In this analysis, small changes in the number of iron and stony-iron meteorites found in Antarctica result in significant changes in the estimate of the total number of individual falls represented. It is unlikely, however, that the number of iron and stony-iron meteorites collected in Antarctica under-represent their true abundance by more than a factor of two. Hence an upper limit of about 1000 individual falls may be placed on Antarctic meteorite collections which currently consist of 9877 specimens (Table II).

Table II. Antarctic meteorite find sites, number recovered and dates of recovery.

Year	Locality	Number of meteorite specimens	Search party
1912	Adélie Land	1	Australia
1961	Lazarev	2	USSR
	Thiel Mountains	2	USA
1964	Neptune Mountains	1	USA
1969	Yamato Mountains	9	Japan
1973	Yamato Mountains	12	—
1974	Yamato Mountains	663	—
1975/76	Yamato Mountains	308	—
1976/77	Allan Hills	9	Japan/USA
	Mount Baldr	2	—
1977/78	Allan Hills	310	—
	Purgatory Peak	1	—
1978/79	Allan Hills	262	—
	Bates Nunataks	5	—
	Derrick Peak	10	—
		6	New Zealand
	Meteorite Hills	28	Japan/USA
	Reckling Peak	5	—
1979/80	Allan Hills	55	USA
	Belgica Mountains	5	Japan
	Elephant Moraine	12	USA
	Reckling Peak	15	—
	Yamato Mountains	3676	Japan
1980/81	Allan Hills	32	USA
	Outpost Nunatak	1	—
	Reckling Peak	70	—
	Yamato Mountains	13	Japan
1981/82	Allan Hills	373	USA
	Yamato Mountains	133	Japan
1982/83	Allan Hills	45	USA
	Elephant Moraine	17	—
	Pecora Escarpment	32	—
	Taylor Glacier	1	—
	Thiel Mountains	18	—
	Yamato Mountains	211	Japan
1983/84	Allan Hills	161	USA
	Elephant Moraine	207	—
	Inland Forts	1	—
	Yamato Mountains	42	Japan
1984/85	Allan Hills	265	USA
	Elephant Moraine	9	—
	Frontier Mountains	42	West Germany
	Yamato Mountains	59	Japan
1985/86	Allan Hills	159	USA
	Lewis Cliff	210	—
1986/87	Asuka	3	Japan
	Lewis Cliff	528	USA
	Yamato Mountains	814	Japan
1987/88	Allan Hills	8	USA
	Elephant Moraine	366	—
	Lewis Cliff	297	—
	MacAlpine Hills	21	—
	Queen Alexandra Range	2	—
	Yamato Mountains	338	Japan

Types of meteorites

Generally, the meteorite specimens recovered from Antarctica are of types that are represented in the collections of non-Antarctic material. There are three main groups of meteorites; the irons, the stony-irons and the stones. This grouping follows from the abundance of metallic nickel-iron: the irons usually contain about 95% Ni-Fe, the stony-irons about 50% Ni-Fe and the stones generally contain less than 20%. Most meteorites are believed to have been derived from fragmented asteroids (the parent bodies) and the main groups result from the variation in the distribution of nickel-iron in these objects. The iron meteorites represent core material, one type of stony-iron meteorites represents the core-mantle boundary (the pallasites) and the stony meteorites (the chondrites and achondrites) represent the surface and near surface rocks.

The chondritic meteorites are the most primitive of the stones and are composed of a mixture of silicates, mainly olivine and low-Ca pyroxene, iron monosulphide (troilite) and Ni-Fe metal alloy. They are so-called because they generally contain chondrules, rounded silicate-rich objects usually between 0.2 mm and 2 mm across. These meteorites are breccias consisting of chondrules and chondrule fragments set in a fragmental matrix (Fig. 5a). The achondrites, on the other hand, are very similar to some terrestrial rocks in that they often have igneous textures, the most common type, the eucrites, has a basaltic texture (Figs 5b, 6). Some are shocked and consist of igneous fragments set in an aggregate of mineral shards. Stony-iron meteorites are rare and only four have been recovered from Antarctica. Iron meteorites, however, are more common and have been divided into about 14 different chemical classes, each of which has been derived from a distinct parent body. The internal structure of many of these meteorites (Fig. 7) may be used to obtain a cooling rate for the parent object. This involves studying the composition of the two metal phases, kamacite and taenite, which form from the homogeneous Ni-Fe alloy on cooling below about 700°C. These cooling rates provide information on the size of the parent bodies (asteroids) which are believed to have been between 50 and 200 km in diameter (Narayan & Goldstein 1985). More detailed discussions of the nature of meteorites in general are given in Dodd (1986) and McSween (1987).

Iron meteorites feature abundantly in collections of non-Antarctic meteorites, forming 40% of all finds. In Antarctica it might be expected that the proportion would be similar but this is not so. If it can be assumed that a total of 1000 individual meteorite falls are represented in the Antarctic collections (accounting for the fragmentation of a single fall into many pieces), the proportion of irons is about 2% of this total. This is similar to, but less than, the non-Antarctic fall data, in which 5% of the falls are iron meteorites. There does seem to be a deficiency in the proportion of meteorites which

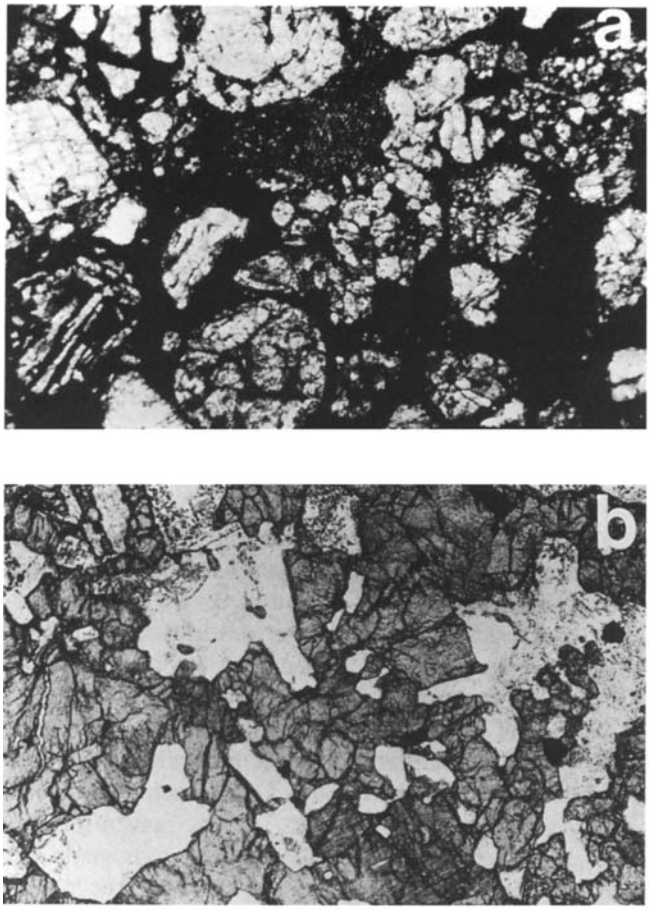

Fig. 5. Photomicrographs, in transmitted light, of thin sections of achondritic meteorites. **a.** The black areas are metal, sulphide and fine-grained matrix. The rounded objects are chondrules. The dominant minerals are olivine and pyroxene. This is a non-Antarctic meteorite, Bovedy. Width of field: 3 mm. **b.** Yamato 82091. The lighter areas are plagioclase and the darker areas are pyroxene. Width of field: 3 mm.

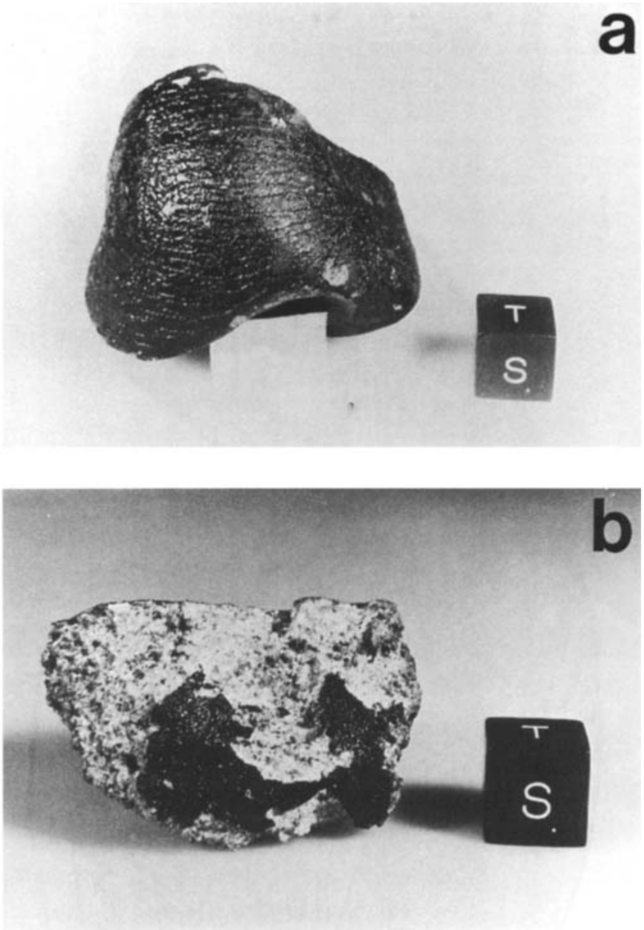

Fig. 6. Achondritic meteorites from the Yamato Mountains area. **a.** Specimen with the glassy fusion crust showing flow lines (Yamato 82082, 662 g). **b.** Weathered specimen with only small portions of the black fusion crust remaining (Yamato 82066, 191 g). Scale for both specimens — cube length 1 cm. (Both photographs courtesy of K. Yanai.)

are irons collected in Antarctica. This may result from the operation of some terrestrial process which acts to reduce the number of iron meteorites available for collection in Antarctic regions. Another possibility is that irons are rarer as falls in Antarctica than in other parts of the world. A further point is that the Antarctic iron meteorites represent a wide range of the more unusual chemical types. They do not, as a population, parallel the distribution of the different chemical classes in the non-Antarctic iron population. This implies that Antarctica is sampling a meteorite flux which differs from that sampled by non-Antarctic areas. A similar suggestion has also been made for the stony meteorites. It has been proposed that there are subtle differences in chemistry between Antarctic and non-Antarctic stony meteorites of the same chemical type. These chemical differences are currently disputed but, nevertheless, the contention is interesting: is the polar region sampling a meteorite population chemically distinct from that sampled by the non-polar regions of the Earth (Dennison & Lipschutz 1987)? However improbable it might seem, if this were the case it might be possible to identify chemical heterogeneity in the meteorite flux reaching the Earth.

Remarkable meteorites from Antarctica

Many of the unusual meteorites from Antarctica are masses of less than 50 g and it is these that have given a new impetus to meteorite research. Fortunately, and largely stimulated by the programme of analysis of the returned lunar samples, it is now possible to obtain information from very small samples, of the order of 50 mg in many cases. Consequently a 20-g meteorite provides an abundance of material for research provided that it is carefully curated.

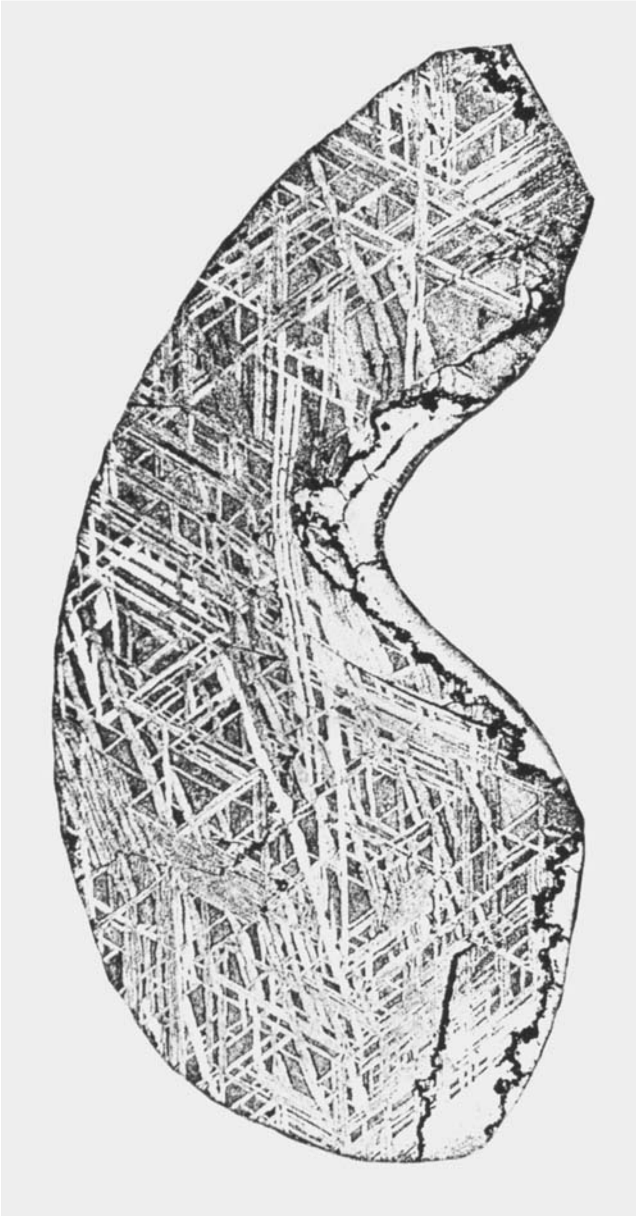

Fig. 7. A polished and etched section of an iron meteorite from Antarctica (Allan Hills A78252, 2.7 kg). The pattern is the Widmanstatten structure formed during cooling of the meteorite within the parent body (asteroid) in space. This consists of two Ni-Fe alloys with distinct Ni contents which have different etching characteristics. Length of specimen 10 cm.

A remarkable discovery among the meteorites from Antarctica was that of six specimens (Table III) which must have come from the moon (Marvin 1983). The lunar meteorites (Fig. 8a, b) are feldspar-rich breccias (anorthositic breccias) derived from the lunar highlands. Their chemical composition indicates not only that they have a source in the lunar highlands but also that they have all come from the far side of the moon, and not from the surface visible from Earth. Although six specimens have been found so far, three of these are from the same fall (Eugster 1988) so only four distinct falls are represented.

Table III. Lunar meteorites recovered from Antarctica.

Name	Weight (g)
Yamato 791197	52.4
Yamato 793274	8.6
Yamato 82192	36.6
Yamato 82193	27.0
Yamato 86032	648.4
Allan Hills A81005	31.4

Note: Yamato 82192, Yamato 82193 and Yamato 86032 are 'paired', that is they are believed to be part of a single fall. They have the same cosmic ray exposure ages and very similar terrestrial ages (Eugster 1988).

Other meteorites have features that are best explained if they were formed on a large, planetary-sized, object. These meteorites are collectively known as the SNC meteorites. They are achondrites typified by the stones Shergotty, Nakhla and Chassigny (hence SNC meteorites). Representatives of this group from Antarctica are, so far, Allan Hills A77005 and Elephant Moraine A79001 (McSween & Jarosewich 1983). As we noted earlier, most meteorites have ages around 4.6×10^9 years and reported ages much less than this are generally caused by shock. Shock may affect the minerals in meteorites and redistribute the radiogenic isotopes used for dating, thereby resetting the radiogenic 'clock'. The age determined in these cases is the time of the shock event and not the time of formation of the meteorite. A few meteorites, the SNC group, have true formation ages between 1.3×10^9 years and 0.2×10^9 years, much younger than 4.6×10^9 years. It is these meteorites that must have formed on planet-sized objects, i.e. those with diameters greater than about 6000 km. Only objects as large as this could have retained enough thermal energy after formation at 4.6×10^6 years ago to melt silicates as recently as 1.3×10^9 years ago. Any smaller body would have cooled far too rapidly. The moon (diameter 3480 km), for example, is too small and the most recently formed lunar rocks have ages of about 2.9×10^9 years. Other chemical evidence strongly suggests Mars as the source for these meteorites and this somewhat far-fetched suggestion was made much more plausible by the recognition of lunar meteorites in the collection from Antarctica. The main difficulty in postulating an origin from a 'planet' had been the requirement to excavate the meteoritic material by impact on the planetary surface and to accelerate it to the required escape velocity. The finding of lunar meteorites in Antarctica indicates that this has certainly occurred on the moon, making the discussion of the dynamics necessary for a Martian origin for some meteorites much more plausible. Consequently, the SNC meteorites are believed to be a source of information about planets in our solar system other than the Earth. Because these

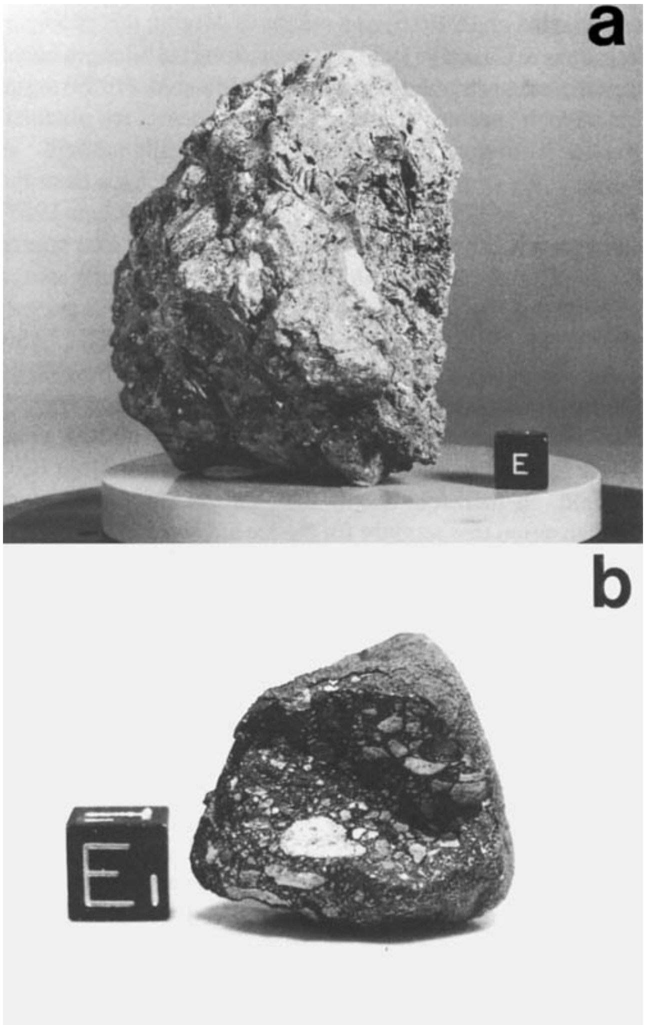

Fig. 8. Lunar meteorites. **a.** Specimen from the Yamato Mountains area, Yamato 86032, 648 g. This is the largest lunar meteorite so far recovered. (Photograph courtesy of K. Yanai.) **b.** Specimen from the Allan Hills region (Allan Hills A81005, 31 g. (Photograph courtesy of NASA.) Scale for both specimens — cube length 1 cm.

meteorites have textures very like those of some terrestrial rocks, they have been recovered from non-Antarctic areas only when seen to fall. However, in Antarctica the conditions for finding meteorites are close to ideal and further types not represented in the existing collections may well be found, thereby adding new insights to the study of the solar system.

Blue ice regions

Meteorites are generally found in 'blue ice' areas of Antarctica, regions where ancient ice has been forced to the surface. According to Lipschutz & Cassidy (1986) the specimens are 'stranded' in places where the forward movement of the ice sheet has been compressively retarded by sub-glacial and/or surface obstructions. Excellent examples of these regions are seen in the two most prolific meteorite search areas, the Allan Hills region (Annexstad 1983) and the Yamato Mountains area (Yoshida & Mae 1978). Although meteorites are predominantly concentrated on these stranding surfaces, several specimens have been located within terminal and radial moraines (W.A. Cassidy, personal communication 1987). Recent recovery parties in the US programme, utilizing detailed search techniques, have been quite successful in looking for meteorites in moraines associated with blue ice fields.

Blue ice is produced by the compression of successive layers of snow which have reached a density of 830 kg m^{-3}. At this density the air spaces between the grains become closed, a process which occurs at a depth of 60–100 m in Antarctica. As the ice moves slowly from accumulation zones towards the sea coast, the flow may be retarded by mountains, nunataks and sub-glacial obstructions. These barriers result in ice upwelling and the surface developing a step-like topography, highly susceptible to ablation by katabatic winds. Regions where meteorites are stranded show compressive retardant flow approaching zero horizontal movement, with an approximate steady-state upwelling/ablation condition of about 5 cm y^{-1}. Surface horizontal data show that ice flow decreases as flow-blocking mountains and nunataks are approached from the plateau side of the continent (Annexstad & Schultz 1983). Further general descriptions of blue ice fields may be found in Bull & Lipschutz (1982) and Annexstad *et al.* (1986).

The surface of the blue ice field is generally rippled with whaleback ridges extending 5–10 cm above the surface and up to 20 cm or more long. An extensive surface crack system aligned along and orthogonally to the direction of ice movement can be seen throughout the field. Dust bands are also commonly visible on the surface of blue ice fields which, if they could be traced, might indicate a source region for the ice (Whillans & Cassidy 1983).

In general, blue ice fields are found both up- and downstream of mountainous regions in Antarctica, in areas where katabatic winds are prevalent. The ice surfaces are swept clean of snow by these winds which also promote ablation (Cresswell 1988) and possibly remove ice by the abrasive action of blown ice crystals (Annexstad 1983).

Meteorites tend to accumulate in basins or regions where the ice field has formed a pocket below a step-like feature which Annexstad (1983) and Faure & Buchanan (1987) believe to be a compressive flow feature produced by a subglacial obstruction. Although these are the regions of highest meteorite accumulation, specimens have been found in blue ice regions that seem to be remnants of past flow regimes (Schutt *et al.* 1983, Delisle *et al.* 1986). Important information missing from the analysis of blue ice fields is the date of formation of the surface ice. It is generally assumed that the stranding surface ice is very old (Cassidy *et al.* 1977, Nagata 1978) but few data exist to show this. Faure & Buchanan (1987) suggest, on the basis of $^{18}O/^{16}O$ ratios, that the ice is old, but there are fluctuations in $\delta^{18}O$ values over short distances. These fluctuations indicate overthrusting and folding of the ice sheet as the flow is retarded and the sheet is compressed. Annexstad (1983), on the basis of $^{18}O/^{16}O$ analyses of surface samples of ice from the Allan Hills area, postulated a number of distinct source regions. While oxygen isotopic data serve to distinguish various ice layers, the relationship between these ratios and the absolute age of the ice is not well defined at present.

Processes of transport and concentration of meteorites

Descriptions of the mechanism of concentration of meteorites by a moving ice sheet were presented by Cassidy *et al.* (1977) and Nagata (1978); Fig. 9. As noted by Drewry (1986), the areas of meteorite concentration are stagnant inter-basin regions found in zones between major outlet glaciers. Actual measurements of the direction, speed and rates of ablation have been reported for the Yamato Mountains meteorite icefield (Yoshida & Mae 1978) and for the Allan Hills icefield (Nishio & Annexstad 1980, Annexstad *et al.* 1983).

An open question relating to ice age, ice depth and the glaciology of the system is that of the origin of the ice in the meteorite concentration region. Studies differ in the estimate of the source of the ice now present in the Allan Hills area. The problem of path length and source regions for stagnant icefields may be a function of each individual area and the characteristics of each icefield. A comprehensive programme of investigation of the Allan Hills icefield has been proposed (Annexstad *et al.* 1986) as a means of solving this problem. Whillans & Cassidy (1983) suggest a long path-length based on theoretical calculations, while Nishio *et al.* (1982) argue for a much shorter path from fabric studies of ice obtained from a 10-m core taken from the Allan Hills icefield. A recent study of the $\delta^{18}O$ values of new surface ice from the Allan Hills and Elephant Moraine (Faure & Buchanan 1987) suggests a nearby source for the Allan Hills and a far source (Dome C) for Elephant Moraine. In the Allan Hills area, a range of $\delta^{18}O$ values was obtained (–34.4 to –43.0 per ml) relative to standard mean ocean water (SMOW). This compares favourably with the range of values previously reported (Annexstad *et al.* 1983). Faure & Buchanan (1987) also note that the $\delta^{18}O$ value of ice (relative to SMOW) was lower for the Elephant Moraine region than the Allan Hills icefield. It therefore seems that, on the basis of a lower condensation temperature for the ice at Elephant Moraine, a long path-length from a Dome C source is indicated. In summary, the oxygen isotopic data indicate both long and short path-lengths in two meteorite collection regions that are fairly near each other.

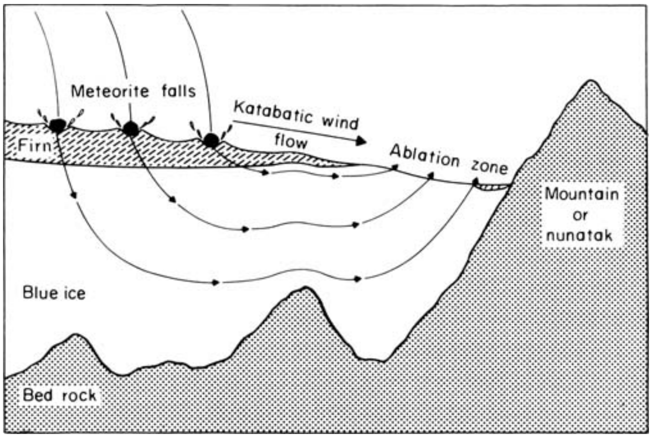

Fig. 9. Diagrammatic illustration of a suggested transport mechanism. The blue ice flows from the centre of the continent carrying a load of meteorites. On meeting an obstruction to this flow, the ice stagnates and is ablated by katabatic winds, leaving the meteorites exposed on the surface.

Terrestrial ages of Antarctic meteorites

The recovery of meteorites worldwide generally occurs within a few thousand years of the fall. The 'half-life' of a stony meteorite for disintegration by weathering in the conditions in the western United States of America is estimated to be about 3600 years (Boeckl 1972). However, the conditions in Antarctica have preserved meteorites for much longer than this and terrestrial ages of meteorites, both irons and stones, of up to 950 000 years have been obtained (K. Nishiizumi, personal communication 1988). Two Antarctic iron meteorites have terrestrial ages of 1×10^6 years (Derrick Peak A78001) and 5×10^6 years (Lazarev) (Nishiizumi *et al.* 1987). These were found, however, on ice-free surfaces and may have a terrestrial history which differs from that of the irons recovered from present-day ice surfaces. Terrestrial ages of meteorites are measured by determining the abundances of radioactive isotopes, for example ^{14}C, ^{26}Al, ^{36}Cl, ^{53}Mn, ^{81}Kr, formed by interaction between the elements in the meteorite and cosmic rays. After capture by the Earth, further production of these isotopes is very limited as the meteorite is then shielded from cosmic rays by the atmosphere and the activity decays. The method of dating and summary of results are reported by Evans *et al.* (1979), Nishiizumi (1984, 1986), and Reedy *et al.* (1983).

The majority of Antarctic meteorite specimens have terrestrial ages between $1–2 \times 10^5$ years (Schultz 1986). Specimens found in the Allan Hills region tend to have older terrestrial ages than those found in the Yamato area (Fireman 1983, Nishiizumi *et al.* 1983, Jull *et al.* 1984). This distinction in age may be accounted for if the Yamato meteorite icefield is either younger than the Allan Hills icefield, or is an area where the ice sheet is only partially blocked. Cassidy (1983) suggests that the icefields on which meteorite concentration occurs are stranding surfaces of varying maturity. It is possible that this maturity could be related directly to the terrestrial age of the specimens. A young icefield, or one that is incompletely blocked and just moving through an area, would tend to flush out specimens with comparatively low terrestrial ages. On the other hand, an icefield that appears blocked completely today may still flush out specimens periodically and thus yield meteorites with old terrestrial ages. Drewry (1986) suggested that meteorites will be lost if the ice sheet thickens over time, resulting in a cut off age for maximum terrestrial residence times in a particular area. Alternatively, specimens do suffer chemical weathering while encased in the ice and this process, albeit slow, may result in destruction of the meteorites in less than 10^6 years. A closer examination of the weathering process of specimens from the Antarctic may shed light on this problem. Gooding (1986), however, found no correlation between the extent of weathering and terrestrial residence ages of Antarctic meteorites. Certainly a major loss of meteorites from Antarctica occurs when ice is lost by the continent to the fringing seas, carrying with it the entrapped meteorites. This could also be a significant factor in the restriction of the measured terrestrial ages to less than 10^6 years.

Curation and distribution of research samples

Since 1977, the finds returned by US sponsored search parties have been carefully collected, stored and curated to preserve their unique condition. The process begins with *in situ* photographic documentation, mapping of the location, collection by specific techniques, and storage/transport while still frozen. The methods (Annexstad & Cassidy 1980) were modelled on the Apollo lunar collection techniques, with subsequent modifications to the basic procedures (Lipschutz & Cassidy 1986). The US effort for curation and distribution of meteorite specimens is a government coalition of three agencies: the National Science Foundation, the Smithsonian Institution and the National Aeronautics and Space Administration (NASA). The lead agency in the curation effort has been NASA through its Planetary Materials Branch, Johnson Space Center, where the lunar samples are also curated. In the laboratory, the Antarctic meteorites have received care and handling similar to, but not exactly like, that given to the lunar samples. Well over 4000 meteorite samples have been distributed for research from the US Antarctic collection to laboratories in 17 countries. In Japan the distribution has been modelled along similar lines (Yanai & Nagata, 1982) and centred on the collection housed at the National Institute of Polar Research in Tokyo.

Specimens found by US field parties are returned to NASA (Johnson Space Center, Houston, Texas) in a frozen state to reduce contamination and to retard chemical weathering. Information about each year's collection, such as characterization, physical features and circumstances of the find, are reported periodically in the *Antarctic Meteorite Newsletter* as well as in the Meteoritical Bulletin (published in *Meteoritics*). Recently, the National Institute of Polar Research, Tokyo, published a comprehensive list of the meteorites curated there which includes a large number of colour illustrations of meteorites from Antarctica (Yanai & Kojima 1987).

Research proposals for the study of specimens in the US collection are periodically reviewed by a committee of peer group scientists called the Meteorite Working Group. A similar committee evaluates proposals for specimens from the collection curated by the National Institute of Polar Research in Tokyo.

The international nature of the scientific effort in Antarctica is well demonstrated by the programmes of research on meteorites. Samples collected by Japanese and American field parties are available to a worldwide community of research scientists. The identification of lunar meteorites is one highlight of the research on meteorites from Antarctica but there are many others providing not only new information on the early history of the solar system, but also a new means of examining the history of ice formation and movement on the polar continent.

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