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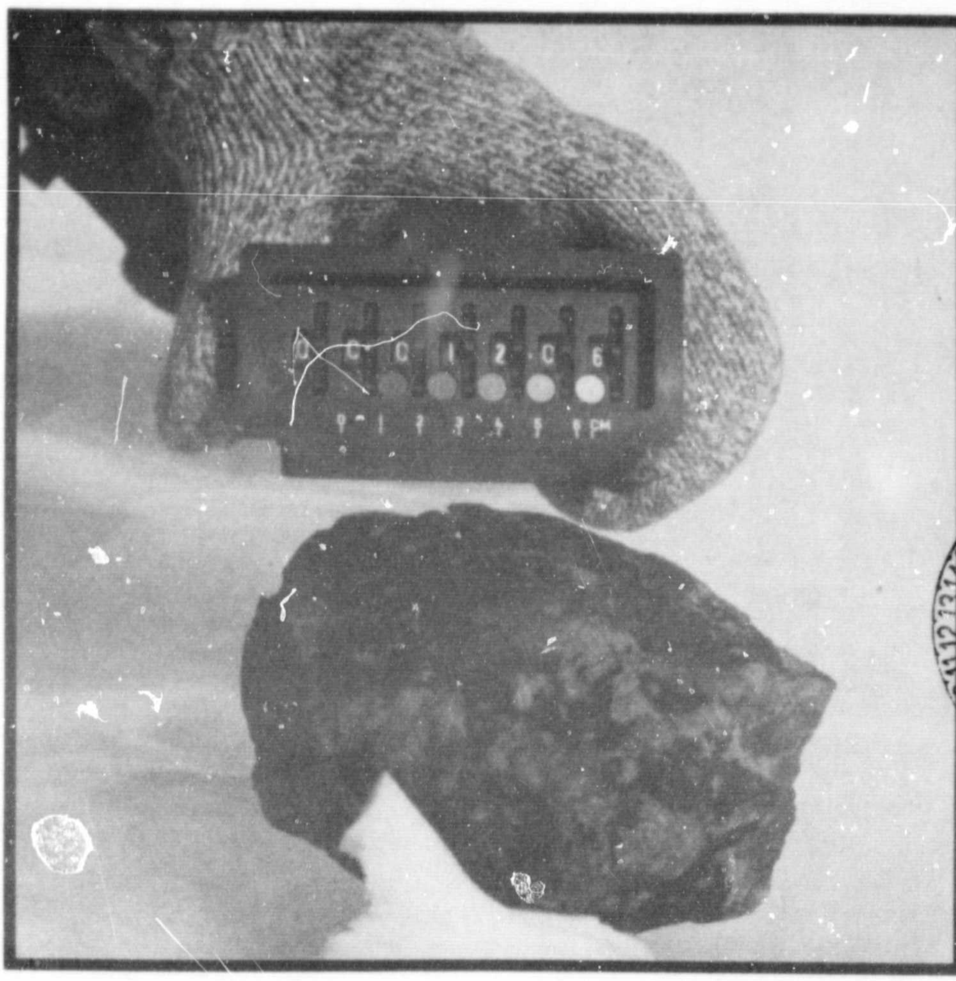
WORKSHOP ON ANTARCTIC GLACIOLOGY AND METEORITES



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LUNAR AND PLANETARY INSTITUTE 3303 NASA ROAD 1 HOUSTON, TEXAS 77058

WORKSHOP ON

ANTARCTIC GLACIOLOGY AND METEORITES

by:
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and
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Sponsored by
The Lunar and Planetary Institute
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Contents

Cover: A three-kilogram achondrite [diogenite] found 300 km northwest of McMurdo near Elephant Moraine [1979–1980 season].

I. Introduction

Early in 1981, the Meteorite Working Group (MWG) of the Lunar and Planetary Institute (LPI) in Houston, a group advising the U. S. National Science Foundation, National Aeronautics and Space Administration, and the Smithsonian Institution, began a review of the U. S. Antarctic Meteorite program. This program is a direct outgrowth of the chance discovery by Japanese scientists in 1969 of remarkable numbers of meteorites on the East Antarctic ice sheet. [A report on that review, "Antarctic Meteorites, An International Resource for Scientific Study," was prepared by MWG (1981) and is available from the Data Center, Curator's Office, Code SN2, Johnson Space Center.] Since 1969, these finds (see index maps, Fig. 1) have been principally in the Yamato Mountains by scientists working with the Japanese Antarctic Research Expedition (JARE) and, since 1976, in the blue-ice areas of the Allan Hills, inland of the Transantarctic Mountains in southern Victoria Land, by scientists of the U. S. Antarctic Search for Meteorites (ANSMET) team. (During the first three years, the ANSMET team included Japanese veterans of the Yamato Mountains searches.)

The review showed the need for advice from the glaciological community on additional sites in Antarctica where meteorites would most likely be present. The MWG also hoped that the study of these meteorites would yield information useful to glaciologists in understanding some aspects of ice sheet dynamics. The beginnings of a dialogue occurred during the Third International Symposium on Antarctic Glaciology (TISAG), held in Columbus, Ohio, in September 1981, at which a few papers were presented on the glaciological framework in which meteorites are found in Antarctica. The formal and informal discussions were extensive and many symposium participants suggested that further examination of the relationships between meteoritics and glaciology might be profitable to scientists working in each field.

Shortly after TISAG, the Director of the LPI prevailed upon us, the co-conveners, to organize a workshop devoted to exploring the interface between antarctic glaciology and meteorites, the former emphasizing the blue-ice areas in Antarctica where most of the meteorites have been found. The purpose of this workshop was to summarize the state of knowledge of meteoritics and glaciology and to suggest future directions for independent or collaborative research. We obtained financial support for the workshop from the LPI and the Division of Polar Programs of the National Science Foundation (NSF). In a preliminary meeting, we, the co-convenors, outlined possible topics for discussion and compiled a list of discussion leaders and other attendees at the workshop. Thirty-six people attended most or all of the workshop; their names and institutional affiliations are given in Appendix II.

The workshop was convened at the LPI. On the mornings of April 19 and 20, 16 presentations of 20–30 minutes each were made, 8 related to aspects of meteoritics or on meteorite-collecting programs in Antarctica, and the other 8 on glaciological considerations (see Program, section II). As expected, there was considerable overlap of interest between the two groups. The afternoons of April 19 and 20 were devoted to discussions of the morning presentations. The morning of April 21 was devoted to further discussions and *ad hoc* attempts to integrate these and define, as closely as possible, the problems and proposed approaches towards their solutions. Although the presentations were quite informal, abstracts from the speakers were distributed at the meeting (Appendix I). [Henceforth, reference to one of these abstracts will be noted as "(Appendix I)." These abstracts include other references and more details can be obtained from abstract authors.]

In some cases, material presented at the workshop was indeed an extension of the abstract; in others, as expected, there were considerable differences between presentations and abstracts. These differences arose partly in response to new information gained by the speakers from previous presentations and from the circulated abstracts, and partly because we had emphasized the informal nature of the presentations, which were given largely as a platform on which to center the discussions and recommendations for future work.

Because the workshop was held in the U. S., most attendees, whether glaciologists or meteoriticists, were more closely allied with the U. S. Antarctic Research Program, or with the meteorites collected from it, than with any other national program. However, the valuable presentations and continued contributions of Prof. Takesi Nagata and Dr. David Drewry gave us the benefit of up-to-date results from the Japanese Antarctic Meteorite Program and the JARE glaciological research program, and of the glaciological and, particularly, the remote-sensing work of the Scott Polar Research Institute group (Cambridge, England), respectively. Prof. Ludolf Schultz of the German Federal Republic had previously participated in various aspects of the U. S. Antarctic Meteorite Program, is actively engaged in the West German Program, and made equally valuable contributions. Often, accounts of research by many other national groups working in Antarctica arose during discussions. Finally, many meteorite chemists had worked with specimens collected in the Yamato Mountains and knew about the glaciological problems in that area. Most attendees at the workshop contributed ideas and questions freely; those who specialized in ice studies realized that they knew little about meteorites, and vice versa. All were prepared to be naive in their questions and insistent on gaining answers free from the jargon of the other science. It was especially gratifying to see how quickly and how well the members of the two communities meshed; in retrospect, additional members of the antarctic geologic community would also have been valuable participants.

In the circumstances of such a rapidly evolving workshop, it is almost impossible to attribute many of the formulations of problems or suggested solutions to individual participants. The meeting, indeed, functioned as a workshop should. All sessions were tape-recorded and the intelligible parts of the tapes were ably transcribed at Purdue University by Ms. Justine Cunningham, with some assistance from others. Transcripts are available from the LPI Publications Office on request.

II. Program

Monday, April 19

Session I

9:00 a.m.

Characterization of Antarctic Meteorites
Brian Mason (presented by Klaus Keil)

Antarctic Meteorites: Some New Problems and Opportunities
W. A. Cassidy

The Japanese Antarctic Meteorite Program—Collection and Curation
*Takesi Nagata and Keizo Yanai

Curation of the U. S. Antarctic Meteorite Collection and some Observations Concerning the Specimens
*D. D. Bogard, C. Scharz, and R. Score

Meteorite Concentration Mechanism Near the Allan Hills and the Age of the Ice
I. M. Whillans

Geography and Glaciology of Selected Blue Ice Regions in Antarctica
John O. Annexstad

Transantarctic Mountains Glacial History—General Problems
Paul A. Mayewski

Radar Sounding of Ice Sheet Inland of Transantarctic Mountains
D. J. Drewry

Session II

1:00 p.m.—2:30 p.m. Tour of the Curatorial Facility at NASA Johnson Space Center, Building 31

3:00 p.m. Discussion of the morning's presentations

Tuesday, April 20

Session III

8:00 a.m.

Petrologic Studies in the Japanese Meteorite Program
Hiroshi Takeda, Keizo Yanai, and *Takesi Nagata

Mineralogy and Petrology of Selected Groups of Antarctic Meteorites
Klaus Keil

Terrestrial Ages of Antarctic Meteorites
*K. Nishiizumi and J. R. Arnold

Weathering Effects in Antarctic Meteorites
Michael E. Lipschutz

Delineation of Blue-Ice Areas in Antarctica from Satellite Imagery
*Richard S. Williams, Jr., Tony K. Meunier, and Jane G. Ferrigno

Glaciologic Notes on the Allan Hills Area
*I. M. Whillans and W. A. Cassidy

Contributions from Oxygen Isotope Studies to Paleoclimatology and the Knowledge of Ice Flow Conditions
P. M. Grootes

Cosmic Dust in Antarctic Ice Cores
*L. G. Thompson and E. Mosley-Thompson

Session IV

1:30 p.m. Discussion of the morning's presentations

Wednesday, April 21

Session V

8:30 a.m. Discussion and Summary

12 Noon Adjourn

*Author to make presentation

III. Discussion

General Significance of Meteorite Studies

Because meteorites "linked" the workshop participants, the value of their study should be summarized; the following excerpt from the MWG (1981) report serves this purpose.

> Meteorite studies constitute an essential part of space science because meteorites include the oldest solar system materials available for research, and they sample a wide range of parent bodies—some primitive, some highly evolved. They carry decipherable records of certain solar and galactic effects, and yield data otherwise unobtainable about the genesis, evolution, and composition of the Earth and other planets, satellites, asteroids, and the Sun. Meteorites also provide an important body of "ground truth," in a chemical and physical sense, critical to interpreting planetary data obtained by remote sensing. Especially advantageous is the fact that meteorites are found on the Earth's surface where they can be studied by the full spectrum of laboratory techniques, from the most simple to the most sophisticated. Recent discoveries demonstrate that Antarctica is a unique collecting ground where large numbers of meteorite fragments can be easily recognized and recovered. Before the discovery of the Antarctic concentrations, only about 2100 different meteorites were known worldwide, and only 5–10 new ones are recovered annually from the rest of the Earth. In dramatic contrast to these figures, thousands of fragments have been collected in the past seven field seasons by United States and Japanese teams in Antarctica (Table 1). These samples are estimated to represent hundreds of discrete meteorite falls.
>
> During the past few years, substantial isotopic anomalies in such elements as oxygen, magnesium, nitrogen, calcium, strontium, titanium, barium, neodymium, samarium, and the noble gases have been identified in portions of several chondritic meteorites. Some of these anomalies apparently reflect processes that occurred prior to the formation of the solar system, such as the possible detonation of a supernova in our vicinity. This event may have injected elements of anomalous isotopic composition into the pre-solar nebula, and may have even have caused the nebular cloud of gas and dust to condense and form the Sun, planets, and moons that now constitute our solar system. Proper interpretation of these isotopic anomalies will lead to better understanding of nucleosynthetic processes and the life and death of massive stars. Some of these anomalies reflect *in situ* decay of extinct radionuclides and provide new data on time scales for solar system formation. They also suggest the possible existence of a heat source in early solar system objects.
>
> Carbonaceous chondrites contain inclusions, highly enriched in calcium and aluminum, that apparently formed at high temperatures during the birth of the solar system. Recently, samples have been identified which may represent the first one percent of the solid matter to have formed in the solar system. Studies of calcium-and aluminum-rich inclusions have provided a strong observational framework for testing theories about the origin of the solar system. Investigations of low-temperature meteoritic materials, some of which contain primordial (perhaps even pre-solar) gases, have shed new light on the later stages of condensation of nebular materials and the accretion of dust and gases into primitive bodies.
>
> Achondritic meteorites have crystalline textures that have long been thought to reflect igneous origins, the details of which were obscure. Comparative chemical and mineralogic studies of these meteorites, lunar rocks, and terrestrial lavas with similar textures suggest an origin in silicate melts that formed in the interiors of parent bodies with compositions like those of ordinary chondrites except for strong depletions in volatile elements. The different varieties of achondrites appear to have crystallized from igneous lavas or subsurface magmas in several different asteroidal parent bodies.
>
> Some stony meteorites are breccias made up of angular fragments embedded in a fine-grained matrix. These meteoritic breccias resemble lunar breccias; both are aggregates of fragmental materials that were crushed and re-cemented by meteorite impacts on the surfaces of atmosphere-free bodies and both are rich in gases implanted by the solar wind. However, meteorite breccias are clearly older and of different compositions than lunar breccias. The meteorite samples preserve a record of

ancient solar winds and flares, and yield information on the evolution of the early Sun. These breccias also preserve a record of an early magnetic field and some of them contain samples of hitherto unrecognized types of primitive mineral associations.

Carbonaceous chondrites, long known to contain many types of organic molecules, have yielded new information in the past few years. The discovery of amino acids of nonbiologic origin in Antarctic carbonaceous chondrites has finally removed all doubts about whether similar molecules in carbonaceous chondrites found on other continents might be terrestrial contaminants. The amino acids may have existed in the primordial solar nebula, or they may have formed during or after the accretion of the carbonaceous chondrite parent bodies, 4.5 b.y. ago. These hydrocarbon molecules in ancient meteorites provide tangible clues to the nature of the organic compounds that were precursors to life.

Some of the simple organic compounds in carbonaceous chondrites are known or suspected to occur in comets. Since radio and microwave studies of interstellar dust also detect molecules like those in comets, a link between these objects is beginning to emerge. In addition, detailed mineralogic investigations of the low-temperature matrix of carbonaceous chondrites, in concert with theoretical studies, have yielded important information on the condensation and evolutionary histories of objects like asteroids and the Earth.

Meteorites constitute a representative sample of objects in earth-crossing orbits, subject to only a small possible bias because small or fragile objects may not survive atmospheric passage. Comparison of reflectance spectra of asteroids with those of crushed meteorites suggests analogies between specific asteroids and meteorite types. Such comparisons of laboratory samples with remote observations should be of tremendous help in designing future missions to asteroids, particularly if a sample return is planned.

The Antarctic Meteorites

As noted (Table 1), four meteorites had been found accidentally in the Antarctic until 1969, when nine were found by a Japanese glaciological party in the blue-ice area of the Queen Fabiola (Yamato) Mountains. From 1969 to March 1982, 4,813 meteorite fragments, representing an estimated 500 individual meteorites, have been found by Japanese parties in the Yamato and Belgica Mountains areas. The U. S. program was initiated in 1976, in cooperation with the Japanese during the first three years. Up to the end of the 1981–1982 field season, a total of 1,187 meteorite pieces had been found, nearly all in the blue-ice areas west (inland side) of the Transantarctic Mountains in southern Victoria Land (Fig. 1).

After meteorites have been collected in Antarctica by Japanese or U. S. parties, they are transported to the curatorial facilities in the respective countries—the National Institute of Polar Research (NIPR) in Tokyo and the NASA Johnson Space Center (JSC) in Houston. At both facilities, samples are characterized (in the U. S., with the help of Brian Mason of the Smithsonian Institution) and processed. A preliminary description of each sample is provided to the scientific community in Newsletter format (Nagata and Yanai, Appendix I; Bogard *et al.*, Appendix I). Requests for samples from interested investigators are evaluated in each country by a group that includes the principal investigator of the collecting team (the MWG in the U. S. and an NIPR committee in Japan). These committees allocate suitable material, if it is available, to any qualified scientist in the world (e.g., Table 2). We do not yet have detailed information from the NIPR in Japan regarding their allocations but they, too, have been most cooperative and generous in providing material for study by interested investigators.

Results of the investigators' research are generally presented at annual Symposia on Antarctic Meteorites at the NIPR in February (the 7th symposium was held in 1982), Lunar and Planetary Science Conferences (LPSC) at JSC in March (the 13th conference was held in 1982), and at Meteoritical Society Meetings held alternately on the American Continent and in Europe in the fall (the 45th meeting was held in St. Louis in September, 1982). Results of their research are generally published in such journals as

Table 1. Antarctic meteorite discoveries

Expedition	Date	Area Investigated (Abbreviation)	Number of Meteorites Found
Mawson (Australian)	1912	Adelie Land	1
Lazarev (Russian)	1961	Lazarev Base	1
U.S. Geological Survey	1962	Thiel Mountains	1
	1964	Neptune Mountains	1
Japanese	1969	Yamato Mountains (Y)	9
	1973		12
	1974		663
	1975 76		307
	1979 80		3671
	1979 80	Belgica Mountains (B)	5
	1980 81	Yamato Mountains (Y)	13
	1981 82		133
Joint United States-Japanese	1976	Mount Baldr (MBR)	2
	1977	Allan Hills (ALH)	9
	1977 78		307
	1978 79	Bates Nunatak (BTN)	4
		Meteorite Hills (MET)	28
		Allan Hills (ALH)	267
New Zealand	1978 79	Reckling Peak (RKP)	5
		Derrick Peak (DRP)	10
United States	1978	Purgatory Peak (PGP)	1
	1979 80	Allan Hills (ALH)	54
		Reckling Peak (RKP)	15
		Elephant Moraine (EET)	11
	1980 81	Allan Hills (ALH)	33
		Reckling Peak (RKP)	67
		Outpost (OTT)	1
	1981 82	Allan Hills (ALH)	373

Geochimica et Cosmochimica Acta and *Earth and Planetary Science Letters* and in the Proceedings of the annual NIPR and LPSC meetings. ANSMET results are also reported annually in the Antarctic Journal of the U. S. A periodically updated Bibliography on Antarctic Meteorites is maintained by the LPI, which can be accessed on request.

Antarctic meteorites have two unique aspects. First, their sheer number and diversity offer greatly expanded possibilities for a more complete sampling of the solar system complex in space and time. Second, they have been preserved in a cold, sterile environment—many for long periods (up to 7×10^5 years). In a presentation at this workshop, Keil described general meteoritic classification and properties. [This was to have been presented by Mason (Appendix I) but circumstances beyond his control presented this.] Later workshop speakers expanded upon the implications of the unique attributes of antarctic meteorites.

Talks by Takeda *et al.* and Keil (Appendix I) focused upon those antarctic meteorites of rare or previously unknown type. Among these are two shergottite-like meteorites which double the size of that rare group of achondrites. Shergottites have startlingly young crystallization ages, only about 1.3 b.y., in comparison with the 4.5 b.y. age of formation of other meteorites. A variety of studies on them are underway by a scientific consortium. The shergottites are of special importance because they represent samples of a planetary object that underwent igneous differentiation only a relatively short time ago. They also are unique among achondrites in being volatile-rich and similar to terrestrial rocks. One of these, EETA 79001, from Elephant Moraine (north of Allan Hills) is the first extraterrestrial rock to show a distinct boundary between two zones that are petrologically quite different. Some investigators have suggested that the shergottites may have come from lava flows on Mars. [Rules for designating each antarctic meteorite are established by the Nomenclature Committee of the Meteoritical Society (see *Meteoritics* **15**, 93–94, 1980). Abbreviations for localities in which meteorites have been found are listed in Table 1.]

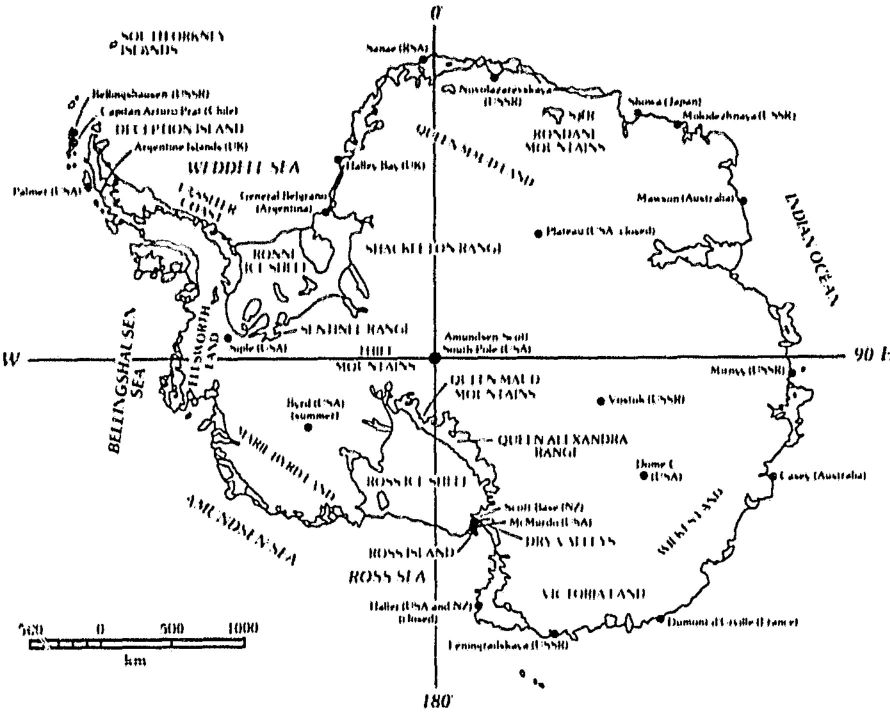


Fig. 1a. Location map of principal physical features and scientific bases in Antarctica (courtesy of National Science Foundation).

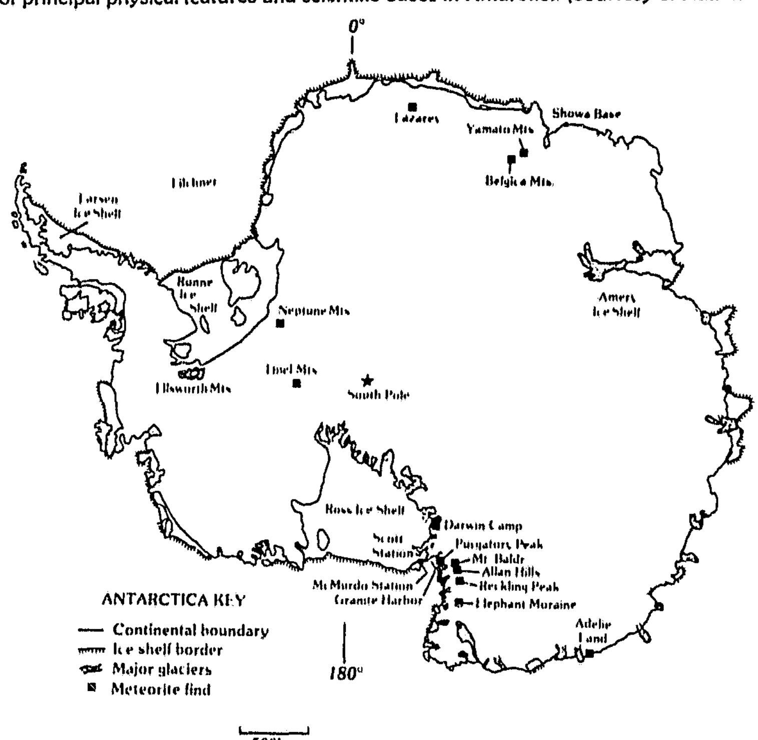


Fig. 1b. Location map of meteorite discoveries in Antarctica.

Table 2. U. S. antarctic meteorite sample distribution as of September, 1982.

Country	Number of Investigators or Research Groups	Samples Allocated
Australia	3	58
Belgium	2	8
Canada	1	5
Denmark	2	5
England	6	70
France	3	18
German Federal Republic	7	83
India	3	11
Japan	3*	21*
Netherlands	1	1
South Africa	2	140
Taiwan	1	7
United States	76**	1343**
TOTAL	110	1770

Notes:
* Does not include 604 samples to Prof. T. Nagata, representing a division of meteorites jointly collected with Japan.
**Does not include 451 samples to Dr. B. Mason for preliminary description.

Large numbers of another achondrite type, the eucrites, have been found in both the Allan Hills and the Yamato Mountains ice fields. These eucrites differ mineralogically and texturally from those found in more northerly latitudes (Keil, Appendix I). Another rare achondrite, ALHA 78113, increases the number of known enstatite achondrites to 10; it also exhibits several unique chemical characteristics. The number of known ureilites has nearly doubled to 15 by the antarctic discoveries (Nagata and Yanai, Appendix I). Among those are two that are relatively unshocked and do not contain the diamonds present in other ureilites; these diamonds were probably formed during a preterrestrial collision that disrupted the ureilite parent object.

Within the past few months, microscopic examinations have revealed tiny vesicles filled with liquid and vapor enclosed within pyroxene crystals in at least one antarctic achondrite, a diogenite. Experiments performed on a heating-freezing petrographic microscope stage show that the contents are probably water vapor and a slightly saline aqueous solution. Calculations indicate that if the fluid inclusions were trapped when the pyroxenes equilibrated (at about 900°C), the pressure of formation may have been about 9 kbars. This entirely new type of evidence suggests that diogenites may be derived from substantial depths within asteroidal or moon-sized bodies.

A meteorite which fell in Acapulco, Mexico in 1976 represented a unique chondrite in the world's collections until a virtually identical meteorite was recovered during the 1978–1979 antarctic field season. This illustrates again the potential of the antarctic collection to alter substantially our view of meteorite statistics. In more temperate regions, carbonaceous chondrites are infrequent, only about two dozen being known. Over forty carbonaceous chondrites have already been recovered from Antarctica and many more are thought to be among the thousands of fragments recently collected and still awaiting definitive classification by Japanese scientists (Nagata and Yanai, Appendix I). Large numbers of unequilibrated ordinary chondrites have been recovered very recently, nearly doubling the number previously known. Such chondrites are extensively studied because they are extremely primitive and undoubtedly contain a record of primary nebular condensation processes, unaltered by secondary thermal events (Takeda *et al.*, Appendix I; Keil, Appendix I). The Antarctic finds include several LL chondrites that apparently were unusually heavily shocked (Takeda *et al.*, Appendix I).

The second known diamond bearing iron meteorite, ALHA 77283, has been found in Antarctica. Unlike the first such meteorite, Canyon Diablo, in which diamonds were formed by shock waves during the impact that excavated Meteor Crater in northern Arizona, the antarctic iron meteorite is a small specimen with a heat altered surface zone, indicating that it decelerated in the atmosphere and made a soft landing. The diamonds in the antarctic iron were probably formed from graphite by shock waves generated during the preterrestrial breakup of the parent body. Keil (Appendix I) also drew attention to a unique mesosiderite, RKPA 79015.

The second unique feature of antarctic meteorites is their relatively old terrestrial ages. Only a few studied so far fell to Earth less than 10,000 years ago; most fell between 30,000 and 400,000 years ago, and at least one has been on and/or in the ice sheet for 700,000 years (Nishiizumi and Arnold, Appendix I). For example, histograms of ^{36}Cl contents in antarctic and non antarctic meteorites show significant lowering in antarctic samples, consistent with terrestrial ages comparable to the ^{36}Cl half-life of 3.1×10^5 years (Fig. 2). Such displacement is less severe in the case of ^{26}Al, which has a half life of 7.3×10^5 years (Fig. 3) and virtually disappears when contents of ^{53}Mn, with a half life of 3.7×10^6 years, are compared (Fig. 4).

It is probable that at least some parts of the antarctic continent were covered with ice for 10^6 years or more; some meteorites may be found that have terrestrial ages approaching this, i.e., that fell over a million years ago. In contrast to the long residence times already measured on antarctic specimens, the great majority of meteorites collected on other continents fell within the past 200 years, with only a few going back some tens of thousands of years. The antarctic meteorites that collided with the Earth hundreds of thousands of years ago are uniquely appropriate for research into possible changes through time in the types of materials perturbed into Earth crossing orbits and in the strength of the cosmic ray flux, which produces measurable radiation effects in meteorites during their flight through space.

The samples also contribute new information for the study of the dynamics of the antarctic ice sheet. The oldest antarctic meteorites probably provide a measure of the minimum age of the portions of the ice sheet on which they are found. For example, Nishiizumi and Arnold (Appendix I) report that samples having long terrestrial ages, i.e., $> 2 \times 10^5$ years, seem to be closer and are aligned parallel to the Allan Hills barrier to ice flow. This is consistent with long stability of the ice sheet and with conventional views of the ice dynamics in such situations; younger samples show no particular trend (Fig. 5).

Despite their long terrestrial ages, the interiors of many fresh-looking antarctic meteorites escaped the weathering process, presumably by being frozen into the ice and protected from atmospheric oxidation (Lipschutz, Appendix I). For example, Nishiizumi and Arnold (Appendix I) find no correlation between weathering type and terrestrial age (Fig. 6). Trace element analyses of many ancient antarctic meteorites yield essentially identical results with those of newly fallen stones collected in other regions. Thus, contrary to some expectations, antarctic specimens can provide highly reliable data on major, minor, and trace element chemistry (Lipschutz, Appendix I).

The Glaciological Background

Over very nearly all of the antarctic ice sheet, the annual snow accumulation exceeds the local losses by wind deflation, melting, and sublimation, so that the surface remains snow-covered. A vertical profile here

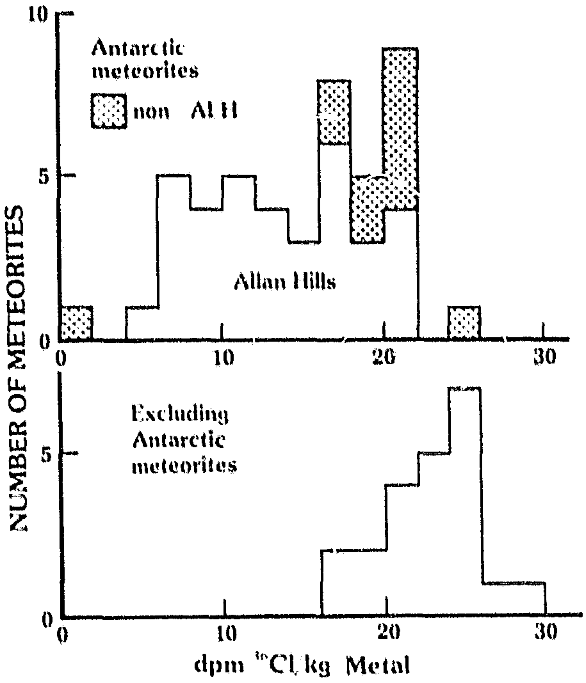


Fig. 2. A histogram of the ^{36}Cl contents of antarctic (preliminary values) and non antarctic meteorites. This clearly indicates that the distribution of ^{36}Cl contents of antarctic meteorites is shifted toward lower values due to long terrestrial ages. ^{36}Cl is one of the most suitable isotopes for terrestrial age determination in antarctic meteorites because of its half life of 3.1×10^5 years. The antarctic meteorites that are not Allan Hills meteorites have shorter terrestrial ages (courtesy of Nishiizumi and Arnold, Appendix I).

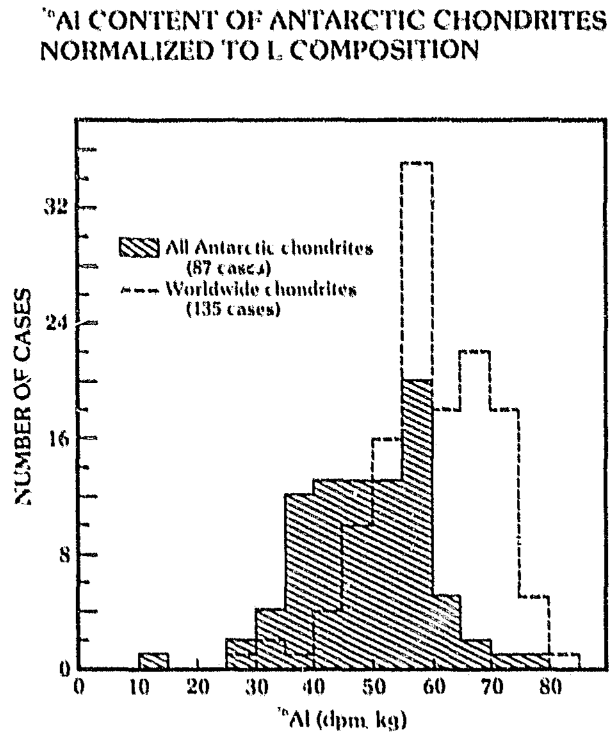


Fig. 3. A histogram of the ^{26}Al (half life, 7.1×10^5 years) contents of antarctic and non antarctic chondrites. The data are normalized to the L chondrite chemical composition. This histogram indicates that the distribution of ^{26}Al contents of antarctic meteorites is slightly shifted toward lower values due to the older terrestrial ages of antarctic meteorites (courtesy of J. C. Evans).

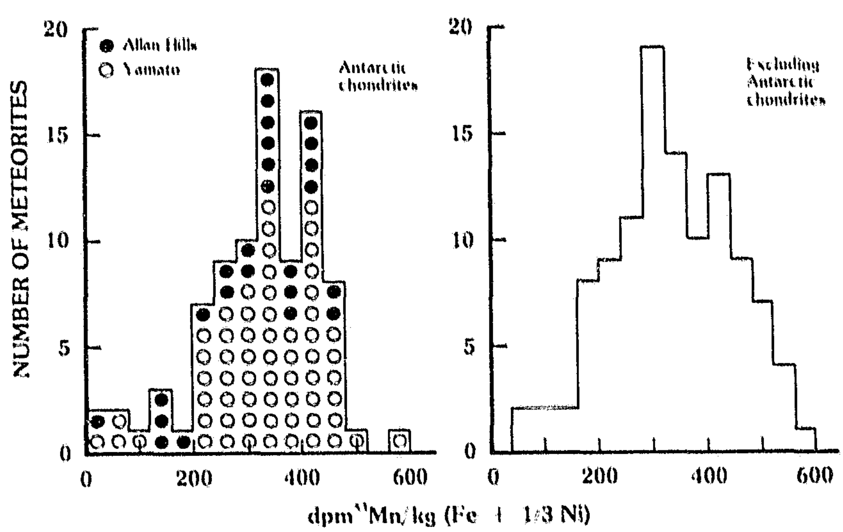


Fig. 4. Comparison of the ^{53}Mn contents of ordinary chondrites from the Yamato Mountains (Y) and Allan Hills (A), to the left. The ^{53}Mn distribution in ordinary chondrites from other parts of the world is shown to the right. The values have not been corrected for undersaturation. The histograms indicate that the terrestrial ages of antarctic meteorites are usually much less than the half-life of ^{53}Mn, 3.7×10^6 years (courtesy of Nishiizumi and Arnold, Appendix I).

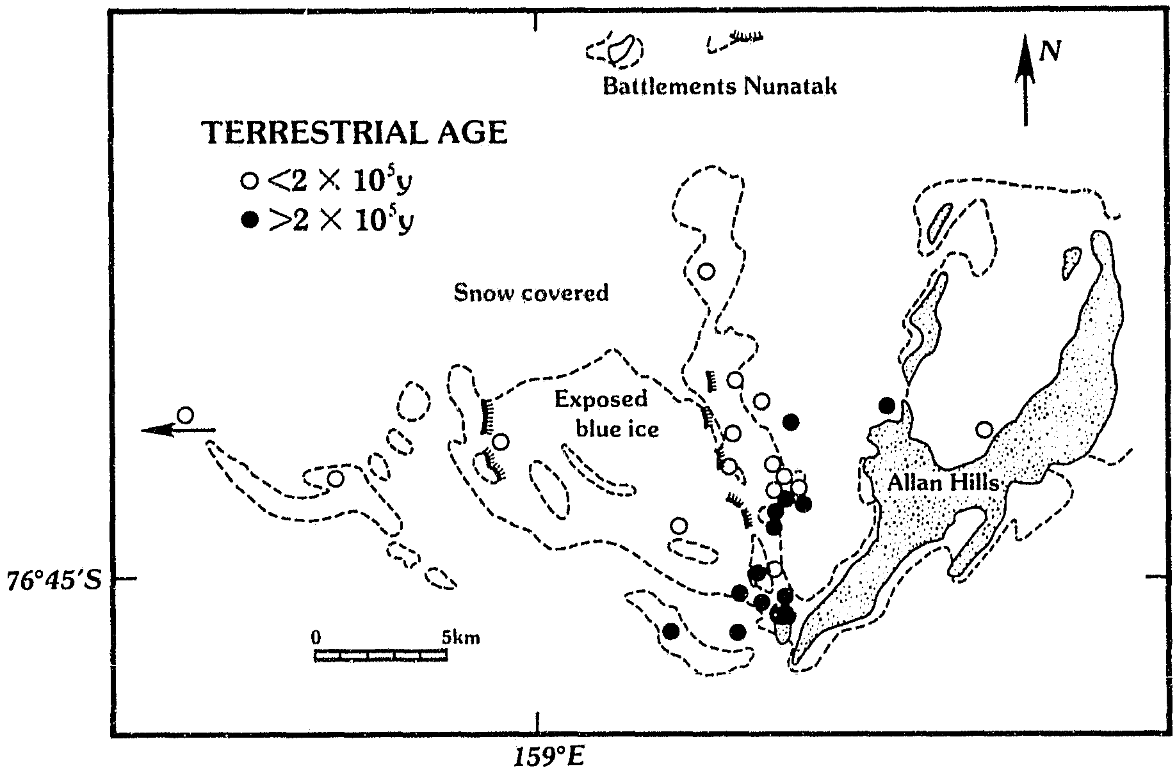


Fig. 5. Correlation between sample locations and terrestrial ages of Allan Hills meteorites. The terrestrial ages are separated into two groups, less than 2×10^5 years (open stars) and more than 2×10^5 years (filled stars). Ice motion is generally from upper left to lower right (courtesy of Nishiizumi and Arnold, Appendix I).

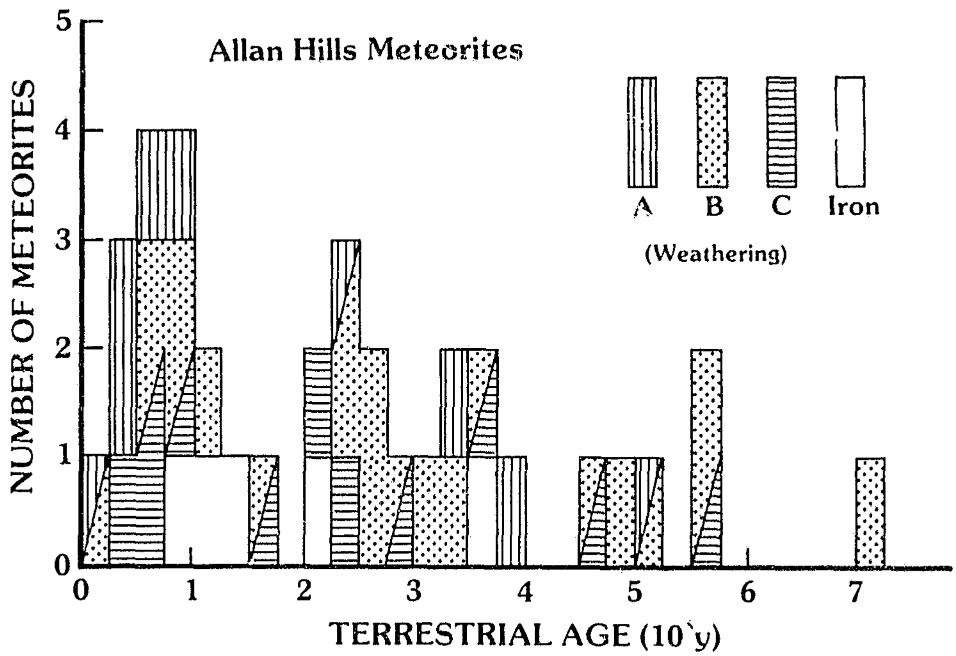


Fig. 6. Terrestrial ages of 36 Allan Hills meteorites (preliminary results) and weathering. There appears to be no relationship between these properties, indicating that meteorites' weathering time on the ice is not related to their terrestrial ages (courtesy of Nishiizumi and Arnold, Appendix I).

would show a stratigraphic succession of annual layers, with density increasing downwards, the result of slow metamorphism of snow into ice in the low temperature regime. At a depth that depends on annual accumulation and air temperatures, typically 100 m, the entrapped air bubbles become sealed and the material is termed "ice." Most of the ice losses from the continent are in the form of icebergs calving from ice shelves and also from outlet glaciers that drain the ice sheet directly to the oceans. The ice shelves are themselves fed mainly by numerous outlet glaciers. Around the coasts, generally near sea level, are found ablation areas where local losses are greater than accumulation, but which probably do not exceed two percent of the total ice-covered area. Overall, the ice sheet is thought to be approximately in balance, with the total snow accumulation over the continent being about the same as the sum of the local losses and the iceberg flux.

In a few inland areas, most of them in or near the fringing mountains of East Antarctica and the Transantarctic Mountains, local conditions are such that ablation losses, mainly by sublimation, exceed the local snow accumulation and apparently have done so for a very long time. In some of these areas, because of physiographic conditions that hinder or limit forward movement of material from the inland parts of the ice sheet, the continued ablation has removed all of the snow and the bare ice exposed at the surface is that previously buried deeply in the ice sheet. From the dominant color, these exposed regions are called blue-ice areas, and it is in them that the conditions for meteorite-collecting mechanism(s) exist.

Thus far, little glaciological work has been done in the very interesting areas of Victoria Land where meteorite accumulations have been found (Mayewski, Appendix I). Lines of markers for surface movement and strain measurement have been established (Annexstad, Appendix I); some plots have been made showing surface form and detailed positions of meteorite finds (Cassidy, Appendix I). In southern Victoria Land, some airborne radio-echo sounding profile lines have been flown in the general area, but not close enough to the Allan Hills to be very useful (Drewry, Appendix I). A few measurements of stable oxygen isotope ratios on surface ice samples have been reported (Grootes, Appendix I) and some studies have been undertaken of ice fabric and bubble orientation in other surface ice samples (Nishio *et al.*, 1982; Whillans and Cassidy, Appendix I). The occurrence of blue ice, the result of negative balance in that area, is a necessary condition for meteorite collection, but so is the existence of a barrier to forward ice movement (Fig. 7). Thus, while blue-ice areas also exist down-glacier from the Allan Hills and other outcrops in the David Glacier system, no meteorites have yet been found on them. In the Allan Hills, the barrier to ice flow is nearly complete; in the Yamato Mountains, it is only partial. This difference may explain the apparent difference in terrestrial ages of the meteorites in the two areas; those from the Allan Hills are, on average, considerably older than those from the Yamato Mountains blue-ice region (Fig. 2). Alternatively, the part of the ice sheet inland from the Transantarctic Mountains may have remained in equilibrium at about its present regime for times much longer than did the ice sheet in the Yamato Mountains area.

From the workshop presentations and discussion, the following seem to be the problems most worthy of fuller attention:

(i) Mechanism of concentration of meteorites in blue-ice zones of eastern Antarctica

Studies of the mass and energy balances in a few areas elsewhere in Antarctica, where most of the ablation is by sublimation, are fairly complete; Yamanouchi *et al.* (1982) made the sole study in one of the main meteorite-collecting areas, and this was of the radiation balance. From a detailed study of the crystal size and fabric of samples collected near the surface in the Allan Hills blue-ice zone, Nishio *et al.* (1982) proposed a mechanism for accumulating meteorites in this area. Following conventional glacier dynamics, Nishio *et al.* suggested that the oldest ice outcrops occur at the surface closest to the Allan Hills. They concluded from fabric studies that the ice here could not have been buried much greater than 500 m and that

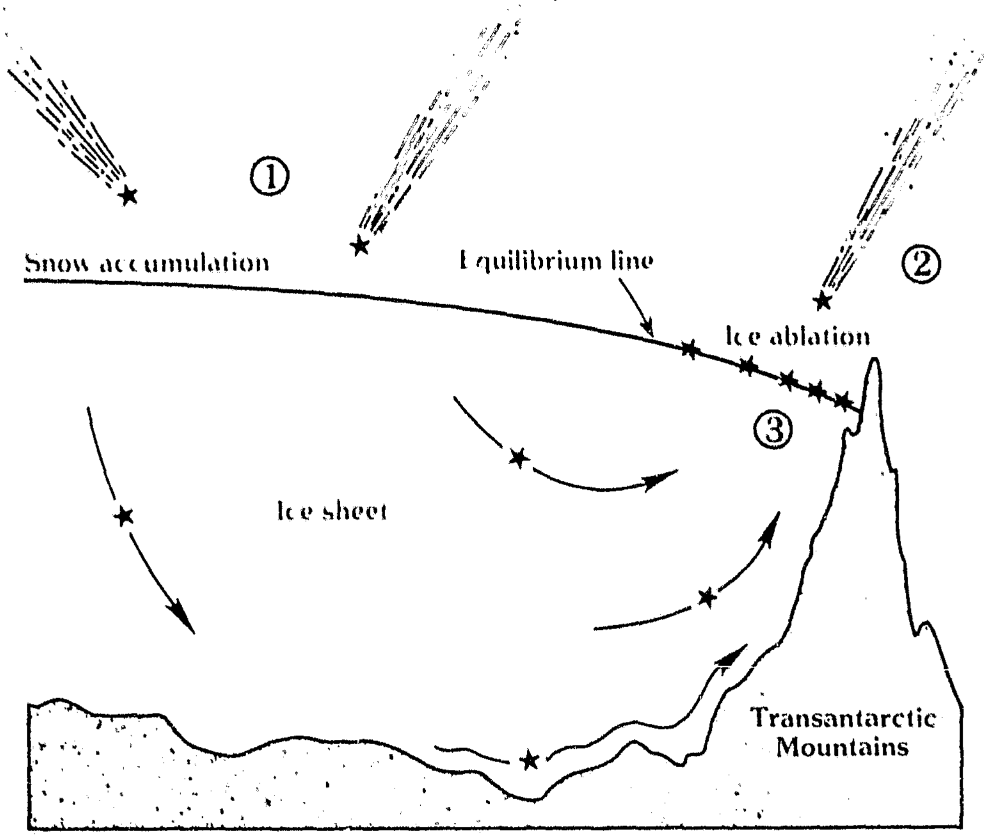


Fig. 7. Meteorite concentration mechanisms into blue ice areas according to the model of Whillans and Cassidy (Appendix I). The processes shown are: (1) meteorites fall into accumulation zone and are transported to ablation zone; (2) meteorites fall directly onto ablation zone; (3) compressive ice flow "crowds" meteorites together.

the ice now on the surface is not more than about 20,000 years old. This is significantly less than the age of the ice near the bottom of the ice sheet near Dome C in East Antarctica, estimated in several models to be perhaps 500,000 years; according to conventional glaciology models, this should also be the age of the ice outcropping at the Allan Hills. Their estimated age of 20,000 years for the ice (Nishio *et al.*, 1982) is consistent with the minimum terrestrial age of meteorites found in that area, but is significantly less than the oldest terrestrial age yet determined for a meteorite from the Allan Hills, 7×10^5 years. They suggest that the maximum terrestrial age of Allan Hills meteorites could indicate a time when the ice sheet began to recede from the Allan Hills and become stagnant. From their estimated maximum age for the ice and measured surface velocities, Nishio *et al.* calculate that the catchment area for meteorites accumulated near the Allan Hills is only 500 km and extends only 40 km up-glacier. Using the current best estimate for the meteorite influx rate, one meteorite/10^6 km^2 year, this gives an expected total number of meteorites much smaller than has been found. Nishio *et al.* suggest that the meteorite catchment area was expanded during a previous ice age and/or that a correction factor is needed for the meteorite infall flux.

Whillans and Cassidy (1982 and Appendix I) also propose a meteorite concentration mechanism based on conventional ice flow concepts, with the oldest ice, nearest the Allan Hills, being about 6×10^5 years and having originated several hundred kilometers inland. They postulate that the glacier regime has been more or less constant during that time so that steady-state conditions may be assumed. Many assumptions and conclusions of their model can and must be tested.

Whillans and Cassidy (Appendix I) identify three mechanisms that concentrate meteorites into a blue-ice area such as that near the Allan Hills. First, meteorites fall (at an assumed constant flux) into the accumulation zone and are buried. These are carried along by the ice and reappear, by ablation, in the blue-ice area (Fig. 7). Second, other meteorites fall directly in the ablation zone and remain relatively close to the surface. Finally, surface areas of the ablation zone (e.g., Fig. 8) show compressive flow (Nishio *et al.*, 1982), so that by whatever mechanism meteorites arrive on the ablation zone surface, they will be crowded together by horizontal compression.

The rate of surface concentration is

$$\frac{dM}{dT} = \gamma A_b + f \quad \epsilon_s M$$

where M is the meteorite concentration; γ is the meteorite flux, f, divided by the accumulation rate, A_c, in the accumulation zone; A_b is the ablation rate in the ablation zone; and ϵ_s is the surface (area) strain rate. Both A_b and A_c are assumed constant across the respective zones. This simple model of ice flow (Fig. 8) predicts variations of meteorite concentration and age of the surface ice with the distance from the barrier, e.g., the Allan Hills (Fig. 9). If the ice flow was and is as simple as implied by Figs. 7 and 8 so that no overthrusting occurred, a horizontal traverse from the equilibrium line (assumed constant in position) to the nunataks should offer a continuous exposure of ice of increasing age, i.e., be equivalent to a vertical section through the ice sheet higher (farther inland) in the accumulation zone.

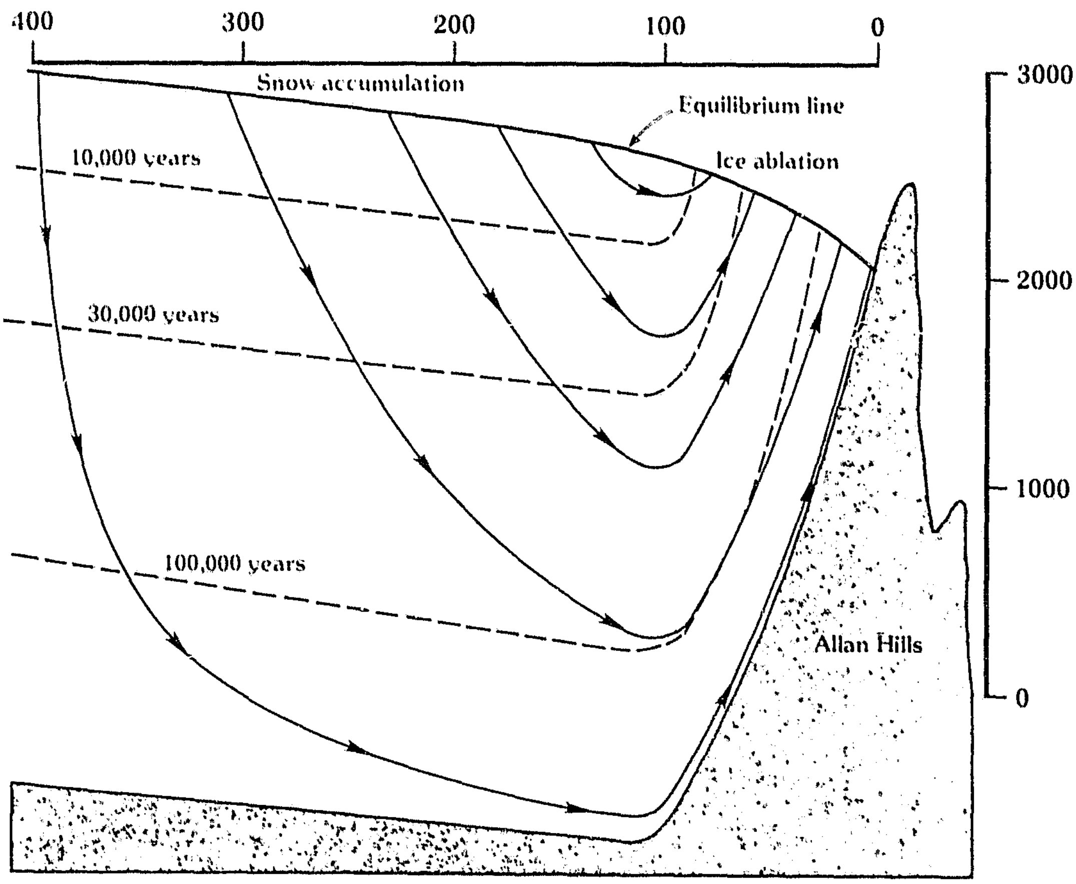


Fig. 8. Highly simplified model of ice flow and profile of the ice sheet in the Allan Hills area. Ice flow trajectories are solid lines; isochrons are dotted lines. Vertical exaggeration is about 100 times (from Whillans and Cassidy, 1982).

Whillans and Cassidy (1982) predict that δD and $\delta^{18}O$ values (SMOW) in ice along a horizontal traverse will be as shown in Fig. 9; the change in $\delta^{18}O$ from glacial to interglacial may be about 8‰ (Grootes, Appendix I). Their prediction can be evaluated by sampling ice along the horizontal traverse and measuring the oxygen isotope ratios. Important information on the extent of the ice sheet in former times can be obtained from measurements of total gas contents. Despite all the difficulties mentioned above, if the exposed ice is in stratigraphic order for 6×10^5 years, it should give a temperature record through several "ice ages." At present, the longest continuous record, from a 1400-m ice core at Vostok Station, probably ranges to 115,000 years b.p. It shows $\delta^{18}O$ variations through the most recent interglacial (7×10^4 10^5 years b.p.) that differ by 2‰ from those in the Wisconsinan and previous glaciations.

The $\delta^{18}O$ values of 39‰ and 45‰ have been obtained for the surface ice near stakes 12 and 11, respectively. If the model of Nishio *et al.* (1982) is appropriate to the Allan Hills blue-ice area and the sequence of exposures is stratigraphically complete, the $\delta^{18}O$ measurements would show only the transition from Holocene to Wisconsin values at about 10,000 years b.p. and not the earlier glacial/interglacial changes. Naturally, absence of a continuous stratigraphy record along the traverse would yield random $\delta^{18}O$ data.

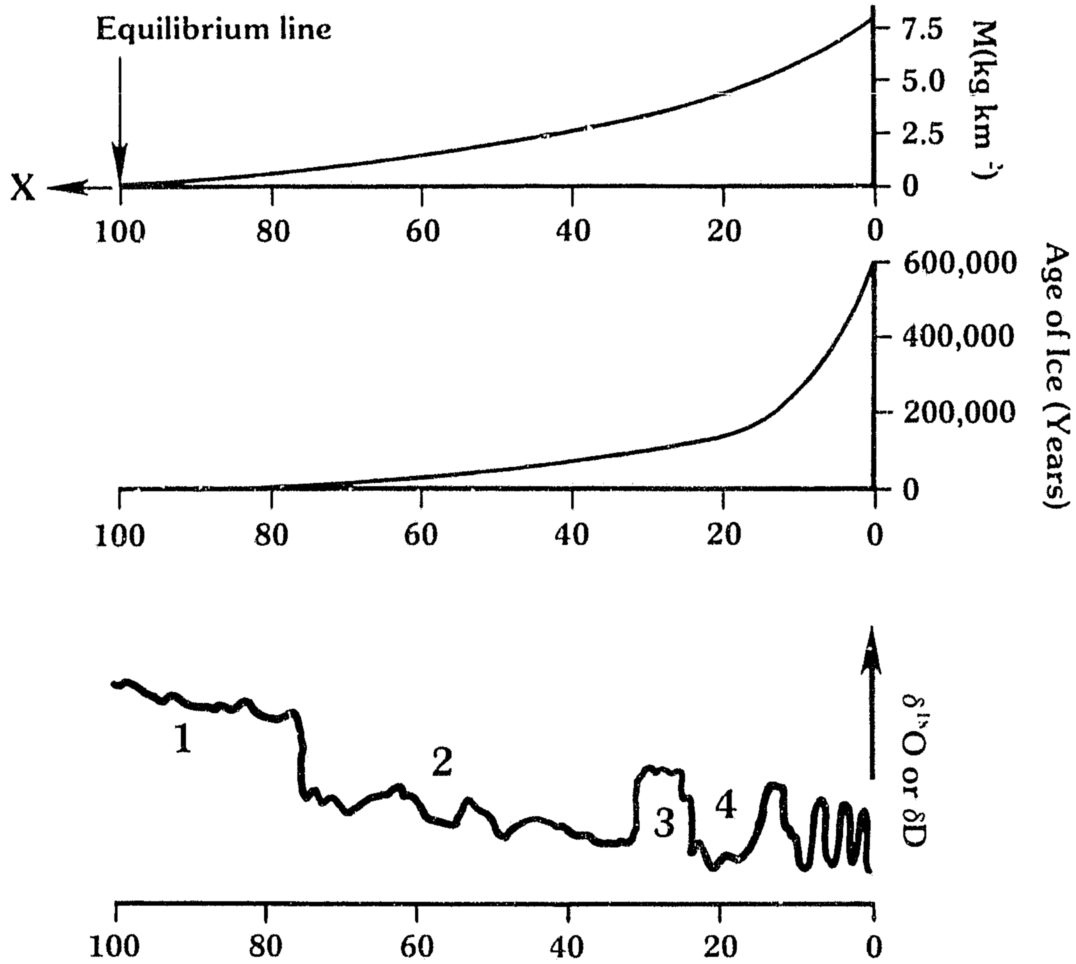


Fig. 9. Estimates of various parameters as a function of distance (in km) up-glacier from the Allan Hills according to the ice flow model in Fig. 8 for an influx rate of 60×10^{-6} kg km^{-2} yr^{-1}. Top—estimated meteorite concentration, M; center—age of ice surface; bottom—possible $\delta^{18}O$ or δD contents spanning several interglacial (i.e., periods 1, 3) and glacial (i.e., periods, 2, 4) episodes, the current interglacial being 1 and the most recent glaciation 2 (courtesy of Whillans and Cassidy, 1982 and Appendix I).

At present, the Whillans-Cassidy model for meteorite concentration and ice flow has some difficulties, but none of them so serious that the model should not be field-tested. These difficulties include:

a) Poor knowledge of the present "catchment" area of ice and meteorites feeding the Allan Hills (Drewry, Appendix I).
b) Complicated surface flow pattern up-glacier from the Allan Hills, and the subglacial land projecting towards the Allan Hills, diverting some ice flow north and some south. This complicated pattern extends over a large catchment area feeding the David and Mawson glacier systems (Drewry, Appendix I; Figs 10–12).
c) Uncertainties that steady-state conditions have existed over 6×10^5 years, as Whillans and Cassidy's model implies. Major changes have occurred in ice sheet thickness (Mayewski, Appendix I), although Thompson and Mosley-Thompson (Appendix I) point to fairly constant microparticle accumulation rates over the last 3×10^4 years at Dome C. On the other hand, in areas adjacent to that in the Allan Hills and elsewhere in the Transantarctic Mountains (e.g., Whillans, Appendix I), glaciers are now flowing in directions opposite to flow directions in previous times, pointing to major changes in ice flow directions over time.
d) Major changes in the equilibrium line position and elevation of the ice sheet relative to the Allan Hills could have swept all previously accumulated meteorites over the Allan Hills barrier.

In addition, the Transantarctic Mountains evidence considerable uplift since the late Cenozoic. Are these structural and tectonic changes more pronounced on the inner side of the mountains? Did this, in fact, elevate the Allan Hills 7×10^5 years ago to a level where the ice flow from inland areas was disrupted, thus initiating meteorite concentration in this area? Did the uplift occur more recently as Nishio *et al.* (1982) suggest? Cassidy (Appendix I) points out that the total number of meteorite fragments found so far is an order of magnitude less than expected if the collection process(es) had continued since the ice sheet first formed, perhaps 1.4×10^7 years ago. However, the presence of a 7×10^5 year old Allan Hills meteorite and the relationship of meteorite terrestrial ages with geographic location (Nishiizumi and Arnold, Appendix I; Fig. 5) suggest the absence of major change. Thus, in addition to systematic studies of surface glaciology and analysis of ice samples for $\delta^{18}O$, total gases, ice fabric, and so on, more knowledge is needed of the catchment area, ice thickness, surface velocity and slope. Much of this information can be acquired from airborne radio-echo sounding profiles using high precision positioning of each traverse.

(ii) Blue-ice areas as meteorite collection sites

The meteorite-rich, blue-ice areas already discovered (Table 1) yielded many exciting extraterrestrial samples for scientific study as we described earlier; unexplored areas of the ice sheet may prove equally productive. The meteorite concentration mechanism(s) are very selective and there is generally little dilution of meteorite samples by subglacial rock or "meteorwrongs." This high signal-to-noise ratio underlies the successes of antarctic meteorite collection and study. It is important to delineate those characteristics that make particular blue-ice regions meteorite-rich, so that other such areas can be recognized and explored.

In an "ordinary" glacier or ice sheet, where much of the ablation occurs by melting close to a glacier terminus on land or by calving into the sea, any meteorites carried from the accumulation area are mixed with local rocks or carried out to sea. Hence, the most favorable areas for successful searches are those of low accumulation and high sublimation, where glacier flow is partly or completely blocked locally—the blue-ice areas. Williams *et al.* (Appendix I) describe the use of LANDSAT MSS band 5 and 7 images for discriminating blue-ice areas. Unfortunately, the limits of this satellite imagery are 82°N to 82°S, thus

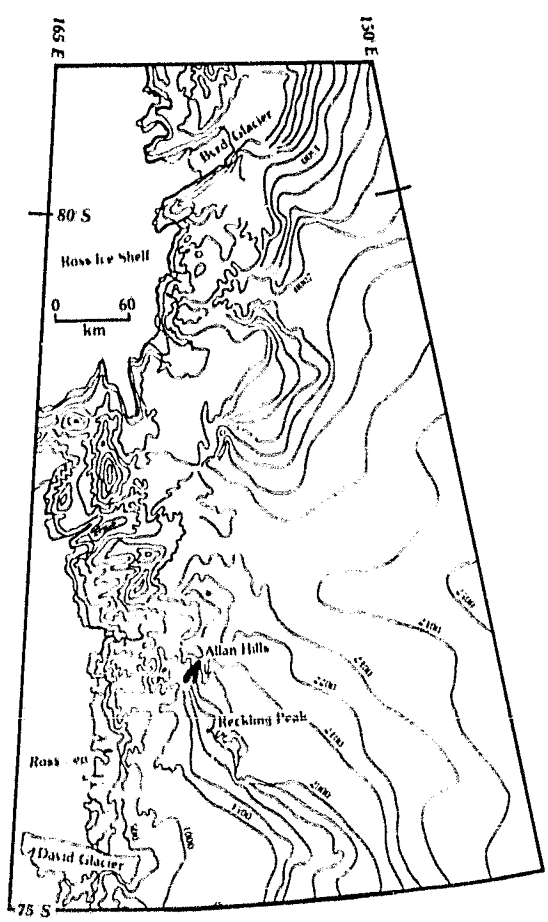


Fig. 10. Ice sheet surface contours (100 m intervals) on the inland side of Transantarctic Mountains, Victoria Land. Areas of rock outcrop are not shown but are also contoured, in some areas at 500 m intervals. Note the ridge of the ice sheet extending towards the Allan Hills (courtesy of Drewry, Appendix I).

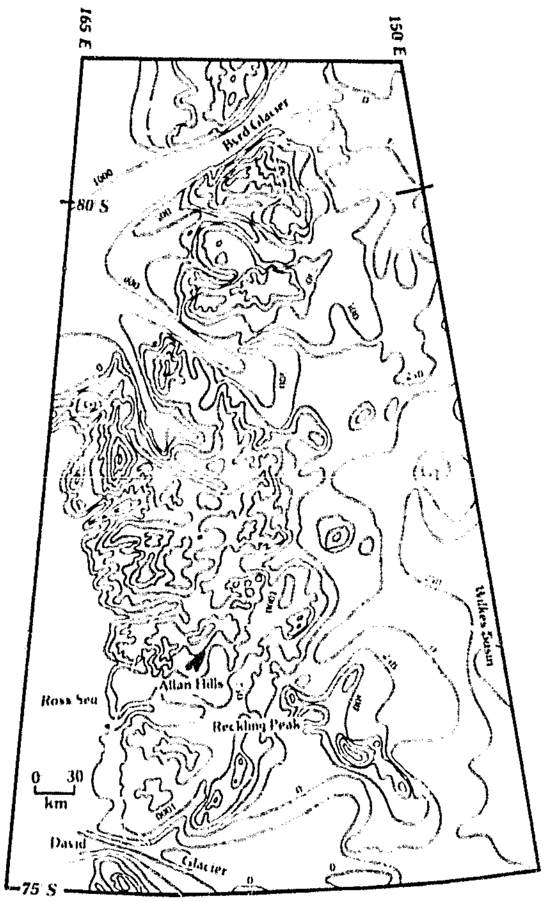


Fig. 11. Map of Transantarctic Mountains and part of the ice sheet of East Antarctica. Bedrock contours at 250 m intervals, both on subglacial and exposed rock (courtesy of Drewry, Appendix I).

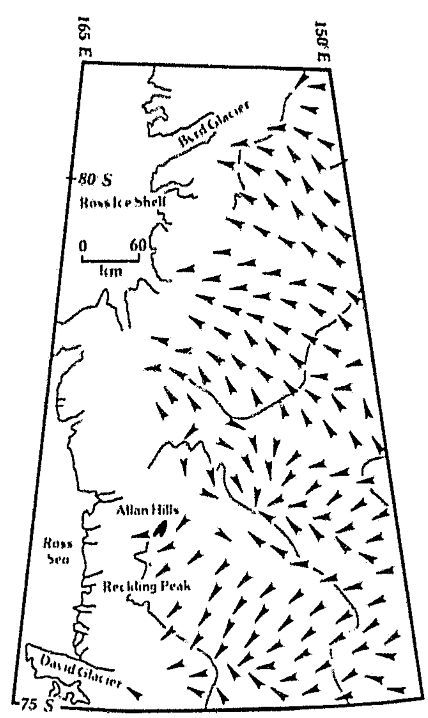


Fig. 12. Computed flow lines for the ice sheet inland from the Transantarctic Mountains, based on 100 km cells moved through data points and least-squares solution for direction of surface slope. Complex flow inland from Allan Hills may be real or may be an artifact of scanty data in that area (courtesy of Drewry, Appendix I).

excluding some parts of the antarctic continent which are candidate areas for meteorite accumulation because of mountain ranges transverse to ice flow and because of low precipitation. LANDSAT images have a spatial resolution of 90 meters and some fill-in, beyond 82°S latitude, may be possible using NOAA 6 weather satellite imagery. NOAA imagery, however, has a resolution of only 1 km. A more detailed search should become possible when the LANDSAT 4 and SPOT satellite systems become available this year and in 1984, respectively. Known blue-ice areas in East Antarctica exist at Bunger's Oasis, around the West Ice Shelf, on the west side of Amery Ice Shelf, in Enderby Land, in Princess Martha Land, in the Sentinel Mountains, and in the Mühlig-Hofmann Mountains. Williams and co-workers have proposed a new initiative for the U. S. Geological Survey in searching for other blue-ice areas and for better delineation of known blue-ice areas. Apart from LANDSAT image maps, most available maps of Antarctica do not show blue-ice areas.

It may be particularly valuable to extend the meteorite search to areas of West Antarctica near the Whitmore Mountains, for example, where accumulation rates may be relatively low and where, over small areas, the balance is negative. Searches in the Arctic at Devon Island and Ellesmere Island by Robertson *et al.* (1982) were unsuccessful. The discovery of meteorites with long terrestrial ages in West Antarctica or northeast Greenland (perhaps at Farvel Nunatak, inland from Dronning Louise Land) would establish the stability and long-continued existence of these ice sheets, as opposed to several existing hypothesized alternatives.

(iii) Terrestrial and surface exposure ages of meteorites from blue-ice areas

Meteorites of any terrestrial age within the range from zero to that of the age of the oldest ice can be found at any location in the ablation zone. Following the glacial flow models of Whillans and Cassidy (Appendix I; Fig. 8) and Nishio *et al.* (1982), meteorites of greatest terrestrial age will tend to be concentrated in areas closest to the Allan Hills, making them important tracers of ice sheet flow and glacier dynamics. As our ability improves to distinguish surface exposure ages from total terrestrial ages of meteorites, the meteorites could be used for stratigraphic correlation across widely separated areas of Antarctica.

Major contributions to glaciological and meteorite problems would result if one could determine the time a meteorite spends within the ice and on its surface. Potentially, weathering effects (Lipschutz, Appendix I) could be used to distinguish the time on the ice and, by subtraction from the total terrestrial age, the transit time within the ice. Amino acid and trace element contents would be particularly useful markers for weathering. The absence of significant weathering makes many antarctic meteorites particularly valuable for examining extraterrestrial genetic processes; others can be used for studying transit and surface times. The exchange of ambient ^{14}C with meteoritic carbon offers the possibility for determining surface exposure, but Fireman, from his CO_2 dating of meteorites, finds substantial difficulty with this chronology method.

Many workshop participants emphasized the importance of simultaneously using several methods described by Nishiizumi and Arnold (Appendix I) to determine terrestrial ages; Evans reported that, by the ^{26}Al method, 15 of 20 dated meteorites from the Reckling Peak area have ^{26}Al contents indistinguishable from those in recently fallen meteorites, i.e., they have terrestrial ages $< 2 \times 10^5$ years. However, as our knowledge of antarctic meteorite terrestrial ages improves, it should be possible to estimate whether meteorite influx rates have been constant during the past 7×10^5 years. Fireman, in discussing ^{14}C as a chronometer, finds that the greatest difficulties arise from uncertainties in the uniformity of exchange of atmospheric CO_2 with carbon-containing phases in the entire meteorite. In many antarctic meteorites, exteriors are more severely weathered than interiors (Lipschutz, Appendix I). For example, ALHA 77002 and ALHA 77003 each showed

CO_2 contents more than a factor of two higher in exteriors than in interiors. Despite difficulties, Fireman was optimistic about the possibility of determining minimum surface exposure ages; however, most workshop participants did not share his enthusiasm.

(iv) Age of dirt bands in blue-ice area near the Allan Hills

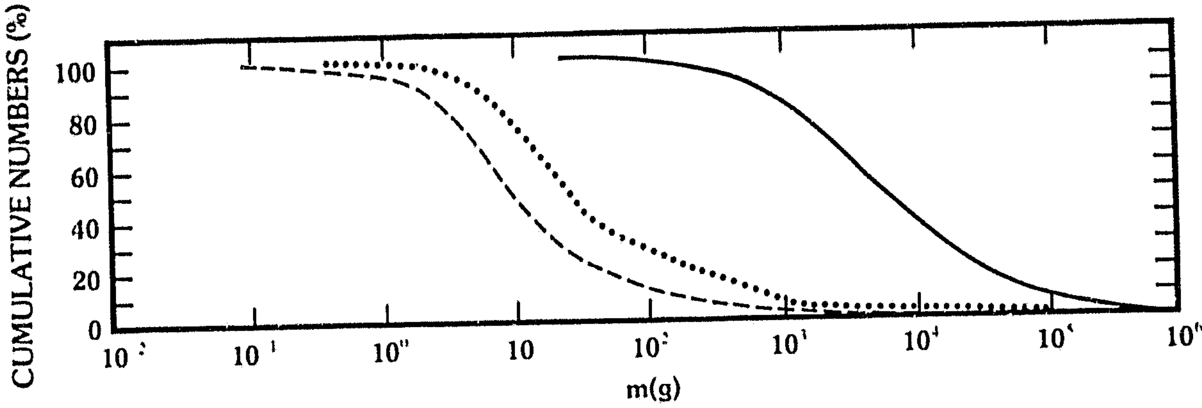
In the Allan Hills blue-ice area, many prominent dust bands occur in the 30 km up-glacier from the nunataks. Apart from their dip up-glacier, little is known of their geometry. Whillans (Appendix I) and Whillans and Cassidy (1982) suggest that they are probably windblown dust, or perhaps even tephra layers, a question that could be decided by the microparticle analysis methods of Thompson and Mosley-Thompson (Appendix I). Obviously, if suitable methods could be applied to this fine-grained material to determine the time elapsed since its deposition in the accumulation zone and the time of exposure of the material on the surface, checks could be made of any stratigraphic age determination from oxygen isotope analysis of surface ice layers.

(v) Systematic differences between meteorite-rich areas and meteorites

The difference between terrestrial ages of meteorites collected from the Allan Hills and Yamato Mountains areas (Fig. 2) suggests other possible population differences between these populations. One such is shown by the cumulative size distribution (Fig. 13); certainly the mass of meteorites recovered from the Yamato Mountains area is smaller than that from Allan Hills despite the much larger number of samples recovered from the former area. To determine whether the difference is significant, it is obviously important to ensure that the two collections were made with equal thoroughness. Were very small fragments better recognized in the blue-ice areas near the Yamato Mountains? Were wind velocities significantly higher in the Allan Hills area so that small samples were preferentially blown away? Did differences in flow regimes in the two areas—complete blockage in the Allan Hills area; partial blockage in the Yamato Mountains—produce differences in meteorite concentration processes and hence in the average terrestrial ages in the two areas? Do differences in the size distribution reflect a temporal or a spatial variation of the size distribution of the incoming material? Is there a systematic difference between the search techniques of JARE and ANSMET parties?

The available evidence hints that some antarctic meteorites form strewn fields. Can one verify the existence of these? If so, do the strewn fields represent material that fell where it is now found or have samples travelled through the ice as a swarm? Does the existence of meteorites that are present in some numbers in Antarctica but rare elsewhere, like polymict eucrites, reflect their better preservation in Antarctica, a variation in the fall frequency with time, a combination of these, or some other cause?

In the Yamato Mountains area, the meteorite-rich surface is uniform blue-ice over large areas (Fig. 14). In contrast, in the area up-glacier from the Allan Hills (and in the Reckling Peak and Elephant Moraine areas) the surface rises inland in a series of steps. However, in the last two areas, there are no obvious ice-flow blocking features. In general, meteorites are found on risers free of snow, while treads are covered with firn to a depth of tens of meters. In the Yamato Mountains area, it is possible to clear all meteorites from the surface, but in one area that was thoroughly searched and cleared in 1977, an additional 17 meteorites were found in 1981. Were they on the surface in 1977 but missed, or did they emerge from the ice after 1977? It would be useful, therefore, if a similar comprehensive search could also be made in the firn-covered treads of the Allan Hills, for comparison.



····· Allan Hills chondrites 1976-80

--- Yamato chondrites 1969, 73, 74, 75

—— World chondrite falls

Fig. 13. Cumulative size distributions for meteorites recovered from the Allan Hills and Yamato Mountains (courtesy of Cassidy, Appendix I).

With regard to improved meteorite detection, Drewry (Appendix I) notes that with normal radio-echo sounding instruments operating at 60 MHz, at 20 db above noise a 10-m-diameter sphere could be detected at 50 to 100 m burial depth. With an impulse radar sounder at 1 GHz, one could detect a foreign body of a few centimeters size at 50 meters distance. Such experiments should be attempted, but the difficulty of excavating a meteorite (or meteorwrong) from 50 m depth should not be underestimated.

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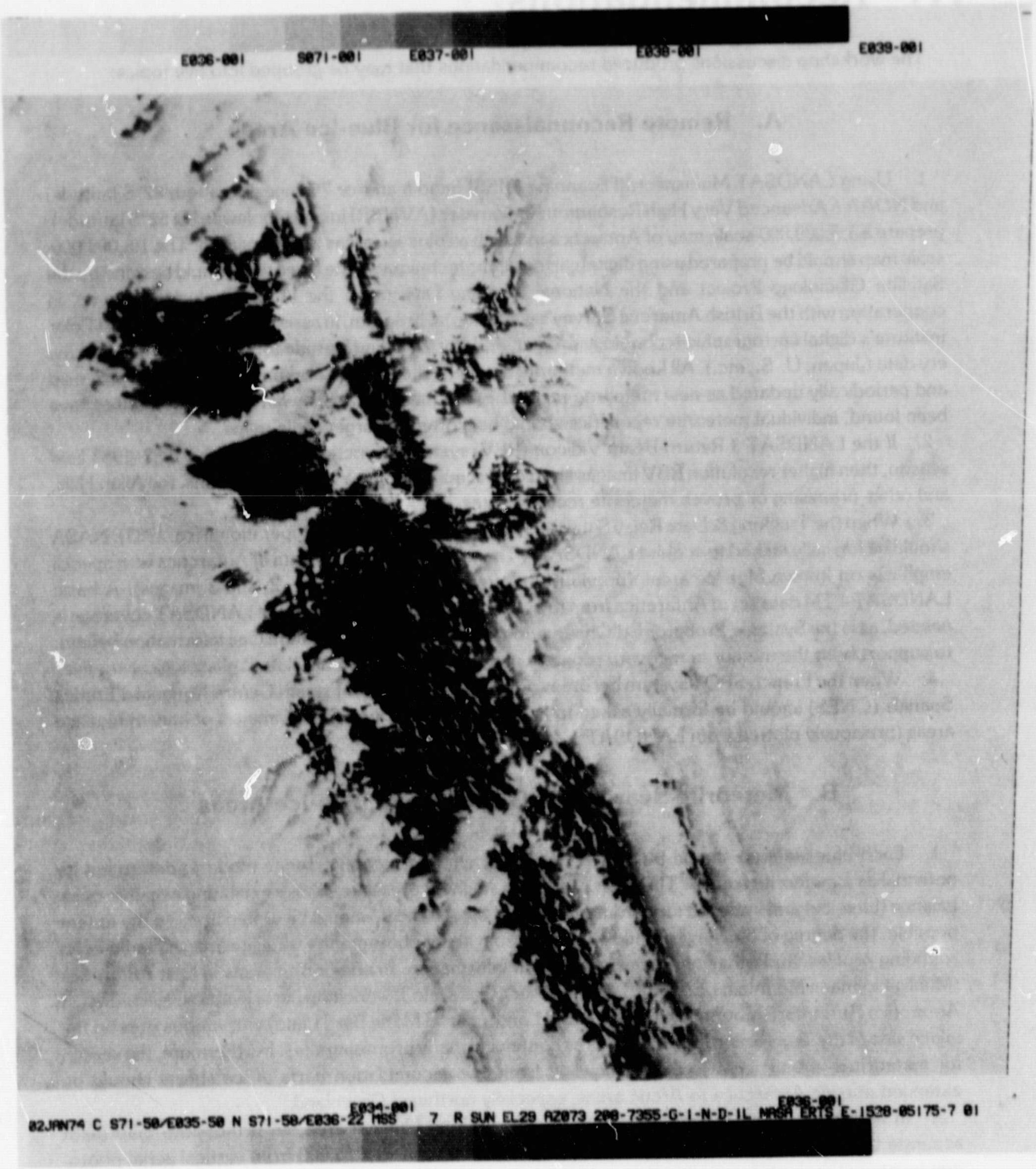

Fig. 14. LANDSAT 1 image (1528-05175) acquired on January 2, 1974 of the Yamato Mountains area, East Antarctica. Nearly all of the dark area is blue ice, but a few bedrock exposures (nunataks) are also present.

IV. Recommendations

The workshop discussions produced recommendations that may be grouped into five topics:

A. Remote Reconnaissance for Blue-Ice Areas

1. Using LANDSAT Multispectral Scanning (MSS) band 5 and/or 7 images (to about 82°S latitude) and NOAA 6 Advanced Very High Resolution Radiometer (AVHRR) images (poleward of 82°S latitude), prepare a 1:5,000,000-scale map of Antarctica in which all blue-ice areas are delineated. The 1:5,000,000-scale map should be prepared using digital cartographic techniques. The basic work could be done by the Satellite Glaciology Project and the National Mapping Division of the U. S. Geological Survey, in cooperation with the British Antarctic Survey's glaciological program, in association with the Scott Polar Institute's digital cartographic technology project, and from existing latitude-longitude meteorite recovery data (Japan, U. S., etc.). All known meteorite recovery sites should also be plotted on the base map and periodically updated as new meteorite recoveries are made. In areas where many meteorites have been found, individual meteorite recoveries should be plotted on larger scale maps.
2. If the LANDSAT 3 Return-Beam Vidicon (RBV) system is functioning during the 1982–1983 field season, then higher resolution RBV images should be acquired of the Yamato Mountains, the Allan Hills, and other promising or proven meteorite recovery sites.
3. When the Tracking & Data Relay Satellite System (TDRSS) becomes operational (ca. 1983), NASA should be formally tasked to acquire LANDSAT 4 Thematic Mapper (TM) data of Antarctica with special emphasis on known blue-ice areas (previously plotted from LANDSAT 1, 2, and 3 images). A basic LANDSAT 4 TM data set of Antarctica from the coast to the 82°S latitude limit of LANDSAT coverage is needed, as is the Systême Probatoire d'Observation de la Terre (SPOT) system (see information below), to support both the meteorite recovery program and related (and also unrelated) glaciological studies.
4. When the French SPOT system becomes operational (1984), the French Centre National d'Etudes Spatials (CNES) should be formally asked to acquire high-resolution SPOT images of known blue-ice areas (previously plotted from LANDSAT 1, 2, and 3 images).

B. Meteorite Search and Glaciology in Blue-Ice Areas

1. Each blue-ice area should be visited systematically in a reconnaissance mode to determine its potential as a meteorite source. The most promising stagnant areas, i.e., those exhibiting negative mass balance (blue-ice) and impeded forward movement of the ice sheet, should be visited first. To the extent possible, the degree of blockage should be judged from aerial photographs, satellite images, radio-echo sounding profiles, and other remote-sensing depth information. In addition to areas in East Antarctica (Mühlig-Hofmann Mountains, Enderby Land, Bunger's Oasis, etc.), workshop participants suggested West Antarctica (Whitmore Mountains, Queen Maud Land, coastal Marie Byrd Land) and various sites on the inland side of the Transantarctic Mountains as containing many promising sites. Furthermore, the search for meteorites in blue-ice areas down-flowline from low accumulation parts of ice sheets should be extended outside Antarctica to Arctic areas, especially northeast Greenland.
2. In advance of a systematic search of each promising blue-ice area, an orthophoto map (with accurate UTM grid and graticule) should be prepared at a scale of 1:25,000 from vertical aerial photographs of each area. It is possible that very high resolution satellite imagery might be obtainable from other U. S. government agencies through the National Science Foundation or National Academy of

Sciences: this should be explored. Orthophoto maps would be used by field meteoriticists and field glaciologists to plot specific meteorite recovery sites and to plot glaciological observations.

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C. Detailed Studies of the Allan Hills Area

The richness of the Allan Hills blue-ice areas as a meteorite source suggests the desirability of using it as a prototype area for further extended study, particularly of proposed models. These studies should include: systematic $\delta^{18}O$ measurements and total gas measurements on samples collected along flow lines from the Allan Hills; ice coring for $\delta^{18}O$ and microparticle measurements; airborne radio-echo soundings and radar studies to establish slope, velocity, and flowlines in the ice sheet and the bed-rock topography; determination of ice depths by gravity measurements; microclimatological studies using an automated station; a variety of studies on the dust bands; additional meteorite collection, etc. Up-to-date maps of ice flow directions, ice topography, and bed-rock topography are needed.

In the Allan Hills area, meteorite searches should be made on the "treads" of the steps, using the SPRI (or similar) 1 GHz monopulse radar. These efforts will require use of a Jamesway hut and establishment of ancillery facilities for this extended study. The combined effort should include glaciologists, geologists, geophysicists, paleoclimatologists, meteoriticists, etc. The study should operate as a consortium, with frequent interchange and dissemination of ideas, results, and suggestions for further projects. We recommend that similar radio-echo sounding work should be done to supplement the surface measurements of ice velocity, etc., in the Yamato Mountains area.

D. Additional Meteorite Collection and Study

1. All workshop participants agreed that antarctic meteorite studies so far have yielded important results and promise continued success. Meteorites from all areas should be studied; particular emphasis should be given to developing techniques capable of distinguishing meteorite transit times through the ice from weathering times on the ice. Total terrestrial age information is of vital glaciologic interest and should be disseminated to this community as well as to meteoriticists.

2. To optimize meteorite collection efforts, a briefing sheet or short pamphlet should be prepared by the Meteorite Working Group and distributed to all field scientists going to Antarctica each year, through SCAR. The pamphlet should contain field photographs showing how meteorites occur on blue-ice areas and a discussion of size distribution, black fusion crust, and history and scientific significance of the recovery of meteorites from Antarctica.

E. Further Communication

1. To aid the members of each community, a selected bibliography of relevant publications in glaciology and meteorites should be prepared by the LPI for dissemination.

2. The success of this workshop will be guaranteed only if communication between the glaciologic and meteoritic communities continues; hopefully additional scientific disciplines will be brought in as appropriate. To enhance this communication, we recommend that relevant results be presented at meetings normally attended by members of the other communities. In addition, a workshop, such as this one but dealing with new results, should be held in about 1985 to assess research status and formulate new directions and objectives, if appropriate.

Acknowledgments

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APPENDIX I

ABSTRACTS

CHARACTERIZATION OF ANTARCTIC METEORITES.

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The broad division of meteorites into stones, stony-irons, and irons serves well as an initial classification, with the further division of the stones into chondrites and achondrites. Chondrites are so named for the presence of chondrules, approximately spherical aggregates ~ 1 mm in diameter consisting largely of ferromagnesian silicates (olivine and/or pyroxene). Achondrites do not contain chondrules (hence the name), and their textures usually resemble those of terrestrial igneous rocks, although frequently modified by brecciation.

Meteorites are designated as falls (i.e. observed to fall) and finds (not observed to fall, but recognized as meteorites by their distinguishing features from terrestrial rocks). The relative abundances of different meteorite groups is normally derived from fall statistics, since the number of finds is highly biased towards the irons (which are very resistant to terrestrial weathering and are readily recognized as exotic objects). Fall statistics are as follows: chondrites, 85%; achondrites, 8%; irons, 6%; stony-irons, 1%. Thus chondrites far exceed all other meteorites in frequency of fall (although calculation on a weight basis would change the proportion in favor of irons, since iron falls are usually much heavier than stones - 23 tons of the Sikhote-Alin iron were recovered, and the total mass entering the atmosphere was estimated at 70 tons).

Chondrites have a rather restricted range in major-element composition (corresponding rather closely in silicate composition to terrestrial peridotites), but they can be divided into five classes based on chemical and mineralogical composition: E (enstatite), H (high-iron), L (low-iron), LL (low-iron low-metal), and C (carbonaceous). These classes are also unequally populated; fall statistics give 45% L, 40% H, 8% LL, 2% E, 5% C chondrites. The chondrite classes are subdivided on textural features into six types, designated by integers 1-6. The simplest explanation for types 3-6 is that they represent a sequence of successively slower cooling from an initially high but subsolidus temperature.

Several classes of achondrites have been recognized, but some comprise only one or two members. The commoner achondrites include the enstatite achondrites or aubrites (14%), the hypersthene achondrites or diogenites (14%), the olivine-pigeonite achondrites or ureilites (6%), and the pyroxene-plagioclase achondrites which include ecurites, howardites, and shergottites (62%).

Stony-irons comprise pallasites and mesosiderites, with a couple of oddballs. Pallasites consist of olivine and nickel-iron, mesosiderites of nickel-iron, pyroxene, and plagioclase (essentially nickel-iron with an admixture of a howardite component). The irons are divided into several classes on the basis of structure (hexahedrites, octahedrites, ataxites) and chemical composition (chemical groups I-IV, and subdivisions thereof).

The recovery of the Antarctic meteorites has resulted in a tremendous increment to the total meteorite collections. Since they represent large concentrations, possibly from extensive areas and over a considerable time period, their distribution over the different classes and types may provide an integrated account of the meteorite flux on Earth. To date we have classified 373 meteorites of the 798 collected in Victoria Land in the 1976-1980 field seasons. Their distribution is as follows: chondrites, 86%; achondrites, 6%; irons, 6%; stony-irons, 2%. This distribution is not notably different from that derived from fall statistics. However, two shergottites have been recovered, doubling the number in that small class, and many of the eucrites belong to a specific group, the polymict eucrites (which are rare in non-Antarctic collections). Among the chondrites, the enstatite and carbonaceous classes seem to be under-represented.

The Antarctic meteorite collections raise some important questions: Over how long a period has the Antarctic icecap been accumulating meteorites? How many meteorites fell in the area where they have been collected, and how many have been transported, and how far, from their place of fall? How many specimens are pieces of a single fall which broke up in the atmosphere, or which has disintegrated since fall? It is hoped that these and other questions can be elucidated during this meeting.

ANTARCTIC METEORITES: SOME NEW PROBLEMS AND OPPORTUNITIES, W.A. Cassidy, Dept. of Geology and Planetary Science, Univ. of Pittsburgh, Pittsburgh, PA 15260

Concentrations of cosmogenic isotopes can be measured to estimate the time since fall (terrestrial age) of a meteorite. A meteorite therefore can be thought of as a type of clock which continuously measures the time since it arrived on the earth's surface. Because meteorites are preserved for a long time in the Antarctic environment, any group of them will show a variety of ages, representing the period of time during which the accumulation of that group took place. Meteoritic "clocks" have been placed all over the Antarctic continent and, if found, will sometimes give information on the antiquity of the surface underlying them. This is information that often has not been available before.

Meteorites can be thought of as clocks in another sense, if we are willing to assume a constant rate of fall onto the earth's surface. Using that assumption, an older surface will have accumulated more meteorites than a younger one in direct proportion to the ages of the surfaces. Recent estimates of current worldwide fall rates (1, 2) are 1-2 x 10^{-6} meteorites km^{-2} y^{-1}. If we assume 1 fall km^{-2} x 10^{-6} y, a surface 1 m.y. old would have received 1 fall km^{-2}. Some of these would be individuals and some would be showers. If the average fall produced ten fragments, the surface density of meteorites should be 10 km^{-2}. All indications so far are that regions such as the Dry Valleys do not yield meteorites, and this says something about the youthfulness of those surfaces. A recent estimate for the age of the Antarctic ice cap is 14 m.y. (3). If the Allan Hills ice patch (area ~ 75 km^2) were an original feature, i.e. had been in existence for 14 m.y., it would have received in that time 1050 meteorite falls. Some of these would be individuals and some would be showers. If the average fall produced 10 fragments the ice patch would be littered with 10500 meteorite specimens from falls directly onto it. In addition to direct falls, however, lateral concentration is occurring due to ice migration which would further increase the surface density of meteorites. To date, repeated searches have produced only about 1000 specimens on this surface; this suggests that the Allan Hills meteorite concentration site is only a transient feature which has been in existence for only a small fraction of the age of the ice cap. Terrestrial ages of the meteorites recovered there seem to support this conclusion: the oldest specimen recovered so far is ~ 700,000 y.

The inferred transient nature of meteorite accumulation zones on the ice suggests that earlier collections of meteorites may have been buried, but still exist, or may have been moved to a new site and then dumped, presumably in a moraine but hopefully not in the ocean. It would be of great interest to locate such a deposit. Questions of climate change must figure in the search for such a "fossil" meteorite accumulation; questions involving climate change may be answered by finding such an accumulation.

The nature of the meteorite flux arriving at the earth's surface and, by inference, the nature of an asteroidal or cometary source reservoir has been estimated only on the basis of worldwide observed falls, because, in most climates, differential weathering rates rapidly distort the numbers based upon finds. In Antarctica, however, all varieties of meteorite seem to be exceptionally well protected against weathering, so that Antarctic finds can be tabulated as a check on existing estimates of the meteorite flux. So far, because of the abundance of material available, both the Yamato and Allan Hills sites seem to be appropriate areas for this type of analysis. A problem to be overcome, however, is that in these areas we find overlapping and superimposed falls, so that unequivocal pairing of specimens from the same fall is a practical impossibility. Total masses of the several meteorite types can be determined, however, so that once the worldwide falls have been tabulated according to mass, a comparison can be made. The same procedure can also be used to intercompare collections from different sites on the ice cap as a measure of the relative maturity of each accumulation site. This, again, will yield information on the duration of current conditions which promote meteorite accumulation at the site.

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THE JAPANESE ANTARCTIC METEORITE PROGRAM - COLLECTION AND CURATION -

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Up to 1969, only 6 pieces of meteorites had been retrieved from Antarctica, but during 12 years from 1969 to 1982, about 4,700 pieces of meteorite have been collected by the Japanese Antarctic Research Expedition (JARE) teams from East Antarctica. Results of the preliminary classifications of these meteorites are summarized in Table 1. As shown in the Table, a large number of Antarctic meteorites are still left unexamined. During 3 years from 1976 to 1978, JARE teams suspended their own activities of searching meteorites in East Antarctica, but instead Japan-US joint programs for searching and collecting meteorites in Victoria Land area were successfully organized, resulting in a collection of about 630 pieces of meteorite during the three years. Results of the preliminary classification of these meteorites an summarized in Table 2.

Table 1. Japanese Collection of Antarctic Meteorites

Meteorite Name	Total	Irons	Stony-Irons	Chondrites						Achondrites					
				E	H	L	LL	C	n.d.	Aub	Ur	Di	Ho	Eu	Sher
Yamato-69	9			1	4	1		1	1			1(A)			
Yamato-73	12				1	2			8				1		
Yamato-74	663		1		62	31	3	3	+		3	22(A)		3	
Yamato-75	307	2			7	31	2	3	+			6(A) 1(B)		5	
Yamato-79	3,600+	4	?		12	14	15	31	+		1	16(A) 16(B)	3	43	
Belgica-79	5							1	4						
Yamato-80	13								11			1(A)			
Yamato-81	133														
Total	4,742+	6	1+(?)	1	86	79	20	39	24+	?	4	46(A) 17(B)	4	51	?

n.d.: not determine, (A): characteristic granoblastic texture, (B): characteristics intermediate composition between diogenites and eucrites

Table 2. Antarctic Meteorites Collected by Japan-U.S. Joint Team

Meteorite Name	Total	Irons	Stony-Irons	Chondrites						Achondrites					
				E	H	L	LL	C	n.d.	Aub	Ur	Di	Ho	Eu	Sher
Mt. Baldr	2				2										
Allan Hills-76	9	1			2	4	1							1	
Allan Hills-77	310	7	1		48	38	1	2	209		1	1		1	1
Purgatory Peak-77	1	1													
Derrick Peak-78	10	9+													
Meteorites Hills-78	28				4	5			19						
Bates Nunatak-78	6					2	1		3						
Allan Hills-78	262	1			24	22	2	1	204	1	2		1	4	
Reckling Peak-78	5				2	1			2						
Total	633	19+	1	?	82	72	5	3	437	1	3	1	1	6	1

CURATION OF THE U.S. ANTARCTIC METEORITE COLLECTION AND SOME OBSERVATIONS CONCERNING THE SPECIMENS; D.D. Bogard, NASA/Johnson Space Center, Houston, TX 77058; C. Schwarz, Northrop Services, Inc., Houston, TX 77058; R. Score, Northrop Services, Inc., Houston, TX 77058.

The U.S. Antarctic meteorite program has drawn on curatorial experience derived from the lunar program to: (1) develop specific collection and preliminary examination protocols; (2) provide documented samples for scientific investigations in response to specific requests; and (3) aid cooperative research by scientific consortia.

Meteorites are shipped frozen from Antarctica via Port Hueneme, California, to the Meteorite Curatorial Facility at Johnson Space Center (JSC). Here they are kept frozen until they can be dried in a gaseous nitrogen cabinet. The larger specimens are dried one at a time to avoid contamination while the smaller ones (<150gm) are dried 10 to 50 at a time. The meteorites are then weighed, photographed, and described by a combination of macroscopic and microscopic techniques. Each meteorite is chipped or sawed to expose the interior surfaces and to obtain a small chip from which petrologic thin sections are made for classification. All tools and equipment used in processing have been cleaned to avoid contamination. Only those made of acceptable materials, including teflon, polyurethane aluminum, and stainless steel, may come in contact with the meteorite samples. Two complete thin section libraries are available for examination, one at the Smithsonian Institution and the other at JSC. After processing, the specimens are stored in a low contamination, gaseous nitrogen environment and a complete inventory is maintained on all subsamples.

Pertinent information on each specimen is compiled in the Antarctic Meteorite Newsletter, which is distributed to about 600 scientists worldwide. Samples are allocated to individual investigators generally twice a year as a result of specific requests to the Meteorite Working Group, a committee set up to evaluate the proposed research. Meteorite allocations are prepared according to the requestor's directions, whenever possible, with particular emphasis on maintaining low contamination levels and full sample documentation. To date, over 1500 meteorite specimens have been provided to approximately 100 scientific groups for study. Several broad consortia are now actively studying a number of complex meteorites. Included in these are the polymict eucrites and a shergottite.

Of the more than 1000 Antarctic meteorite specimens in the U.S. collection, approximately 20 are irons and 23 are achondrites, the majority being ordinary chondrites whose distribution of chemical and petrological types are similar to non-Antarctic meteorites. Many of these specimens are paired, meaning they were once a single meteorite that broke up as it fell through the Earth's atmosphere. The meteorites show a diverse range in evidence to terrestrial weathering. Weathering ranges from almost nil with intact fresh black fusion crust, to reddish-brown patchy fusion crust, to essentially no fusion crust but a deep reddish-brown surface. Some meteorites show a glassy-like patina, a result of abrasion by wind blown ice. The interior of these specimens also range from unweathered, to oxidation halos only around metal grains, to a totally oxidized reddish-brown matrix. Upon drying, a few different types of meteorites show surface deposits of leached salt in the polygonal fractures in the fusion crust and/or large fractures in the meteorites which were not apparent when the specimens were cold and wet.

METEORITE CONCENTRATION MECHANISM NEAR THE ALLAN HILLS AND THE AGE OF THE ICE; I.M. Whillans, Institute of Polar Studies, and Department of Geology & Mineralogy, Ohio State University, 125 S. Oval Mall, Columbus, OH 43210

Meteorite concentrations can be caused by a combination of (1) ablation of formerly deep ice exposing its contained meteorites, (2) direct falls onto the ablation zone, and (3) compressive ice flow. A steady-state model of these three processes is sufficient to explain the observed meteorite concentrations (Cassidy, this conference).

Ice flow trajectories and isochrones are calculated using a steady-state model. The exposed ice ranges in age from 0 to 600 000 years and this agrees with the reported terrestrial ages of the meteorites.

GEOGRAPHY AND GLACIOLOGY OF SELECTED BLUE ICE REGIONS IN ANTARCTICA; John O. Annexstad, NASA/Johnson Space Center, Houston, TX 77058.

Major concentrations of meteorite fragments have been discovered on blue ice fields located near the Yamato Mountains (72°S, 36°E) and the Allan Hills (77°S, 160°E). These icefields are similar in physical characteristics and dynamical features which indicate that a general model on meteorite concentration in Antarctica could be proposed.

A general definition of blue ice is an ablation area created by wind erosion on the Antarctic ice sheet, characterized by bare glacier ice showing at the surface. In an early description,(1) blue ice regions are characterized by high ablation, high wind speeds, slow horizontal movement, and a crystal size that indicates a deep source for the ice. Other workers(2) observed trough systems with 250 meter wave lengths perpendicular to the direction of motion, and sun cupped surface features; they suggested a mechanism of formation by horizontal compression with katabatic winds removing snow accumulation.

The interest in blue ice by some researchers is a result of its relationship to meteorite concentration. Blue ice fields are generally found within the vicinity of coastal mountains and nunataks but they can appear as isolated fields within the main flow pattern of the ice sheet. Although blue icefields can be found upstream and downstream of these features, meteorites are generally found on the icefields that are upstream of mountains and nunataks. As the mountains are approached on the upstream side the horizontal velocity of the ice sheet tends to decrease. Within a short distance, the surface features change from firn to crevassed and broken bare ice to a step-like topography (monocline) to stagnant ice. Other features common to blue ice fields are moraine, scoops, furrows, hills, valleys, pinnacles and flow line streaks.

Triangulation chains have been established near the Yamato Mountains(3,4) and the Allan Hills(5,6) for the purpose of measuring ice movement and ablation. Although these areas are over 3000 kilometers apart the data obtained from each is remarkably similar. Ablation rates are variable throughout both regions but average about 5 cm per year. Horizontal velocity is slow and ranges from 2.0 to 2.5 m/yr. to zero. The vertical or emergent velocity nearly approximates the ablation rate in the stagnant area. Limited depth measurements(7) suggest that stagnant blue ice is produced by a steep subglacial rise culminating in a flow blocking mountain or nunatak. The general flow direction is perpendicular to the elevation contour as indicated by stake measurements, crevasse patterns and flow line streaks. The main ice sheet in both areas exhibits a small shift in flow direction as the obstructing features are approached.

It appears that meteorites captured by the ice sheet over the last 10^5 to 10^6 years are transported to coastal areas where they are concentrated in stagnant blue ice regions. Although Antarctica acts as a large collector, concentrator and preserver of specimens, we do not yet have a quantitatve model of concentration mechanisms that can relate directly to meteorite residence age, type and numbers.

Annexstad, J.O.

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TRANSANTARCTIC MOUNTAINS GLACIAL HISTORY-GENERAL PROBLEMS

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Studies concerning the glacial history of the Transantarctic Mountains have classically dealt with the frequency and magnitude of glacier fluctuations in this region. To briefly summarize, the region has experienced approximately six major events (1) in the last 3.7 m.y. and since this time a maximum volume increase of approximately 60% over present (computed over the entire ice sheet (2)). By comparison with the fluctuation history of the late Wisconsin North American and European ice masses the ice cover on the Transantarctic Mountains has, therefore, been relatively stable. Based on the latter statement, deduced largely on the basis of the glacial record, the dynamics of the former and current ice masses in the Transantarctic Mountains might be considered simple. This is hardly the case. Resolution of the complex ice mass interactions that characterize the Transantarctic Mountains and similarly, the widest application of glacial geologic studies in this area could be intensified if the following are addressed:

(a) detailed examination of erosion and deposition processes in polar ice masses since they provide the mainstay of glacial geologic interpretations

(b) clarification of the dimensions and basal environment of the ice cover in this region for both early and late glacial periods

(c) compilation of stratigraphic records based on comparable types of information and, preferably with sufficient absolute-dating, to detail the timing of events that comprise this record

(d) unravelling of the interplay between eustatic, tectonic, glacio-isostatic and erosional and depositional isostatic forces as they impact on the distribution of glacio-geomorphic features and hence on the reconstruction of ice surfaces

(e) differentiation and interpretation of the fluctuation records of the several types of ice masses found within the Transantarctic Mountains (ice sheet, ice shelf, lacustrine, snowpatch and outlet, alpine, piedmont and rock glaciers) to enhance time-scale resolution of the glacial events in this region

(f) characterization and monitoring of modern ice masses for purposes of adequately assessing their fluctuation records

(g) definition of ice mass fluctuations in terms of climatic and/or non-climatic causes

(h) detailing of climatic causes for ice mass fluctuations to include data on former temperature, precipitation and wind regimes

(i) examination of those ice masses which have the greatest potential as proxy indicators of recent changes in climate

(j) choice of 'representative' areas in which to concentrate the highly logistic intensive efforts required to answer pertinent questions concerning the glacial record.

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RADAR SOUNDING OF ICE SHEET INLAND OF TRANSANTARCTIC MOUNTAINS, D.J. Drewry, Scott Polar Research Institute, University of Cambridge, England CB2 1ER

Airborne Radio Echo Sounding (RES) of the Antarctic ice sheet, though not specifically integrated into meteorite studies, does provide data of significance: 1) ice sheet surface morphology, 2) regional ice flowlines, 3) ice thickness, 4) driving stresses, 5) subglacial bedrock morphology, 6) tracing of internal flow features and isochronous layers, 7) detection of meteorites in upper ice/snow horizons. Some data are available in the vicinity of the Transantarctic Mountains (at Allan Hills and nearby Reckling Peak and close to several nunataks at the head of Darwin Glacier) from collaborative SPRI-NSF-TUD programmes.

Detailed maps have been prepared of the ice sheet inland of the Transantarctic Mountains in Southern Victoria Land and also adjacent to Darwin Glacier. Surface information (contoured at 50 m interval) has also been used to calculate the magnitude and direction of surface slopes for the construction of ice flow lines.

On a regional scale the Allan Hills area is located on the northern edge of a major ridge, or ice drainage divide, which extends eastwards to the Mountains from central East Antarctica. At a local scale the area occupies a distinctive zone between the Mackay Glacier to the south and the Mawson Glacier to the north. At both scales such positioning results in a restricted drainage basin feeding the meteorite area and only relatively weak ice flow. Calculated regional values for the ice driving stress are between 40 and 60 kPa. Maps of subglacial bedrock topography (contour interval 250 m) show that ice sheet form and flow in the Allan Hills area is complex influenced by thin ice (rarely > 1.5 km) and rugged relief (RMS elevations $\sim$ 400 m) - the inland flank of the Transantarctic Mountains here extends to about 155 E. In the neighbourhood of Reckling Peak ice surface and flow characteristics are primarily influenced by thin ice and drainage into the major David Glacier outlet.

The Darwin Glacier area is similarly placed in a relatively stagnant zone between the Byrd Glacier (south) and Darwin Glacier (north), and likewise displays a restricted catchment and ice flow regime. Regional driving stresses are between 40 and 80 kPa. Subglacial topography does not appear as complex as in Southern Victoria Land, when account is taken of more limited RES coverage. The width of the subglacial Mountains is only half the width at Allan Hills.

A general pattern for the location of many meteorite sites emerges - they usually lie between sets of diverging flow lines where surface slopes are low, ice thickness small; where driving stresses and flow velocities are consequently of small magnitude. Based upon such a general model it is possible to predict other potential meteorite accumulation sites along the inland flank of the Transantarctic Mountains. Candidates are: between Byrd and Nimrod Glacier; at head of Lennox King Glacier, at various localities in the Mohn Basin, Queen Maud Mountains and between the Scott and Reedy Glaciers.

No RES flight track crosses meteorite concentration areas parallel to an ice flowline. Inspection of weakly developed internal reflecting horizons 100 km south of Allan Hills, however, does suggest the probable intersection of internal "layers" with the ice sheet surface and thus a possible compressive stress regime.

The detection of meteorites in transit within an ice sheet may be possible by RES. Limiting values to the size of meteorite bodies may be modelled for conventional RES sounders. The SPRI high frequency impulse system (operating at 1 GHz) can resolve isolated targets to within 150 mm at depths up to 50 m.

PETROLOGIC STUDIES IN THE JAPANESE METEORITE PROGRAM.

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According to results of the scientific examination, the Japanese collections of Antarctic meteorites in 1969-1981 cover a wide variety of meteorites and contain many unique meteorites (Antarctic Meteorite Catalog, complied by Yanai, 1981). Some important petrologic and mineralogical result can be sum-marized under four items.

1. Unequilibrated ordinary chondrites

Petrology of each chondrules in petrologic type 3 (e.g. Y-79191) chondrites has been extensively studied (e.g. Ikeda, 1980; Nagahara, 1980). The textures of chondrules are mainly controlled by chemical composition, especially SiO_2 MgO and FeO contents. Another controlling factors are found to be subordinate. Effects of precooling thermal history and cooling rate on the texture of chondrules were studied by experimentally reproducing the chondrule textures (Tsuchiyama and Nagahara, 1981). The chemistries of chondrules in H, L, and LL groups of their bulk chemistry suggest that their precurxors may be olivine, pyroxene and plagioclase. A relic olivine crystal which had already existed before chondrules formation has been found in Allan Hills 77015 L3 Chondrite, and secondary origin of chondrules has been suggested (Nagahara, 1981). Chemical compositions of matrices of unequilibrated ordinary chondrites were found to be different from those of chondrules (Ikeda et al., 1981; Fujimaki et al., 1981).

2. LL-Chondrites

Of 2,000 samples processed to date among about 3,600 Yamato-79 meteorites, there were found many unusual meteorites of a type not seen before in meteorite collections. Dark colored stones have a very fine-grained texture and are full of voids and contain both light-colored and black inclusions in hand specimen. The bulk chemical composition of Yamato-790964 of this type (analyses by H. Haramura) indicates it is a LL-group chondrite. The microscopic examination of polished thin sections and the electron microprobe analyses of selected specimens revealed that these meteorites are similar to some lithic fragments known in LL-group chondrites described by Fodor and Keil (1978). Other unusual, heavily shocked chondrites in the Yamato-79 collection have close affinity to the above unusual meteorites. They can be classified into three categories; heavily shocked chondritic material (e.g. Yamato-790519), fine crystalline material (e.g. Yamato-790964) and vesicular glassy material formed from a melt (e.g. Yamato-790143).

The three types are genetically related each other and even transitional. These textures are often recognized within one meteorite, such as Y-790964. These meteorites are large samples of lithic fragments common in the brecciated LL-chondrites, and are interpreted as surface regolith materials of the LL-parent body that were subjected to various degree of shock melting, crystallization from a melt, shock recrystallization, and brecciation due to intense impacts and eventually consolidated into coherent rock. The large amounts of these meteorites will significantly contribute to reconstract the LL-chondrite parent body and the shock process on the surface.

3. Ureilite

Six ureilites recovered from Antarctica and described by Takeda et al., (1980) extended the range of known variability within the group as could be expected since there were only eight known ureilites prior to the Antarctic discoveries. Yamato-79659 is a low Fe ureilite carrying the most magnesian pigeonite recorded from the group. Yamato-74130 carries augite (Takeda and Yanai, 1989). ALH-78019 has Fe-rich olivine. Yamato-790981 found in the

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MINERALOGY AND PETROLOGY OF UNIQUE AND RARE METEORITES RECOVERED IN ANTARCTICA. Klaus Keil, Department of Geology and Institute of Meteoritics, University of New Mexico, Albuquerque, New Mexico, 87131.

Much of the evidence for hypotheses on the origin and early history of solids in the solar system and the formation of planets is derived from the study of meteorites. Meteorites, besides lunar samples, are the only extraterrestrial material available in abundance for laboratory analysis, and this alone is reason enough for their study. However, their incredible scientific significance stems from the fact that they are "fossils" left over from the time solid materials, asteroids and planets, formed in our solar system. This is evidenced by the fact that many meteorites are the most ancient rocks ever recovered (4.55 b.y. old) and that many are chemically, isotopically and texturally primitive and have preserved their primitive properties for 4.55 b.y. Furthermore, meteorites allow us to date the time interval between nucleosynthesis and formation of solids and even contain the record of the isotopic make-up of pre-solar and extra-solar system materials. Finally, meteorites record the origin, evolution and properties of their parent bodies (asteroids), namely their accretion, structure, break-up and reassembly; their melting, differentiation, cooling and solidification; and their regolith history. It is therefore not surprising that meteorites have become the treasured objects of study by scientists from many different disciplines.

Since 1492, about 2,000 meteorite finds and falls have been recovered the world over. However, since 1969, more than 5,300 meteorite specimens, representing at least several hundred separate falls, have been found in Antarctica, thus increasing the world's supply of meteorite falls by probably 25% or more. The greater number of meteorites available for study increases significantly the chances of finding new, heretofore unknown rock types as well as more of the rare classes that may be the missing links in the puzzle of the early history of the solar system and the evolution of the planets. This has indeed been borne out, and I briefly summarize here the mineralogy and petrology of a few examples of unique and rare meteorites from Antarctica, to illustrate the importance of the continued recovery and study of Antarctic meteorites.

ALHA 77005 is a unique and previously unknown achondrite type. It is a cumulate rock akin to terrestrial ultramafic, deep-seated rocks. It is heterogeneous on a cm-scale and consists of euhedral to subhedral olivine (Fo_{74}) and chromite poikilitically enclosed by low- and high-Ca pyroxenes. Other areas consist predominantly of subhedral olivine with interstitial maskelynite (Ab_{45-43}) and accessory phases (1). Petrofabric analysis on olivine shows a weak preferred orientation primarily consisting of a YZ foliation plane containing a weak [001] lineation, indicating that the rock is a cumulate that solidified in the act of flow and accumulation (2). This rock is closely related to the shergottites, as indicated by maskelynite and pyroxene composition, but is different in its high olivine content. It yields important clues to the heating and differentiation history of its parent body.

EETA 79001 is also a unique achondrite and is the first extraterrestrial example showing igneous layering, as is indicated by a gradational (on a cm-scale) contact between 2 distinct but related lithologies. One consists of phenocrysts of olivine, orthopyroxene and chromite in a fine-grained groundmass of pigeonite, augite, maskelynite and accessories. The other lithology is coarser-grained and consists of pigeonite, augite, maskelynite and accessories. Both lithologies appear to have formed by fractionation from a common magma and the rock has strong affinities to the shergottites (3).

Polymict eucrites are brecciated, basaltic rocks consisting mainly of pigeonite and plagioclase similar to those of monomict eucrites but contain a variety of clasts of different composition, frequently with eucritic affinities, and of highly variable textures. These are rocks that formed originally by igneous volcanic and intrusive processes but were later brecciated, annealed and mixed. Polymict eucrites are rare outside Antarctica but, curiously, are common at Allan Hills (4) Elephant Moraine (5) and Yamato Mountains (6). Perhaps polymict eucrites, for dynamical reasons and because they may come from a different source than monomict eucrites, may have fallen more frequently in the more distant past than today. Since old eucrites may not preserve well in climates outside Antarctica, they are not abundant in the world's collections. However, in Antarctica, old polymict eucrites do not weather much in the cold storage of the ice and are readily recognized and, thus, their proportions are much higher in the Antarctic collections than in those from the rest of the world.

A significant number of unequilibrated ordinary chondrites have been recovered from Antarctica, adding new and important specimens to this relatively rare, primitive chondrite class. One, ALHA 77001 and 33 other specimens paired with it, is unique. It contains sharply defined chondrules with glassy groundmasses, heterogeneous olivine (Fa_{1-39}), pyroxene (Fs_{1-40}) and metallic Fe,Ni but is the only L3 chondrite that contains a few vol.% of aggregates of graphite-magnetite, besides the common opaque and recrystallized silicate ("Huss") matrix. It is suggested that ordinary chondrites accreted from at least four separate components available in the early solar system that formed under dramatically different conditions: Mg-rich chondrules, Fe-rich "Huss" silicate matrix, metallic Fe,Ni-troilite and graphite-magnetite (7).

RKPA 79015 is apparently a unique mesosiderite very rich in metallic Fe,Ni. The rock was at first classified as an iron meteorite with silicate inclusions. However, the brecciated silicates that are mixed with metallic Fe,Ni and troilite consist of orthopyroxene ($En_{74}Wo_{2.3}$) with minor merrillite, chromite, a silica polymorph and schreibersite. Thus, this rock consists of troilite-metallic Fe,Ni-rich orthopyroxenite clasts embedded into metallic Fe,Ni. Mineral compositions are similar to those of mesosiderites, but differences are the high metallic Fe,Ni and troilite contents, the lack of plagioclase, olivine and basaltic clasts, and the low merrillite content. Further work, particularly oxygen isotopic measurements, are required before the true nature of this unique meteorite can be assessed (8).

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TERRESTRIAL AGES OF ANTARCTIC METEORITES. K. Nishiizumi and J. R. Arnold, Dept. of Chemistry, B-017, University of California, San Diego, La Jolla, CA 92093.

Both stable and radioactive nuclides, the so-called cosmogenic nuclides, were produced by nuclear interactions between cosmic rays and meteorites. The measurement of two or more cosmogenic nuclides in a meteorite gives us the exposure and terrestrial age of the meteorite. The exposure age is the time period between the breakoff of the meteorite from a large parent body and the meteorite's fall to earth. The terrestrial age is the time period between the meteorite's fall and its discovery. The exposure ages of stone meteorites range from less than a million years to about 100 million years. The terrestrial ages of stone meteorites outside of Antarctica are less than about 30×10^3 years (but some iron meteorites have terrestrial ages $>10^6$ years). The terrestrial ages are obtained from the decrease in the abundance of cosmogenic nuclides such as ^{14}C ($t_{1/2}$ = 5740 years) [1-4], ^{36}Cl (3.0×10^5 years) [5-6], and ^{26}Al (7.2×10^5 years) after arrival on earth [8]. However, the activity of ^{53}Mn ($t_{1/2} = 3.7\times10^6$ years) has not significantly decayed on earth [i.e. 9].

We have measured ^{36}Cl and ^{53}Mn in over 100 Antarctic meteorites. Table 1 shows a summary of terrestrial ages of Antarctic meteorites. By measuring ^{10}Be and ^{36}Cl (produced by cosmic rays in the earth's atmosphere) in ice samples associated with specific meteorites, we can get some information also on the age of the ice itself. Even though the accumulation mechanism of Antarctic meteorites is not yet understood, several features are clear.

(1) The terrestrial ages of Antarctic meteorites range from 1×10^4 to 7×10^5 years.
(2) Many meteorites whose terrestrial ages are very different from each other were collected from the same bare ice region.
(3) All meteorites found on the southeast part of the exposed blue ice region of Allan Hills (except ALHA 77256) have terrestrial ages longer than 2×10^5 years.
(4) There is no clear relationship between the terrestrial age of a meteorite and its weathering features.
(5) So far, Allan Hills finds generally have had older terrestrial ages than Yamato meteorites.
(6) The preliminary results show that young terrestrial age meteorites were found on old ice and an old terrestrial age meteorite was found on young ice. The interpretation is not clear.

To understand the accumulation mechanism of Antarctic meteorites further information is needed -- such as:

(1) Accurate velocity of vertical and horizontal ice flow.
(2) Mechanism of formation and maintenance of blue ice regions.
(3) Age of blue ice.
(4) Age of meteorites in the blue ice.

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TABLE 1. Terrestrial ages of Antarctic meteorites.

Meteorite	Class	Terrestrial age (10^3 yr)	Method	Reference
ALHA 76002	Iron	210±80	^{36}Cl	7
ALHA 76005	Eu	>34	^{14}C	1
ALHA 76006	H6	>34	^{14}C	1
ALHA 76007	L6	>34	^{14}C	1
ALHA 76008	H6	>32	^{14}C	1
		<160	^{36}Cl	5
ALHA 77001	L6	<130	^{36}Cl	6
ALHA 77002	L5	690±170	^{36}Cl	5
ALHA 77003	H3	35	^{14}C	4
ALHA 77004	H4	36	^{14}C	4
		180±80	^{36}Cl	7
ALHA 77015	L3	470±230	^{26}Al-^{53}Mn	7
ALHA 77167	L3	400±180	^{26}Al-^{53}Mn	7
ALHA 77214	L3	41	^{14}C	4
		130±80	^{36}Cl	6
ALHA 77249	L3	500±180	^{26}Al-^{53}Mn	7
ALHA 77256	D	11	^{14}C	2
ALHA 77257	U	370±90	^{36}Cl	6
ALHA 77258	H6	270±80	^{36}Cl	7
ALHA 77260	L3	270±190	^{26}Al-^{53}Mn	7
ALHA 77272	L6	540±80	^{36}Cl	6
ALHA 77278	LL3	320±90	^{36}Cl	6
ALHA 77282	L6	∿30	^{14}C	3
ALHA 77285	H6	220±80	^{36}Cl	7
ALHA 77294	H5	30	^{14}C	3
ALHA 77297	L6	>35	^{14}C	3
ALHA 77299	H3	<150	^{36}Cl	6
ALHA 78084	H3	140±70	^{36}Cl	7
ALHA 78112	L6	230±80	^{36}Cl	7
ALHA 78114	L6	460±80	^{36}Cl	7
ALHA 78115	H6	<90	^{36}Cl	7
ALHA 78130	L6	<100	^{36}Cl	7
META 78001	H4	<120	^{36}Cl	7
PGPA 77006	Iron	90±70	^{36}Cl	7
Yamato 7301	H4	<190	^{36}Cl	5
Yamato 7304	L5	7.5	^{14}C	4
Yamato 74156	H4	<120	^{36}Cl	7
Yamato 74492	H3	<100	^{36}Cl	7

WEATHERING EFFECTS IN ANTARCTIC METEORITES. Michael E. Lipschutz, Dept. of Chemistry, Purdue Univ., W. Lafayette, IN 47907.

Macroscopically, stony meteorites from Antarctica are classified by degree of weathering and fracturing, each increasing in severity from class A to C. On sectioning, some specimens are found to exhibit weathering rinds. Surficial deposits of hydrated magnesium carbonates and sulfates found on 7 of ∿300 specimens of the 1977/78 collection are attributed to early stages of weathering after exposure on the ice surface (Marvin and Motylewski, 1980); 5 of the 7 were of weathering type A. No correlation appears between terrestrial age (Fireman, and Norris,1981; Nishiizumi K. and Arnold J. R., 1981) and weathering type, indicating no regularity in the portion of terrestrial residence spent within the ice sheet as opposed to on it.

To establish chemical alteration effects by antarctic weathering, comparisons must be made between antarctic meteorite compositions and those of non-antarctic meteorite falls and/or between exterior and interior portions of antarctic specimens. Chemical studies so far emphasized relatively unweathered specimens. Indigenous amino acid composition and contents in exterior and interior portions of a C2 chondrite seem unaffected by weathering (Cronin et al., 1979); organic contamination in Antarctica seems unimportant.

Trace elements (ppm-ppt levels) are particularly useful in establishing weathering effects since small absolute changes result in large relative ones. Some data exist for C and S (Gibson and Yanai, 1979a,b,; Gibson and Andrawes, 1980); Ag, As, Au, Bi, Cd, Co, Cs, Cu, Ga, In, Rb, Sb, Se, Te, Tl and Zn (McSween et al., 1979; Biswas et al., 1980a,b,; 1981) and cosmochronologic isotopes of Hf, Lu, Pb, Th and U (Patchett and Tatsumoto, 1980; Tatsumoto et al., 1981). In general, interior samples of antarctic specimens (both volatile-rich and volatile-poor) seem compositionally unaffected by weathering. Exterior samples (i.e. 0-1 cm depth) indicate contamination by C and alkalis and, on occasion, other elements or loss (by leaching) of still other elements - Ag, Bi, Cd, In, Sb, Se, Te and Tl (Gibson and Andrawes, 1979, Biswas et al., 1980a,b). Six elements - As, Au, Co, Cu, Ga and Zn - seem unaffected by weathering even in exterior samples. Where comparison is possible, trace elements contents in interior samples of antarctic meteorites correlate with contents in congeneric non-antarctic meteorite falls at least as well as do the falls themselves (Biswas et al., 1981). Some interior samples indicate re-distribution, contamination and/or loss of cosmochronologic nuclides; other specimens seem unaffected by antarctic weathering (Patchett and Tatsumoto, 1980; Tatsumoto et al., 1981).

It seems therefore that results of cosmochronologic studies of antarctic meteorites should be viewed with caution. From the chemical standpoint, interior samples of weathering type A or B meteorites, at least, yield trace element data as reliable as those from non-antarctic falls (Biswas et al., 1981). Weathering type C meteorites have yet to be studied. From a compositional standpoint, antarctic meteorites undoubtedly constitute extremely valuable material to learn of extraterrestrial genetic processes. They also hold the promise of teaching us about weathering processes in Antarctica.

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DELINEATION OF BLUE-ICE AREAS IN ANTARCTICA FROM SATELLITE IMAGERY

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Areas of bare glacier ice are present in many parts of Antarctica, although they occur primarily in coastal areas or in the interior upstream and/or downwind from nunataks. Such areas of exposed glacial ice are called "blue ice" because of the stark contrast between the turquoise-blue color of the ice and the adjacent, much more extensive white snow-covered regions. The term blue ice is still used in the vernacular; it does not appear, for example, in the authoritative second edition of the Illustrated Glossary of Snow and Ice (Armstrong and others, 1973). Areas of blue ice are caused by ablation, in which the principal processes are: (1) sublimation; (2) wind deflation of the snow-mantled surface; and (3) wind erosion of the ice by ice particles.

Prior to the 1970's, meteorites were only rarely found in Antarctica, and most were accidently discovered during overland traverses (Hey, 1966). During the 1969-70 field season, however, Japanese scientists discovered nine stony meteorites in a blue-ice area of the Queen Fabiola (Yamato) Mountains and suggested that Antarctica might be a rich source of meteorites (Yoshida and others, 1971). In just over a decade, approximately 5,300 meteorite fragments have been recovered by Japanese (4,200 specimens) and U.S. (1,100 specimens) scientists, nearly all from blue-ice areas of the Queen Fabiola (Yamato) Mountains and the Allan Hills, respectively (Cassidy, 1979, written communication, 1982).

Most of the meteorites recovered to date in Antarctica have been from areas of blue ice, especially from areas around nunataks or where the normal flow of glacier ice is impeded or stopped. Such concentrations of meteorites represent a special type of lag deposit. Therefore, areas of blue ice are of special significance in the search for more meteorites. However, areas of blue ice must first be identified by surface traverse (least efficient means), aerial reconnaissance, use of aerial photographs (vertical or trimetrogon), or satellite images (Landsat or NOAA) (which are the most efficient means). Favorable areas may then be visited in the field.

The launch of the first of three successive Landsat spacecraft in July 1972 provided the first opportunity for systematic satellite image coverage of Antarctica. Thanks to the late William R. MacDonald of the U.S. Geological Survey, whose ERTS-1 experiment (SR 149) was directed at the systematic acquisition of Landsat images of Antarctica to support the preparation of Landsat image maps (MacDonald, 1976), 70 percent of the Landsat imaging area (from the coast to about 82^{o} South latitude), or 55 percent of the continent, now has cloudfree or near-cloudfree (less than 10 percent cloud cover) coverage (Williams and others, 1982). Excellent Landsat images of the Queen Fabiola (Yamato) Mountains were first acquired in December 1973. By 1976, the National Institute of Polar Research in Tokyo, Japan, had published a 1:200,000-scale Landsat image "(Working) Map of the Meteorite Ice Field, Yamato Mountains, Antarctica" (1976), which delineated areas of blue ice, nunataks, morainic debris, and spot elevations (from ground surveys).

In our work on the "Satellite Image Atlas of Glaciers" project (Williams and Ferrigno, 1981), we have devoted considerable effort to identifying all optimum Landsat 1, 2, and 3 MSS (multispectral scanner) and RBV (return beam vidicon) images of Antarctica. Landsat 1, 2, and 3 MSS and Landsat 2 RBV images of Antarctica have a pixel (picture element) size of about 80 m; the Landsat 3 RBV image has a pixel size of about 30 m.

Landsat 1, 2, and 3 MSS images are normally acquired in four spectral bands: MSS band 4, 0.5 to 0.6 μm; MSS band 5, 0.6 to 0.7 μm; MSS band 6, 0.7 to 0.8 μm; and MSS band 7, 0.8 to 1.1 μm. The Landsat 3 RBV image is recorded in one broad spectral band, 0.505 to 0.750 μm. In the identification of blue-ice areas, MSS bands 6 and 7 are similar, with band 7 somewhat better than MSS band 6. MSS band 5, however, is best in areas of bedrock exposure (nunataks) to properly differentiate between areas of blue ice and bedrock (or morainic debris). On MSS bands 6 and 7, blue ice and bedrock/morainic debris usually have a similar spectral response. Mark F. Meier (written communication, 1982) has suggested experimenting with computer-assisted analysis of different MSS bands, because, "Blue ice ought to be distinctive enough (spectrally) for a computer to identify with high accuracy".

From the coast of Antarctica to the limits of Landsat coverage, only about 519 Landsat images are needed to achieve complete coverage out of 2,470 nominal scene centers that cover the area (because of sidelap of adjacent images caused by convergence of Landsat orbits). In the region beyond 82° South latitude, advanced very high resolution radiometer (AVHRR) images from the NOAA series of weather satellites can be used to identify areas of blue ice, although the 1-km pixel size of the image provides tenfold less detail than that available from the Landsat MSS image. Both the U.S. and the U.S.S.R. have the capability of observing Antarctica from sophisticated surveillance satellites; however, data from such satellites are not available to the general scientific community.

The Landsat MSS band 7 images, in particular, represent a means of systematically searching for and delineating areas of blue ice from the coast to north of about 82° South latitude. This technique was apparently first suggested informally by William R. MacDonald and subsequently used by William A. Cassidy. NOAA AVHRR images could be used for the area poleward of 82° South latitude. A combination of Landsat and NOAA images could be used to compile, at a scale of 1:5,000,000, a special thematic map: "Blue-Ice Areas of Antarctica and Locations of Meteorite Finds." Such a map, or a larger scale version thereof, could then be used in conjunction with Landsat MSS bands 5 or 7 images in field surveys to systematically visit each area of blue ice.

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GLACIOLOGIC NOTES ON THE ALLAN HILLS AREA; I.M. Whillans, Institute of Polar Studies, and Department of Geology & Mineralogy, Ohio State University, 125 S. Oval Mall, Columbus, OH 43210, and W.A. Cassidy, Department of Geology and Planetary Science, University of Pittsburgh, Pittsburgh, PA 15260

Some of the glaciologic features near the Allan Hills are described and discussed. These include:

(1) Anomalous "wrong way" or abandoned glaciers which may be relicts from a former more extensive ice sheet.

(2) Small accumulation zones, for example at the 1981-82 camp, may be the result of the drift snow flow pattern. The importance of these firn fields to the location of especially,small meteorites is discussed.

(3) Ice and firn pinnacles are believed to be ablation-albedo feed-back features occurring at the lower extent of firn fields.

(4) Microcracks, spaced about 3 cm apart, are probably thermal in origin.

(5) The dust bands are probably tephra or other rock debris deposited on the main accumulation zone of the ice sheet. Their surface expression is consistent with normal glacial flow.

(6) Ice ripples and whaleback forms are aerodynamic features formed during evaporative sublimation.

(7) Bubbles appear to occur along crystal boundaries. The only other known investigation of normally exposed deep ice obtained the same result (C.C. Langway, Jr., personal communication, Feb. 1982, for north Greenland).

(8) The processes controlling ablation near the Allan Hills are not properly understood, but we speculate that ablation rates there are not unusual for South Victoria Land.

All of these points need closer investigation if the meteorite occurrences and the underlying ice are to be more fully understood.

CONTRIBUTIONS FROM OXYGEN ISOTOPE STUDIES TO PALEOCLIMATOLOGY AND THE KNOWLEDGE OF ICE FLOW CONDITIONS

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In the Quaternary Isotope Laboratory at the University of Washington, Seattle, water samples are equilibrated with CO_2 in a Micromass 5020 sample system on line with a Micromass 903 triple collector mass spectrometer. Sample equilibration and mass spectrometer measurement are controlled by an HP-1000 computer. Forty-eight samples can be measured in a 24-hour period with a precision (including sample preparation) of 0.1‰. The system is used for paleoclimatic studies measuring ^{18}O variations in precipitation preserved in ice cores.

Precipitation reflects in its isotopic composition variations over a wide frequency spectrum, ranging from isotopic differences within a 10-minute shower, via differences between showers and seasons to glacial/interglacial effects on a time scale of 10^5 years. Post-depositional processes can reduce and eventually eliminate the variations in isotopic composition. These processes are mixing and erosion by wind, partial melting with percolation of the meltwater down into deeper layers, vapor transport in the unconsolidated firn, and diffusion in the solid ice after firnification has reached a density of 550 kg/m^3.[1] The first two influences are unpredictable and make the deposit unfit for study. The remaining factors reduce differences in a gradual and regular way, depending on the steepness of the concentration gradients. Minimum requirement for signal preservation in polar ice seems to be an ice layer thickness of at least 0.20 m[1]. Snowfall in events with frequencies higher than 1 per year rarely reaches this layer thickness and these events are thus rapidly obliterated. In areas with relatively high precipitation in Greenland, the annual accumulation is in excess of 0.20 m of ice and seasonal fluctuations are preserved in the ice to considerable depths. In Antarctica, annual precipitation is much lower and a continuous record of annual layering has so far not been observed.

To study the changes of climate with time, recorded in an ice core, the core has to be dated. Age determination using radioactive isotopes trapped in the ice is difficult due to their low concentrations and consequently the large sample size required to make this determination.[2] The development of direct detection of cosmogenic isotopes using accelerator mass spectrometry improves this situation, because this technique requires only about 1 mg of sample (carbon, beryllium, chlorine, etc.). Meanwhile, it would be very useful if a time scale could be obtained from periodic fluctuations in the $\delta^{18}O$ record itself. The search for annual cycles enabling a year by year count-down analogous to tree rings has been successful on Greenland, where three cores of about 400 m length were obtained that showed distinct annual cycles (Milcent: 796, Crête: 1426, and Dye 3: 728 annual layers). Comparison of these annual records with a time scale based on ice flow calculations proves the reliability of the ice flow equations when used to study the top layers of an ice sheet. On Greenland, a reliable time scale for the last two millennia has been established and the pattern of ^{18}O depletion has been interpreted in terms of temperature change in the past. Spectral analysis of the well dated ^{18}O records with different low-pass filters identifies different $\delta^{18}O$ (= climatic) cycles.

If one assumes that the period of these cycles (78, 181, 350, and 2100 years in the Camp Century core[3]) is constant, one can use them to extend the time scale of a $\delta^{18}O$ record beyond the range of observable annual layering. For the Camp Century ice core the long cycles of 350 and 2100 years were identified with solar variations of 405 and 2400 years, showing up in the dendrochronologically calibrated ^{14}C record.[4] A good correlation with ^{14}C dated climate records from North America and Europe was obtained. The 2400 year cycle then provided the time scale for the Camp Century ice core through the last glacial into the previous interglacial.[3] A problem in establishing the older part of the climate record and its time scale is that due to thinning about 90% of the record is contained in the lower 15% of the ice.

In Antarctic ice cores, the lack of annual layering makes it hard to establish a reliable time frame for the climatic variations recorded in the ice. The Byrd Station ^{18}O record has been correlated with that of Camp Century[5] and a few ^{14}C dates have been obtained. The Dome C time scale was derived from ice flow calculations and subsequently adjusted by correlation with a ^{14}C dated marine sediment core from the Indian Ocean.[6] The time frames for other cores like Vostok, Dome Summit, D10, Little America, and J-9 are equally uncertain. Prominent features like the ~5‰ increase in $\delta^{18}O$ at the transition from the last glacial to the present interglacial are evident in several cores. Low accumulation, changes in thickness of the ice sheet and the lack of time control make detailed correlations difficult. More work is needed to improve this situation.

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SPHERICAL PARTICLES IN ANTARCTIC ICE CORES. L.G. Thompson and E. Mosley-Thompson, Institute of Polar Studies, Ohio State University, Columbus, OH 43210.

Antarctica is considered an ideal site for investigating the natural particulate content of the global background aerosol. The four primary sources of Antarctic particulates are the desert regions of the Southern Hemisphere, ocean surface aerosols, volcanic emissions and extraterrestrial sources. The spherical particles expected to be cosmic in origin have received more attention than the irregular particles as they are more easily identified. In 1870 Nordenskold (1) first discovered nickel-iron dust on the Greenland Ice Cap and suggested that the metallic particles might be of cosmic origin. Since then spherical particles have been reported (2,3,4) in numerous snow and ice samples.

The concentration and size distribution of insoluble particles within firn and ice cores are measured by the Coulter technique conducted within a class 100 clean room. The remaining sample is filtered onto 0.45 μm millipore filters. The retained particles are further examined using a light microscope and scanning electron microscope coupled with elemental analysis by an x-ray energy dispersive system. Each millipore filter contains the filtrate from approximately 10 samples (≅120 ml of meltwater). In a typical Holocene sample (snow deposited in the last 10,000 years) a filter contains an average of 1.6 million particles (diameters >0.63 μm). Approximately 1% or 15,000 particles exceed 2 μm in diameter and thus can be easily examined using a light microscope and classified as to particle type. A total of 4992 particles (14 filters) for the Byrd Station core, 7929 particles (23 filters) for the South Pole core and 9461 particles (77 filters) from the Dome C core were visually examined by light microscope and classified into particle types based on morphology. A minimum of 350 particles are randomly examined per selected core section for classification.

Using this classification the number of spherical particles of possible cosmic origin were identified as follows: (a) eight spheres in the 2164-m Byrd Station core representing 0.2% of the classified particles, (b) six spheres in the 101-m South Pole core representing 0.11% of the classified particles, and (c) one sphere in the 905-m Dome C core representing 0.01% of the classified particles. Thus of the total particles examined from these three Antarctica ice cores less than 0.1% are spherical and of possible extraterrestrial origin. The diameters of these spherical particles range from 1.1 μm to 15.2 μm, with the majority measuring less than 10 μm. No significant variations in the numbers of the spherical particles were noted with depth in these cores. The most striking particle is the steel-gray spherule with a shiny, metallic luster and a high degree of reflectivity. The lack of tarnish or oxidation is the most remarkable feature of these particles. Roughly half of the spherules were composed primarily of silicon and iron with lesser amounts of aluminum and potassium. The other half were found to be very predominantly iron with small quantities of silicon and aluminum. No nickel was found in these particles.

Certainly not all extraterrestrial dust in ice cores is spherical, but these are most easily identified. Ice cores provide an abundance of particles from a variety of sources; therefore, it may be beneficial to become more familiar with the identification procedures employed by scientists associated with NASA's dust program.

The 905-meter Dome C core (74°39'S, 124°10'E, 3240 m above sea level) was drilled approximately 1000 km up flowline from the Allan Hills area. Approximate dates for this core were assigned by using "annual" microparticle concentration peaks (5). The maximum estimate for the age at the bottom is 30,000 years, slightly older than 27,000 years derived from Nye's model (7). On the basis of the 51 sections of the Dome C core analyzed no consistent or substantial reduction in the net surface accumulation exists. This supports a steady state condition for this region of the East Antarctic Ice Sheet over the last 30,000 years.

Ice flow in the bare ice area near the Allan Hills has been examined (8). Average rates of emergence of the bare ice in the region of high meteorite accumulation is estimated to be 0.045 m a^{-1}. On average the ablation rates are balanced by the emergent velocity of the ice. If the ice flow is uncomplicated the ice core stratigraphic parameters (7,9) such as microparticle concentrations and oxygen isotope ratios used in the Dome C core to define the glacial history of the ice sheet might reappear at the surface up flowline from Allan Hills and be employed to determine whether the ice is Holocene or Wisconsin in age.

Accurate dating of ice cores is essential for interpreting the records contained therein. The potential for dating errors increases with depth in the core and is a particular problem on the central Antarctic plateau where accumulation rates are low (<0.1 m a^{-1}) and where the deepest cores and hence the longest records, will be obtained. If older ice (>30,000 years) is identified in the Allan Hills region and dated by the entrained meteorites or radioactive decay dates on the ice, it may be possible in the future to correlate these layers with similar horizons of microparticle concentrations and oxygen isotopic ratios in deeper ice cores further inland. If accomplished this would provide very valuable time-stratigraphic markers in the East Antarctic Ice Sheet.

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