

**WORKSHOP ON
DIFFERENCES BETWEEN ANTARCTIC AND
NON-ANTARCTIC METEORITES**

**Edited by
Christian Koeberl and William A. Cassidy**

**Held at
Vienna, Austria
July 27 - 28, 1989**

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Introduction

Until about 20 years ago, non-Antarctic meteorites were the only available samples of the meteorite parent body population. A few thousand individual meteorites of different types were known. This has changed rapidly with the discovery of meteorites on the bare blue ice areas in Antarctica. From 1969 onward, an ever increasing number of meteorites has been recovered from remote locations in Antarctica by expeditions from the United States of America, Japan, and other countries. To date, more than 12,000 individual specimens have been collected in Antarctica. The question of pairing among these samples is not easy to solve, but it may be estimated that they represent about 2000-4000 distinct falls. This is a number that is at least equal to, but most probably larger than, the number of known non-Antarctic meteorites (which is on the order of 2500). Meteorites are of crucial importance for the Earth and planetary sciences, because they are the oldest materials available from our solar system and sample a large variety of parent bodies. They carry unique information about the origin and evolution of the solar system, and are especially valuable because they can be investigated in the laboratory with a complete set of sophisticated techniques.

What has made Antarctic meteorites so valuable is the realization that the Antarctic collection contains a large number of meteorite types that were either unknown from or underrepresented within the non-Antarctic collection. The most famous examples are the lunar meteorites, which have so far been recovered exclusively from Antarctica. But rare iron meteorites, SNCs, and other unusual achondrites have also been found in Antarctica. The investigation of these samples has been of great importance to our understanding of meteorites and their parent bodies (including the Moon). However, Antarctic meteorites are also important because of their sheer numbers, thus providing a wealth of material for statistical analysis. Gradually it was realized

that there are some apparent differences between the Antarctic and the non-Antarctic meteorite populations; some subtle, some not so subtle.

Only a very short time ago these differences between Antarctic and non-Antarctic meteorites were by no means generally accepted. (One reason for this was the lack of extensive datasets; this situation is changing, albeit slowly.) As this subject had been a point of discussion at several recent meetings, however, we felt that the time was ripe to hold a workshop entirely dedicated to the question of differences between Antarctic and non-Antarctic meteorites.

The objective of the workshop was to review the known facts, together with new research results, in order to examine apparent differences between the Antarctic and non-Antarctic populations. In view of the statistically significant number of Antarctic meteorites, and the existence of rare or previously unknown types of meteorites among the Antarctic meteorite collection, the question was really not so much whether there *are* differences, but to define which ones are significant and what their origin is. Two main causes for the possible differences have been suggested previously, namely differences in the meteorite parent populations and secondary effects (e.g., weathering).

In assessing the reality of differences between the two collections the considerably different terrestrial history of Antarctic meteorites must be considered. The average terrestrial age of Antarctic (stony) meteorites is much greater than that of non-Antarctic meteorites. During their time on Earth, most Antarctic meteorites have remained buried in ice, subjected to a conserving but nevertheless extreme climate. The effects of the Antarctic environment on meteorites are not well known, partly due to the timescales involved, and must be taken into account when discussing any differences. Furthermore, Antarctic meteorites are much smaller than non-Antarctic meteorites, thus mass and size frequency effects may play a prominent role.

All of these questions had to be addressed in order to have a balanced discussion of the problem. The workshop was thus structured to contain sessions on chemical, isotopic, petrological, and mineralogical studies of meteorites from the two collections; terrestrial age determinations; discussions on mass frequency distributions; relative abundances of meteorite types; and terrestrial meteorite flux rates and their possible changes with time.

The workshop on "Differences Between Antarctic and Non-Antarctic Meteorites" was held July 27-28, 1989, in Vienna, Austria, at the Institute of Geochemistry of the University of Vienna. The meeting was attended by 45 participants from 10 countries (22 from the U.S., 5 from West Germany, 4 from Austria, 3 each from France, Japan, and Switzerland, 2 from the United Kingdom, and 1 each from Denmark, the Netherlands, and the U.S.S.R.). The workshop was structured using invited and contributed papers that were presented in talks or posters, and ample time was devoted to discussions. Each of the five sessions was followed by a general discussion of all papers presented at the respective session. Toward the end of the workshop, a panel discussion was held, and three participants were asked to provide summaries of the workshop sessions. This was followed by a general summary and recommendations for future work.

The workshop has been successful in clearly defining the problem and leading everyone to at least agree that differences between the Antarctic and non-Antarctic meteorite collections are present. Studies of the distribution of trace elements in meteorites, as well as textural and isotopic studies, have shown that differences do exist. However, first results from the investigation of weathering processes and their effect on meteorites in the Antarctic environment indicated that some of the mineralogical and chemical effects observed in Antarctic meteorites may have been influenced by terrestrial processes. These studies have just begun, so no clear-cut evidence is available at this time. Furthermore, the (previously suggested) influence of mass frequency distributions has emerged as a possible factor for explaining the differences.

It is clear that the workshop could not answer all of the questions pertaining to differences between Antarctic and non-Antarctic meteorites, but it was important to raise the questions and provide an evaluation of the current state of the problem together with directions for future research. The long discussion periods were essential in showing that some pieces of the puzzle have been solved, but that there is still much that we do not know.

This report contains abstracts of papers presented at the technical sessions of the workshop, together with summaries of the five sessions and a general summary of the workshop with recommendations for future work. Several abstracts have been expanded and revised after the meeting, thus providing up-to-date discussions of the respective research topics. We feel that the workshop was highly successful in defining the problem and showing directions for the future.

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November 1989

Program

Thursday, July 27

- 10:00 - 12:00 Registration and small welcome party at the Institute of Geochemistry,
University of Vienna
- 12:00 - 13:20 Lunch break
- 13:20 Workshop begins
- 13:20 - 13:30 Welcome, definition of the problems, and ground rules for the workshop

SESSION A: CHEMISTRY AND PETROLOGY Chairman: D. W. G. Sears

- 13:30 - 13:50 Lipschutz M. E.*
*Chemical Compositional Comparison of Antarctic and Non-Antarctic
Meteorite Populations*
- 13:50 - 14:10 Jarosewich E.*
Chemical Composition of Antarctic and Non-Antarctic Chondrites: A Comparison
- 14:10 - 14:30 Mittlefehldt D. W.* Lindstrom M. M.
Eucrites: Antarctica Versus the Rest of the World
- 14:30 - 14:50 Takeda H.*
*Comparisons of Antarctic and Non-Antarctic Achondrites and a Possible Origin
of the Difference*
- 14:50 - 15:30 General Discussion
- PRINT ONLY Tomeoka K. Kojima H.
*Yamato-82162 and 86720: New Kinds of Carbonaceous Chondrites; Mineralogical
and Chemical Comparison*
- 15:30 - 16:00 Coffee break and poster viewing

SESSION B: EFFECTS OF WEATHERING AND THERMOLUMINESCENCE Chairman: M. E. Lipschutz

- 16:00 - 16:20 Velbel M. A.* Gooding J. L.
Terrestrial Weathering of Antarctic Meteorites: Developments 1985 - 1988
- 16:20 - 16:40 Buchwald V. F.*
*On the Difference Between Weathering Products on Antarctic and
Non-Antarctic Meteorites*

*Denotes speaker.

- 16:40 - 17:00 Nishiizumi K.*
Weathering Effects on and Terrestrial Ages From Cosmogenic Radionuclides in Antarctic and Non-Antarctic Meteorites
- 17:00 - 17:20 Sears D. W. G.*
A Comparison of the Induced Thermoluminescence Properties of Antarctic and Non-Antarctic H Chondrites
- 17:20 - 18:00 General Discussion
- POSTER Ebihara M. Shinonaga H. Nakahara H. Kondoh A. Honda M.
Miyamoto M. Kojima H.
Depth-Profiles of Halogen Abundance and Integrated Degree of Hydration Band Near 3 μ in ALH 77231, Antarctic L6 Chondrite
- PRINT ONLY Miyamoto M.
Differences in the Degree of Weathering Between Antarctic and Non-Antarctic Ordinary Chondrites

Friday, July 28

SESSION C: ISOTOPES AND AGES
Chairman: D. W. Mittlefehldt

- 9:00 - 9:20 Clayton R. N.* Mayeda T. K.
Oxygen Isotopic Composition of Antarctic Meteorites
- 9:20 - 9:40 Grady M. M.* Wright I. P. Pillinger C. T.
Comparisons Between Antarctic and Non-Antarctic Meteorites Based on Carbon Stable Isotope Geochemistry
- 9:40 - 10:00 Schultz L.* Weber H. W. Begemann F.
Exposure Ages of Antarctic and Non-Antarctic H-chondrites
- 10:00 - 10:30 General Discussion
- POSTER Englert P.
The Use of Cosmogenic Radionuclides in the Search of Distinct Group Characteristics of Antarctic Meteorites
- POSTER Bhandari N.
Terrestrial Ages of Antarctic Meteorites
- PRINT ONLY Herpers U. Vogt S. Signer P. Wieler R. Beer J. Wölflí W.
Cosmogenic Radionuclides and Noble Gases in Allan Hills C-Chondrites
- 10:30 - 11:00 Coffee break and poster viewing

SESSION D: POPULATION DIFFERENCES
Chairman: L. Schultz

- 11:00 - 11:20 Huss G. R.*
Meteorite Mass Distributions and Differences Between Antarctic and Non-Antarctic Meteorites
- 11:20 - 11:40 Harvey R. P.*
Statistical Differences Between Antarctic Finds and Modern Falls: Mass Frequency Distributions and Relative Abundances by Type
- 11:40 - 12:00 Cassidy W. A.*
Are There Real Differences Between Antarctic Meteorites and Modern Falls?
- 12:00 - 12:30 General Discussion
- POSTER Samuels S.
Application of Statistics to Antarctic, Non-Antarctic Differences
- PRINT ONLY Lipschutz M. E.
Differences Between Antarctic and Non-Antarctic Meteorite Populations
- 12:30 - 14:00 Lunch break

SESSION E: METEORITE FLUX RATES
Chairman: R. P. Harvey

- 14:00 - 14:20 Wetherill G. W.*
Dynamical Time Scale of the Terrestrial Meteorite Flux
- 14:20 - 14:40 Yiou F.* Raisbeck G. M.
Cosmic Spherules from Antarctic Ice Cores as Proxy Indicators of Extraterrestrial Matter Influx During the Last ~ 150,000 Years
- 14:40 - 15:00 Maurette M.* Bradley J. P. Hammer C. Pourchet M. Veysieres P.
Micrometeorites from the Greenland and Antarctica Ice Sheets: Preliminary Comparison With Deep Sea Micrometeorites, Stratospheric IDP's, and Primitive Meteorites
- 15:00 - 15:30 General discussion
- 15:30 - 16:00 Coffee break and poster viewing
- 16:00 - 17:00 Panel discussion and general discussion
 Panel members: R. Clarke, D. Lal, M. Lindstrom, M. Lipschutz, and G. Wetherill
- 17:00 - 17:45 Summaries of sessions
- 17:45 - 18:00 Koeberl C. Cassidy W. A.
 General summary, recommendations, and closing remarks

Summary of Technical Sessions

These summaries of presentations and discussions are based on notes taken by the respective participants who kindly agreed to serve as summarizers and (for the general summary) on recordings made during the discussion parts of the workshop. The following summaries represent the recollection and perception of the authors.

SESSION A
CHEMISTRY AND PETROLOGY
and
SESSION B
EFFECTS OF WEATHERING AND TL
Summarized by D. W. G. Sears

Those who spoke during the sessions, both during presentations and discussions, universally accepted that there were differences between the meteorites collected in the Antarctic and those collected elsewhere in the world. However, the significance of these differences was not obvious, and two questions repeatedly emerged whenever the interpretation of these differences was addressed. One of these questions concerned the effect of weathering. No one at the meeting felt that the present system of "weathering category" (A-C) was sufficiently sophisticated for scientific studies of weathering effects, although it does constitute a reasonable record of the curators' observations based on the hand specimens.

The other question concerned the amount of pairing present in the Antarctic meteorite collection. This question arose whenever distributions of a statistical nature were discussed, especially in connection with the extraordinary number of rare and unusual meteorites in the Antarctic collections. M. Lipschutz reviewed a wide variety of data that display differences between Antarctic and non-Antarctic meteorites. In particular, Lipschutz described the statistical analyses he and S. Samuels have made of 13 minor and trace elements. In a typical run, they have found that four or five elements differ significantly when Antarctic and non-Antarctic meteorites are compared. Lipschutz argued that these differences are not due to weathering but rather indicate that the source of meteorites reaching Earth has changed since the Antarctic meteorites fell.

E. Jarosewich also found differences in the composition of chondrites between Antarctic meteorites and non-Antarctic meteorite finds, with the latter being lower in Fe, Na, and S and higher in water. However, since non-Antarctic finds are in some cases intermediate to the previous two groups, he concludes that those compositional differences reflect weathering. Jarosewich

also pointed out that there was no correlation between the alteration indicated by bulk chemistry and weathering category.

D. Mittlefehldt (with M. M. Lindstrom) described rare earth element data for eucrites and showed that Antarctic eucrites were not only depleted in REE with respect to non-Antarctic eucrites but also showed positive Eu anomalies and both positive and negative Ce anomalies. This is readily interpreted in terms of leaching out REE during weathering, but with much of the Eu not being leached out because it is located in plagioclase. The Ce is suggested to be oxidized to +4 and fractionated relative to the +3 REE. However, the process is more complicated than this. Mittlefehldt also found that even in interior chips from little-weathered stones Ce can be either enriched or depleted with respect to non-Antarctic eucrites. Another significant difference between Antarctic and non-Antarctic eucrites was described by Mittlefehldt, namely that Se is always considerably enriched in Antarctic eucrites.

M. Velbel identified five or six processes that occur during weathering, of which only one or two are represented in the weathering category (oxidation and hydration). Other processes may be even more important, such as those (solution and chelation) that result in the appearance of evaporites on meteorite surfaces. As with bulk composition, there is no correlation between weathering category and the appearance of evaporites. Some major and trace elements are likely to be mobilized (leached) during weathering.

The complexity of the weathering process was further demonstrated by V. Buchwald, who described six commonly found oxides or hydroxides of iron that are weathering products, including akaganeite (β FeOOH). This mineral is produced by a process catalyzed by Cl and occurs in the solid state at subzero temperatures, quite unlike conventional views of "weathering" that involve fluids. There is a sufficient supply of Cl in the Antarctic environment (e.g., snow and ice introduced from marine sources) leading to the formation of akaganeite with up to 5 wt.% Cl.

D. Sears ascribed the threefold difference in TL sensitivity between Antarctic and non-Antarctic H chondrites to weathering, even though TL sensitivity did not correlate with weathering category. He argued that the TL was probably affected by smaller levels of weathering than would significantly affect the appearance of the hand specimen.

K. Nishiizumi described measurements that explored the possibility that weathering affected terrestrial age measurements based on cosmogenic isotopes. Terrestrial age differences between collection sites and, in

one case, from one end of a site to the other, have considerable implications for concentration mechanisms. However, since metal and silicate separates gave the same results, suggesting no redistribution of isotopes, and since this was true of all the meteorite classes, he was confident that his terrestrial age data were reliable. Nishiizumi suggested that the influx of different classes of meteorites relative to each other may change with time if the measured age frequency distribution is real. However, more terrestrial ages of meteorites are necessary to support this suggestion.

Two new methods of terrestrial age determination were described by N. Bhandari in a related poster paper in Session C, one involving the use of three cosmogenic isotopes whose activities show little depth dependence and one involving the measurement of TL buildup in and near the fusion crust. As mentioned above, pairing might explain a number of differences between Antarctic and non-Antarctic meteorites when the data are of statistical significance. The difference between Antarctic and non-Antarctic H chondrites in the temperature-width data of their induced TL peaks described by D. Sears is a case in point. If there is considerable pairing between the Antarctic meteorites studied, then the data would suggest that there are just one or two meteorites with an unusual postmetamorphic history, and not the whole Antarctic population.

Similarly, K. Nishiizumi observed that the terrestrial age distribution he reported could be seriously affected if there were significant pairing among his samples. The anomalously large number of rare and unusual meteorites in the Antarctic collection might also be less "anomalous" if considerable pairing occurs.

H. Takeda pointed out that the 27 Yamato diogenites are actually from only 2 separate falls and that at least 9 of the 27 polymict eucrites from the Antarctic are paired, as are 3 of the 5 Yamato lunar meteorites. He further described some Antarctic ureilites that are unlike non-Antarctic ureilites. Takeda showed that there are textural and chemical differences between Antarctic and non-Antarctic monomict eucrites, and that there is an overabundance of polymict eucrites in the Antarctic collection. He also stated that Antarctic diogenites are distinctly different from non-Antarctic ones, and reported the discovery of Antarctic HEDs that fill the compositional gap between diogenites and cumulate eucrites.

Most of the Antarctic C2 chondrites have extremely low cosmic-ray exposure ages (<200,000 yr), which may also indicate considerable pairing. However, U. Herpers and his colleagues, in a related poster paper in Session C, urge caution in pairing all of these meteorites since the Al-26 and Be-10 activities they reported at the meeting are so variable. It remains true, however, that a great many types of meteorites are found in the Antarctic collection that are not found elsewhere in the world.

K. Tomeoka and H. Kojima, in a print only contribution, describe two meteorites (Yamato 82162 and Yamato 86720) whose oxygen isotope data indicate that they are CI but whose mineralogy and petrology indicate that they are metamorphosed CM chondrites.

To those participating, the sessions seemed well worthwhile. Considerable agreement was reached that there were differences, and that weathering and pairing must be carefully taken into account in discussions of those differences. It was also clear that weathering was an extremely complicated process whose effects would probably need to be evaluated independently for each technique applied, and that problems addressed through statistical distribution of data will first have to settle the pairing details for the samples involved.

SESSION C ISOTOPES AND AGES *Summarized by F. Begemann*

In this workshop, or at least in this session, we learned that the term "differences" does not mean that Antarctic meteorites must have properties that are not also found in non-Antarctic meteorites. Rather, what is meant is that there is a range in features that are common to both sets of meteorites, but that the members of the two subsets either form different number frequency distributions or at least lie in different parts within a single distribution.

We have also learned from R. Clayton's oxygen data that uniqueness of a meteorite in one respect or another can be a very temporary feature. Six non-Antarctic meteorites that are "ungrouped" among the members of their set are no longer mavericks, but each has at least one closely matching partner among the Antarctic set.

I was somewhat dismayed to discover that there are two fundamentally different attitudes once differences (in the above sense) have been established to exist between the two subsets of meteorites. One attitude is that *all* differences are due to terrestrial contamination or weathering; the other attitude at the other extreme is that all differences are indigenous and genuine and of preterrestrial origin.

That the truth presumably lies somewhere between these two extremes was evident from the oxygen isotope data presented by Clayton (with T. Mayeda). Oxygen is, of course, the element in which contamination is the least problem, simply because in stony meteorites oxygen is not a trace constituent but rather a major, rock-forming element. It nevertheless has been found to have a distinctly different isotopic composition in (some) Antarctic meteorites as compared to non-Antarctic meteorites. At the same time, however, the data also show that in some of these isotopically anomalous meteorites there occur some minor constituents that have entirely different oxygen isotope abundances. Since these data points fall on the

terrestrial fractionation line they are most easily explained as being due to terrestrial weathering products -- to introduce another controversial term.

Another property in which neither contamination nor weathering (as long as it is moderate) must be feared to affect the results inordinately is the concentration of spallogenic noble gases, as reported by L. Schultz (with co-workers). Hence, the cosmic-ray exposure ages will in turn not be seriously affected. There is also no need to change the conclusion that there is no evidence as yet in the number frequency distribution of the cosmic-ray exposure ages that would support the contention that Antarctic and non-Antarctic meteorites sample different populations. There is also no evidence that if they sample the same population the relative yields for individual components of this population are any different for the two sets. Perhaps I should add, as a word of caution, that the data do not rule out such differences either; perhaps closer scrutiny will bring to light some surprises.

Most prone to be influenced by the effects of contamination and/or weathering are the carbon data. This holds for the carbon contents as well as for the isotopic data. M. Grady (with co-workers) reported the results of carbon stable isotope studies of Antarctic and non-Antarctic meteorites. Stepped combustion after acid treatment of the samples appears to be the way to avoid compromising interferences. The resulting data seem convincing, and I share the authors' belief that among the carbonaceous chondrites there are differences between Antarctic and non-Antarctic samples, in the sense that the relative proportions of carbon-containing components with distinct isotopic signatures are different. But I am as puzzled as Grady et al. as to the meaning of this.

The controversy between the two camps (contamination vs. genuine differences) should at least have made everybody aware that taking clean samples is of crucial importance. Perhaps in the past this problem has not always been fully taken into account, and indeed it may be difficult to solve. Should samples be cut, sawed, or broken? Breaking off a chip from a sample, if feasible, may be the best solution. But then the fracturing will presumably occur along preexisting cracks and it remains to be shown that such cracks have not served as easy conduits for the very contamination one is trying to avoid.

SESSION D POPULATION DIFFERENCES

Summarized by G. F. Herzog

The first papers in this session dealt with the distributions of Antarctic and non-Antarctic meteorites compared by mass, number, and type (G. Huss, R. Harvey, and W. Cassidy). The mass distributions of Antarctic finds and modern falls clearly differ: The

most probable mass for an Antarctic meteorite find is about 1/100 that of a modern meteorite fall. Furthermore, the Antarctic collection includes types of meteorites absent among modern falls. Workshop participants could not agree on whether the differences reflect a change over time in the flux of meteorites hitting the Earth or in the processes associated with impact and recovery. As Cassidy noted, the problem is of interest since a preterrestrial difference could imply the existence of meteorite streams and because it would mean that Antarctic specimens give us a more representative sample of meteorites.

Huss argued against preterrestrial differences. He began with the premise that a power law characteristic of grinding processes in general ought to represent the preterrestrial number distribution. All meteorite populations deviate from the power law at low masses because of collection bias: It is harder to find small meteorites at any location. However, as recovery conditions in the Antarctic are more favorable in this regard than those elsewhere, one expects a smaller average mass for Antarctic meteorites, in agreement with observation. How to translate this expectation into a more quantitative statement is not so obvious.

Huss suggested that the Roosevelt County, New Mexico site (a place where completeness of collection may rival that in the Antarctic ice fields) has a low mass-number density much like that of the Allan Hills and Yamato samples. All meteorite populations also deviate from a power law distribution (and a Gaussian distribution; see below) at high masses. Here workshop participants seemed to agree that we confront a statistical problem, part of whose solution may lie in the presence or absence of stones from just a few large showers. In summary, Huss argued that all differences (regarding mass distribution and relative abundances of meteorite types) between Antarctic and non-Antarctic populations could be explained by terrestrial sampling or statistical effects.

Harvey did not accept Huss's contention that any known collection site represents a good sample of a single, static population of meteorites. Harvey fitted the distributions of modern and of selected Antarctic meteorite populations with log normal (Gaussian) curves, which he noted did not have any particular physical meaning. The best-fit parameters differed significantly. Harvey argued against attempts to rationalize the parameters of the main Allan Hills (ALHA) population in terms of a few large showers, concluding that the ALHA meteorites are either not a good sample or comprise an unusually large number of paired samples.

Cassidy presented a careful comparison of mass distributions by meteorite type. He excluded stony irons and irons from the discussion for statistical reasons. The raw data show an overabundance of ordinary chondrites and underabundances of achondrites and carbonaceous

chondrites in the Antarctic collections compared to modern falls. Recognizing the problems associated with sampling of large masses in particular, Cassidy attempted to remove this effect by fitting the distributions at intermediate masses and extrapolating to larger masses. This procedure shows that carbonaceous chondrites and achondrites occur in the Antarctic and non-Antarctic (modern fall) collections in the same proportions relative to each other but not to ordinary chondrites. Indeed, the whole pattern of differences between Antarctic and non-Antarctic populations is then simply explained if the abundance of ordinary chondrites arriving at Earth in the recent past were some 10% lower than over the last 0.3 Ma.

In the discussion that followed, various possible sources of bias were considered. R. Clarke noted that the collection of modern falls favors showers at the expense of smaller meteorites; D. Lal doubted that modern falls could be regarded as representative; Nishiizumi pointed out that the ALHA collection has relatively few small meteorites; Schultz called for the development and application of better methods for establishing pairing. Begemann asked whether the ablation of Antarctic meteorites might differ from that suffered by meteorites of modern falls. G. Wetherill answered that in the frame of the Earth, the velocity distribution of incoming meteoroids is isotropic.

SESSION E METEORITE FLUX RATES *Summarized by G. F. Herzog*

Session E began with a discussion by Wetherill of dynamical timescales associated with meteorite impact. The average terrestrial age of Antarctic meteorites is about 0.1 Ma. Accordingly, any preterrestrial difference between Antarctic and non-Antarctic populations implies a dramatic change in the source of meteoroids on a timescale of less than 0.1 Ma, perhaps because of the existence and persistence of meteoroid streams. Wetherill argued forcefully against this idea. His dynamical calculations showed that 2 Ma is a hard upper limit on the lifetime of a meteor stream and that 0.2 Ma is a more likely upper limit. Because of the long orbital evolution times necessary to supply meteorite material from the asteroid belt to the Earth, pulses and supply discontinuities would be smoothed and would not cause intrinsic differences between Antarctic finds and modern falls.

As it happens, most meteorites have cosmic-ray exposure ages of more than 1 Ma and appear to have had simple, one-stage exposure histories. Thus it appears virtually impossible that an object with an exposure age of, say, 7 Ma (such as those in the H-chondrite cluster) could preserve the orbital elements of a stream, assuming one existed at the time of a major event. Wetherill suggested that the best place to look for

evidence of meteoroid streams would be among the youngest meteorites, Innisfree and its cohorts in particular. He argued that (postimpact) size-related effects would be the best way to explain differences between Antarctic and non-Antarctic populations.

The second part of this session dealt with flux rate determinations using micrometeorites (F. Yiou and M. Maurette). Yiou (with G. Raisbeck) reported the collection of micrometeorites from 120 kg of a Vostok ice core. Fourteen chondritic spherules were recovered, implying a terrestrial influx of 1500 T/y for particles with radii greater than 50 μm , a somewhat lower value than that obtained by other means. The vertical distribution of the particles hinted at a slightly greater flux in the recent past.

Maurette (with co-workers) compared collections of micrometeorites from the deep sea, Greenland, and the Antarctic. The fraction of glassy and unmelted particles increases steadily as one goes from the deep sea to the Antarctic. Weathering in the deep sea particles is associated with hydrolysis and in the Greenland particles with biogenic action. It is evident that the Antarctic micrometeorites are the best preserved. Maurette suggested that petrologic examination of micrometeorites containing both glassy and crystalline silicates might provide a uniform basis on which to assess weathering. It became clear, however, that it is not easy to calculate past/present variations in the extraterrestrial matter flux rate using the present Antarctic micrometeorite collection.

Another important parameter regarding flux rate determinations of Antarctic meteorites is their terrestrial age. The terrestrial age of Antarctic meteorites can be measured with several different methods, including cosmogenic radionuclides or thermoluminescence. These techniques, as well as results, have been discussed in poster contributions to Session C by N. Bhandari and P. Englert.

GENERAL SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK *C. Koeberl and W. A. Cassidy*

It is evident that all participants at the workshop will accept the conclusion that there *are* differences between Antarctic and non-Antarctic meteorites. All individuals who presented papers and took part in the discussions agreed with this statement. However, the interpretation of the causes of the differences was not by any means unanimous. There are obvious differences in major and minor properties of the two collections. Major differences include different meteorite type frequencies, such as the occurrence of previously rare or unique meteorites (e.g., lunar meteorites, rare iron meteorites, and achondrites). Further differences are exhibited in meteorite textures, the content of trace elements, or the oxygen isotopic compositions. However, these dif-

ferences are not indigenous to all Antarctic meteorites, but rather are indigenous only to meteorites of a certain type.

But there are other, more obvious, differences between the Antarctic samples and others, which are usually not included in this discussion: Antarctic meteorites have greater terrestrial ages, smaller typical masses (per individual sample), and are found in a restricted geographical location on Earth. Even if these last characteristics are not necessarily genetic properties of the individual meteorites, they nevertheless have a direct influence on all other "real" differences. Furthermore, it should not be forgotten that the Antarctic meteorites do not represent a homogeneous sample. The collection of modern falls, usually taken to represent the "non-Antarctic meteorites," is a snapshot in time. It includes meteorites that have been collected over approximately the past century, which is a mere instant compared to the hundreds of thousands of years of "integration time" for the Antarctic samples.

It should be noted, however, that there are considerable terrestrial age differences between meteorites from different parts of Antarctica. Meteorites from the Allan Hills area have consistently greater terrestrial ages than, for example, meteorites from the Yamato Mountains. Furthermore, it would be interesting to find Antarctic meteorites with greater terrestrial ages than presently known. The Antarctic ice sheet has been in existence for several million years, but most of the Antarctic meteorites have terrestrial ages of less than 0.5 Ma. Perhaps some day these old meteorite accumulations will be discovered somewhere in Antarctica.

In this respect, we have to ask if either of the two collections represents a characteristic sample of the meteorite parent body population. This question was frequently asked during the workshop. The Antarctic collection may in some ways represent a better sample of the parent population, because it has been accumulated over a longer period of time. It has been argued that some of the otherwise rare or unknown meteorites that have been found frequently in Antarctica are only abundant there because we are getting down to smaller masses, and the size and mass frequency distribution differences of the Antarctic and non-Antarctic samples may simply be due to the analysis of a more numerous sample. But is it logical to assume that some of these "rare" meteorites should occur exclusively as small specimens? Why does the non-Antarctic meteorite collection contain none or only very few meteorites of these types?

Another question concerns the lunar meteorites. By now we have at least five specimens from the Japanese collection and three from the U.S. collection, all from the highlands. Just recently a mare basalt was identified in the 1987 Elephant Moraine (EETA) collection; this basalt was previously classified as a eucrite. The data favor the number of impacts responsible for delivery of

these samples as at least four. Of course these impacts did not occur simultaneously, thus it is somewhat surprising that we did not find any lunar meteorites among the non-Antarctic samples. A possible explanation might be that because of their similarity with some terrestrial rocks they are not easily identified. Because of the increasing number of lunar meteorites found in the Antarctic collection, however, we have to assume that they are part of the normal influx of extra-terrestrial matter onto the Earth. This in turn indicates that there are differences between the meteorite type frequency distribution between the Antarctic and non-Antarctic populations, which favors the interpretation that the Antarctic collection may be more representative of the parent sources than the non-Antarctic one.

One of the essential problems we are facing at this point is the incompleteness of the data. A number of very specific studies have been made on a few meteorites representing a few types, but not all meteorite types have been investigated in the same way. For example, the siderophile element contents of Antarctic and non-Antarctic ureilites (at least for some of them) seem to differ, but no comparable data are available for most other meteorites. The same holds true for Hg-isotopic ratios, texture studies, and certain trace element studies. The carbon and oxygen isotopes present a diffuse picture. Some of the Antarctic meteorites seem to have a different isotopic ratio; others do not, and even different fractions and leachates of a single meteorite behave differently. The picture that emerges seems to be that the Antarctic meteorites expand the range of characteristics and compositions previously known, without being consistently different. This would be in agreement with the idea that Antarctic meteorites present a more representative sample of the parent population. However, it would seem pertinent to expand past and ongoing studies that are done at different laboratories to include a larger number of meteorites and all available meteorite types. It is clear that this amounts to an increase in research efforts (and the time required for a study) but, in view of the importance of meteorites for solar system studies, the reward is obvious.

The study of Antarctic meteorites has already required some revision of our traditional classification scheme for meteorites. As mentioned before, some meteorite types have been found that were previously unknown. For example, Antarctic carbonaceous chondrites have been identified with properties that are intermediate between CI and CM (e.g., Y-82042, Y-82162) or intermediate between CM and CO (e.g., Y-86720). Achondrites have been found that bridge the traditional gap between, for example, the cumulate eucrites and the diogenites, or extend the known compositional range (Mg-rich ureilites). Antarctic monomict eucrites differ chemically and texturally from non-Antarctic eucrites, and may have experienced a

different thermal history. Some Antarctic CI and CM meteorites have probably experienced open-system thermal metamorphism in the parent bodies at temperatures that so far have been unknown from non-Antarctic carbonaceous chondrites. All these, and other, observations lead to an extension and modification of previously established meteorite classification schemes.

Other issues discussed at the workshop led to specific recommendations for future research. Several participants, in talks and in discussions, commented on the problem of pairing. The question is, how many individual falls are represented in the Antarctic collection? For iron meteorites and other rare samples, this question is answered more easily than for the bulk of the samples, the ordinary chondrites. However, we know from the studies of lunar meteorites that there is no easy answer concerning pairing even for very peculiar samples. Lipschutz suggested that the determination of the noble gas content and cosmogenic nuclides can help identify paired samples. However, as Schultz pointed out, there is a spread in the measurements, and the answer obtained by these measurements is not absolute proof for or against pairing. Measurements of cosmogenic radionuclides and terrestrial ages, as discussed by Nishiizumi, Englert, Bhandari, and others, can help; however, due to the rather high uncertainty in the analytical data, these measurements cannot provide a unique answer.

Thus we can conclude that the question of pairing among Antarctic meteorites has not been solved, and it does not seem likely that there will ever be an unambiguous answer. Petrological, chemical, and isotopic properties vary to some extent within individual meteorites, and in the case of meteorites of the same type (for example, H5 chondrites) it is almost impossible to determine if the similarity between two specimens is due to pairing (blurred by the limits of the analysis) or is merely within the natural range of individual samples. It seems likely that we will be unable to reach a conclusion about pairing with certainty, unless the pieces are found and fit together like pieces of a puzzle. However, it is of great importance to know the exact number of falls that are represented in the Antarctic collections in order to make definitive statements about the meteorite type frequency distributions. It is possible that our current knowledge of pairing is not complete, and that there may be, especially among ordinary chondrites, more samples paired than we previously thought.

It should be noted, however, that not all differences found to exist between Antarctic and non-Antarctic meteorites are affected or can be explained by pairing. Differences in textures and in chemical and isotopic compositions still exist, even if the number of paired samples increases or decreases; only the relative number of specimens that show these differences increases or decreases. Thus, as more specimens are

found to be paired, the greater will become the proportion of unique and rare specimens.

Another very important problem involves the terrestrial history of the Antarctic meteorites. The long terrestrial residence times of most Antarctic meteorites, and the unusual environment, may have had effects that cause differences between non-Antarctic and Antarctic meteorites. One of the most important factors in this respect is weathering. Velbel, Buchwald, and others showed that for weathering under Antarctic conditions a number of processes occur that under non-Antarctic conditions are not of great importance. One of the major elements of uncertainty in weathering is the timescale. We do not know exactly how long meteorites are buried in the ice, how long they are exposed, and if climate changes over the past 10-100,000 years had any influence on this cycle. We do not know the long-term interaction between the meteorites and solid ice. Buchwald suggested that CI, which is essential for the formation of akaganeite and other corrosion products in meteorites, enters the meteorites by solid-state diffusion from the ice. Nishiizumi, however, pointed out that Antarctic ice contains only very little (about 200 ppb) CI. Buchwald further stated that we do not really know the timescales involved to corrode Antarctic meteorites, and there does not seem to be a direct correlation of the corrosion state of a meteorite and its terrestrial age. Furthermore, the corrosion is slower in Antarctica (maybe by a factor of 100 or more) than under non-Antarctic conditions.

Velbel noted during the discussion on weathering and weathering products that there is a connection between the internal chemistry of meteorites and the occurrence of evaporites on their surface. Elements such as Rb, Co, I, and in some cases Ca, are depleted in the interior of evaporite-bearing meteorites. It has to be shown in a more systematic study, however, whether this holds true for all meteorite types and whether other elements are equally affected. Efflorescences, such as nesquehonite, found on Antarctic meteorites have, according to Velbel, formed only very recently. Some meteorites continue to form efflorescences even while resting in storage. The timescale for the formation of evaporites is very short compared to the terrestrial age of the meteorites. Previously formed efflorescences may have been eroded, with unknown chemical effects. No obvious connection between the locality of meteorite finds and the occurrence of evaporites on the meteorites has been established; maybe microenvironmental reasons (which cannot be quantified so far) are responsible for this.

Even if some chemical changes, such as the depletion of certain elements in evaporite-bearing meteorites, can be ascribed to weathering, no clear pattern emerges. Some elemental abundances may change, others do not; some types of meteorites show such an effect, others do not. It will be very difficult, however, to simulate these

long-term weathering effects in the laboratory, especially since a number of variables (e.g., the influence and variability of the microenvironment) are not known. Furthermore, it will be very difficult to explain effects that are probably caused by thermal metamorphism with terrestrial weathering.

Lipschutz proposed that the chemistry of volatile elements in a number of Antarctic carbonaceous chondrites can be modeled by heating, for example, a sample of the Murchison carbonaceous chondrite. This effect will have to be checked by analyzing a larger number of Antarctic carbonaceous chondrites and by heating different chondrites in laboratory experiments. In addition, leaching experiments are needed that duplicate the weathering markers introduced by Antarctic processes. We need to find a more sensitive indicator to identify meteorites that are not obviously weathered but are otherwise altered. For example, we know that alkali halides can be introduced by Antarctic processes. What is missing, however, is data on what terrestrial alteration under Antarctic conditions does to the same property in different kinds of meteorites.

In conclusion, the workshop was very successful in determining that differences do exist between Antarctic and non-Antarctic meteorites, but no solution as to the origin of the differences was found. It became clear, however, that more data are needed and that a series of future investigations (along the lines of some of the points listed above) will help to clarify the open questions. Chemical, isotopic, petrological, textural, and terrestrial age determinations on a larger number of samples of different meteorite types will have to be performed. The influence of weathering, which is not well known at this stage, will have to be investigated further. Changes in the meteorite flux and in the meteorite type frequency distribution need to be studied

in detail, possibly using micrometeorite distributions.

Antarctic meteorites may represent a better sample of the meteorite influx onto Earth, and continue to yield unique samples and invaluable information on the origin and evolution of our solar system. A better understanding of these samples and their terrestrial history will further help us to understand our solar system.

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Abstracts



TERRESTRIAL AGE OF ANTARCTIC METEORITES; N.Bhandari, Physical Research Laboratory, Navrangpura, Ahmedabad, India.

Terrestrial age (T_E) of antarctic meteorites is an important parameter which can be used to determine frequency of their fall and to understand the dynamics of their accumulation in certain regions of Antarctica. T_E for a large number of antarctic meteorites has been calculated from the extent of decay of radioactivity of some cosmogenic nuclides from their assumed levels in the interplanetary space (1-3) or from the extent of fading of low temperature thermoluminescence (TL) in interior samples of meteorites (4,5).

Both these methods have several inherent problems. The equilibrium activity of radionuclides depend on size and shape of the meteoroid, shielding depth of the sample as well as on the degree of saturation attained in space (exposure age). It has been shown (6) that the production rate of some cosmogenic radionuclides eg. ^{26}Al and ^{53}Mn , and hence their equilibrium value in space, varies by more than a factor of 2 in meteoroids with effective radii between 6 and 20 cm., thus introducing uncertainty in the terrestrial age estimates. Furthermore, many meteorites have complex exposure history due to fragmentation on the parent body or in the interplanetary space, which does not allow the activity at the time of fall to be predicted reliably. The TL method also does not give reliable T_E because its level in space may depend on orbital parameters of the meteoroid (specifically, its perihelion distance) and shock history. In addition fading characteristics of different meteoritic minerals are not identical and some of them exhibit anomalous (non-thermal) fading. Also depth and size dependence of TL is not known although magnitude of its variation may be small (7).

Here we describe some procedures for minimising these difficulties in order to obtain reliable terrestrial ages by both the techniques.

1. Cosmogenic radionuclides: Calculations as well as measurements in several chondrites (8,9) show that, although the production rates of different isotopes vary by more than a factor of 2 with depth and size of the meteoroid, some isotope pairs such as ^{21}Ne , ^{26}Al and ^{53}Mn have nearly parallel depth profiles. Therefore, their production ratio remains nearly independent of size, shape or shielding depth. If such isotope pairs are used, then the terrestrial age can be calculated without the knowledge of absolute activity levels of individual radioisotopes in the

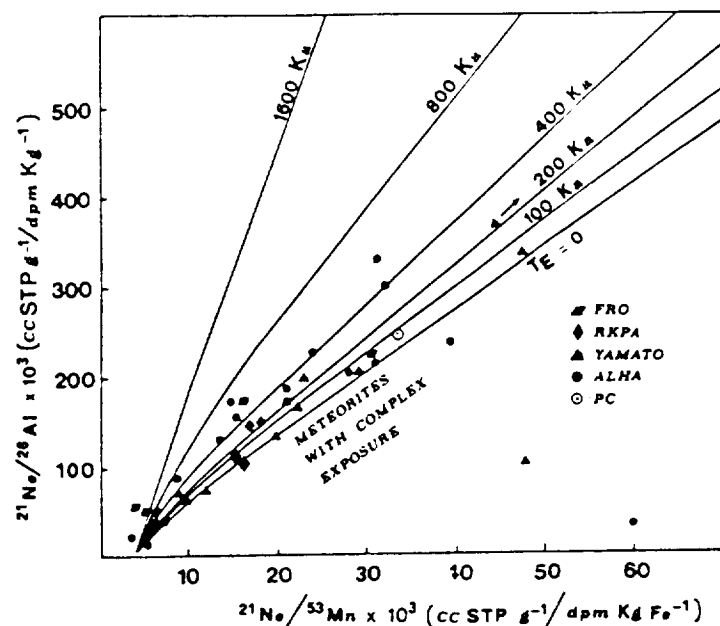


Fig. 1. Iso-terrestrial age contours on the three isotope (^{21}Ne - ^{26}Al - ^{53}Mn) diagram. Meteorites with complex exposure history lie below the curve $T_E=0$. Distribution of terrestrial ages of antarctic meteorites from various sites can be seen on this diagram.

meteoroid at the time of fall. Fig.1 shows the correlation for three isotope pairs ^{21}Ne - ^{26}Al - ^{53}Mn and the calculated contours for different terrestrial ages. Production ratios $^{21}\text{Ne} : ^{26}\text{Al} : ^{53}\text{Mn} = 0.31 : 60 : 415$ (expressed in the conventional units of measurement : ^{21}Ne in 10^{-8}cc STP/g meteorite , ^{26}Al in atoms / min. kg meteorite and ^{53}Mn in atoms / min. kg Fe) have been used for sake of convenience in this figure for calculating these curves. These ratios are revised from the values used earlier (8,9) because better estimates have become available. There is some dependence of the production ratios on the target element chemistry in chondrites belonging to different classes but this is expected to be small (<10%) and has not been considered here. The choice of the radioisotopes is made because of large amount of data available although the half lives of ^{26}Al (0.7 Ma) and ^{53}Mn (3.7 Ma) are most suitable for estimating terrestrial ages $>0.2\text{Ma}$. They do not give good resolution for meteorites with short terrestrial ages. This procedure works, in principle, for any pair of isotopes whose production ratios are independent of size or shielding depth (9) and radioisotopes, ideal for the purpose of estimating short terrestrial ages are ^{14}C (5730 a) and ^{36}Cl (0.3 Ma). The measured ratios for some chondrites taken from the compilation of Nishiizumi (10) are also plotted in fig. 1. The errors of measurement are not shown but they range between 5 to 15%. Meteorites with complex exposure history generally fall below the curves, and those falling below the curve labelled $T_E=0$ can be easily identified. Fig. 1 shows that three chondrites, ALHA 77297, ALHA 76008 and Y 74116, have had a complex exposure. In such cases, it is not possible to obtain terrestrial ages from this procedure. Also meteorites with short exposure ages (<8 Ma) form a cluster near the origin of the curves and it is difficult to estimate their terrestrial ages accurately. None the less , the procedure has certain advantages since it gives terrestrial ages without necessitating shielding correction and eliminates meteorites with complex exposure history. The frequency distribution of terrestrial ages of some chondrites collected from different locations can be inferred from this figure. A combined histogram is shown in Fig. 2 because statistics is too low to be meaningful for individual collection sites. From Fig. 1 it appears that ALHA has the widest distribution of terrestrial ages and some Yamato meteorites have the youngest terrestrial ages.

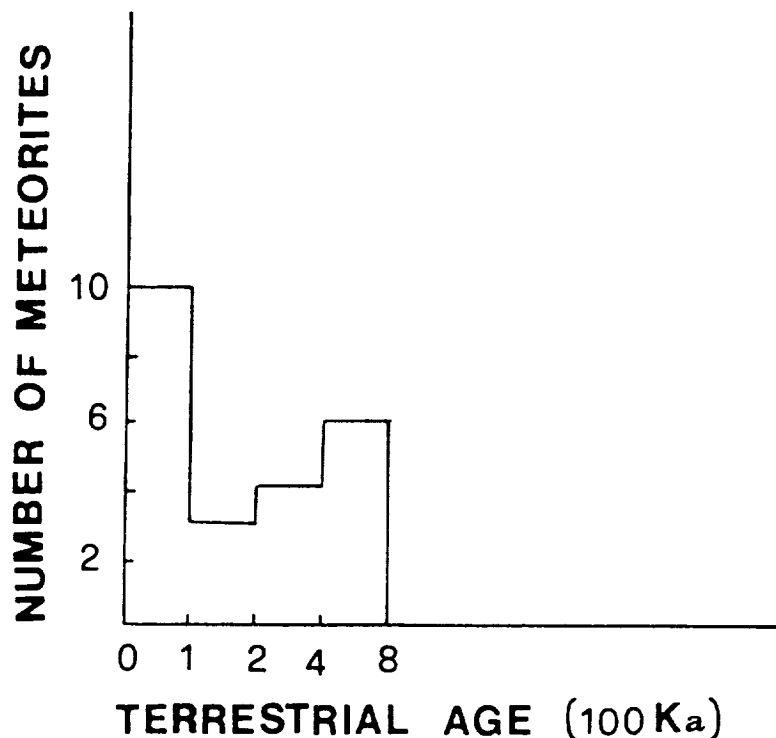


Fig. 2. Histogram showing the distribution of terrestrial ages of antarctic meteorites based on Fig.1.

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2. Thermoluminescence of the fusion crust : Severe Frictional heating in the atmosphere results in vaporisation and melting of the surface regions of the meteorite and the surviving meteorite surface layer gets converted into fusion crust . Since this is a new phase formed during ablation, the interplanetary TL gets erased in the crust. After the fall, the TL builds afresh from the dose it receives on the earth. Thus, whereas the TL in the interior sample decays, in fusion crust it increases after the fall. Therefore, the TL level in the fusion crust is a measure of time the meteorite spends on the earth. Ninagawa et al ., (11) measured the TL level in the fusion crust of an antarctic meteorite and tried to relate it to its terrestrial age .

We have measured natural TL (NTL) in the fusion crust as well as interior samples of eight antarctic meteorites and three recent falls . The details can be found in Sen Gupta (7,12). The equivalent dose, ED, was estimated by second glow normalisation and, in some cases, by additive dose method (Table 1) . The results show that:

(i) NTL levels in the fusion crust of antarctic meteorites are about 100 times higher than the levels in the fusion crust of recent falls viz. Dhajala, Jilin and Bansur , thus supporting the assumption that it increases with time.

(ii) The levels are significantly lower (1/100th) than the NTL levels in the interior material of these antarctic meteorites, thus supporting the assumption that the interplanetary TL gets erased during ablation.

(iii) The TL sensitivity of the fusion crust was found to be about 10 to 50 % of the value for the interior samples, adequate to give a good signal.

(iv) The fusion crust shows no evidence of anomalous fading in laboratory experiments for storage periods of 100 days.

If the dose rate due to cosmic rays, surrounding ice and the internal dose from the inherent radioactivity present in the meteorite is known, then it is possible to estimate the terrestrial residence times of these meteorites. We are now planning to measure the dose rate at the sites where the meteorites have been collected but , in the meanwhile, we can use the data given by Prescott and Stephan (13) to estimate the dose rate . At about 70°S and altitude of 1500 to 2000 m, where most of the meteorites have been found, the dose rate ranges between 0.6 to 0.8 Gy/ka.

Table 1. TL DATA AND THE ANTARCTIC SURFACE AGES BY THE FUSION CRUST METHOD.

Meteorite	Equivalent Dose (Gy)			TL Age ⁺ T _s (ka)	Known Ages T _E (ka)
	Second Glow Low Dose (9 Gy)	Normalisation High Dose (500 Gy)	Additive Dose		
Recent Falls					
Bansur	0.6	0.7		<0.323	0.096
Dhajala	-	0.1		<0.085	0.011
Jilin	0.3	0.3		< 0.185	0.0 11
Antarctic Finds					
ALHA 76008	8.4	5.7	9.5	10	100±70 *
ALHA 77231	43.3	37.0		54	600±70.31±4 *
ALHA 77256	-	42.0		53	11±2 *
ALHA 77257	-	123.0		150	360±90 *
ALHA 77282	21.2	17.5	20.8	26	270±70 *
EETA 79001	-	57.0		62	12±1 *
MBRA 76001	17.1	14.0		21	>39 *
META 78028	-	67.0		97	70±40 *

+ The error in TL ages calculated from the range in ED values is ±15%.

* Ages based on Cosmogenic radionuclides (1-3).

We consider other sources of radiation and show that they contribute little compared to the cosmic ray dose. The K content of ice is small, about 0.4 ppm (15) and the dust content, which is the main source of natural radioactivity, is also low, implying that the external β and γ dose rates are low . U and Th occur at sub ppm level and K content is about 0.07 to 0.1%

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in chondrites, the achondrites being further depleted in K. Using their standard concentrations in meteorites of different classes, we estimate the internal dose to be less than 0.1 Gy/ka. Only in case of fresh falls, the ambient dose is significant because they are stored in high K surroundings (Table 2). The dose in modern buildings is estimated to be 1.6 Gy/ka, about twice as much as the cosmic ray dose rate in antarctica and, after a lapse of some time, this may become the main TL inducing source in the antarctic meteorites. For such a work, as reported here, they must, therefore, be stored in radiation free environment.

The other source of radiation is emissions due to cosmogenic radionuclides. The short lived radionuclides decay soon after their fall and, in the present context, we need to consider only major radioisotopes with half life > 1 ka ie. ^{14}C , ^{59}Ni , ^{36}Cl , ^{26}Al , ^{10}Be and ^{53}Mn . Their activity levels in fresh falls vary with size and depth of the meteorite and can be predicted reasonably well. Of these radioisotopes ^{26}Al deposits largest energy because it emits energetic β^+ ($E_{\text{max}}=1.16$ MeV) and also a high energy γ ray (1.809 MeV). In order to determine the activity levels of antarctic meteorites, we have measured γ spectra of some chondrites by whole rock counting on a low background HP Ge detector. The results, given in Table 3, show the presence of three main γ lines: 661 KeV due to ^{137}Cs , 1461 KeV due to ^{40}K and 1809 KeV due to ^{26}Al . Potassium is probably homogeneously distributed in chondrites and, therefore, can be used as an internal standard for geometry and efficiency calibration. The data show that $^{26}\text{Al}/^{40}\text{K}$ (and hence, ^{26}Al) varies little in different parts of the meteorite (within 20%), but $^{137}\text{Cs}/^{40}\text{K}$ (and hence, ^{137}Cs) varies widely by as much as a factor of 4. In two cases where

Table 2. Dose Rate for Meteorites.

Meteorite	Class	Latitude , Longitude	Altitude (m)	Cosmic Ray Dose (Gy/ka)	Total Dose (Gy/ka)
<u>Recent Falls</u>					
Bansur	L6	27°42'N,76° 20'E	65	0.26	1.89
Dhajala	H3/4	22°23'N,71°26'E	65	0.26	1.89
Jilin	H4	44°N,126°30'E	65	0.26	1.89
<u>Antarctic Finds</u>					
ALHA 76008	H6	76°45'S,159°20'E	2000	0.79	0.80
ALHA 77256	DIO	"	2000	0.79	0.80
ALHA 77257	UREI	"	2000	0.79	0.79
ALHA 77231	L6	"	2000	0.79	0.80
ALHA 77282	L6	"	2000	0.79	0.80
EETA79001	SHERG	77°15'S,156°30'E	2000	0.79	0.92
MBRA 76001	L6	77°35'S,160°19'E	2000	0.79	0.80
META78028	L6	79°41'S,155°45'E	1500	0.62	0.69

freshly cut faces were also measured, it was found that the activity of ^{137}Cs was lower compared to that in their crusted surfaces. ^{137}Cs has presumably originated from nuclear tests conducted around 1950-63 and has got absorbed by the meteorite from precipitation. Since ^{137}Cs is introduced only during the past 30 years, its contribution to the dose is not important over the terrestrial age of the meteorites and can be neglected. The estimated ^{26}Al activity values are given in Table 2. Two meteorites A77280 and A77288 where ^{26}Al has been measured by the Battelle group (1,15), there is a good agreement. The dose rate due to ^{26}Al is estimated to be about 0.01 Gy/ka and it is even smaller due to other long lived radionuclides mentioned above. The dose rate in shergottites may be slightly higher because of higher ^{26}Al production.

Thus we conclude that cosmic ray dose is by far the largest, but it decreases sharply with the over burden of ice. Since meteorites spend only a part of their time on the surface of

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ice and a part buried deep within it, the age estimates using the cosmic ray dose give only the surface residence times, T_S (12). These estimates are given in Table 1 where we compare them with terrestrial ages, T_E , determined from cosmogenic radioisotopes (1-3). The error in estimating ED is $\pm 15\%$ and there may be other sources of errors in estimating T_S and T_E . In all the chondrites, T_S and T_E are comparable or $T_S < T_E$ as expected, but there are two

Table 3. Gamma Radioactivities in Antarctic Chondrites.

Meteorite	Weight (kg)	Face ¹	Net Count Rate (cpm)			¹³⁷ Cs/ ⁴⁰ K	²⁶ Al* (dpm/kg)
			¹³⁷ Cs	⁴⁰ K	²⁶ Al		
A77280.9 (L6)	1.507	F	0.21	0.89	0.18	0.24±0.02	46.6±1.6
		Cr	0.78	1.16	0.23	0.66±0.02	
		Cr	0.42	0.96	0.17	0.43±0.03	
		Cr	0.44	0.54	0.12	0.81±0.03	
A77288 (H6)	0.826	F	0.25	0.81	0.17	0.31±0.02	42±2
		Cr	1.03	0.73	0.154	1.39±0.06	
A78130.2 (L5)	1.049	Cr	0.76	0.79	0.19	0.96 ± 0.03	54 ± 2.3
		Cr	0.3	0.63	0.15	0.47 ± 0.05	
A81018 (L5)	2.215	Cr	0.49	1.26	0.25	0.38±0.01	44.2±1.3
		Cr	1.66	1.2	0.23	1.4 ± 0.03	
A81027 (L6)	2.675	Cr	0.94	1.29	0.241	0.73±0.02	42.6±1.3
		Cr	1.15	0.91	0.19	1.27±0.04	
		Cr	1.14	1.18	0.22	0.96 ± 0.03	
A81030 (L3)	1.7	Cr	2.1	0.93	0.22	2.25±0.05	49.5±2.2
		Cr	1.49	0.66	0.13	2.24 ± 0.09	
		Cr	0.63	0.33	0.08	1.92 ± 0.1	
Dhajala	2.2	Cr	0.0	1.313	0.244	0	45±2.7
Background			0.035	0.404	0.184		

*: F = Freshly cut Face; Cr = Crusted face.

±: Attenuation and Efficiency corrections relative to ⁴⁰K have been made. Mean Standard K content for different classes of chondrites has been used to determine the strength of ⁴⁰K in the meteorite. 1σ errors in counting are indicated.

achondrites ALHA 77256 and EETA 79001 where $T_S > T_E$. We are now investigating the cause of this discrepancy since both the methods have many inherent problems, as discussed earlier.

We thank Dr. P.N.Shukla for counting of the antarctic meteorites and Mr. K.M.Suthar for assistance. We are grateful to NASA and to Dr. D.Sears for kindly supplying us the antarctic meteorite samples.

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ON THE DIFFERENCE BETWEEN WEATHERING PRODUCTS ON ANTARCTIC AND NON-ANTARCTIC METEORITES. V.F. Buchwald, Department of Metallurgy, Building 204, Technical University, 2800 Lyngby, Denmark.

The weathering products of about 80 Antarctic and non-Antarctic meteorites have been studied by classical microscopy, microprobe analysis and X-ray diffraction. Iron meteorites were examined in polished section, while stony meteorites were examined in thin section.

Chlorine is an important element in the corrosion process of all meteorites. Chlorine is part of the mineral akaganeite, β -FeOOH, which under active corrosion conditions contains about 5 wt.% Cl and may be written $[\text{Fe}_{15}\text{Ni}] [\text{O}_{12}(\text{OH})_{20}] \text{Cl}_2\text{OH}(1)$. Akaganeite forms veins and films in the interfaces between uncorroded iron and stable oxides. Akaganeite has ion-exchange capacity. In cold, dry environments (< 20% R.H.), the akaganeite is relatively stable and long-lived. When temperature and humidity increase, chlorine ions from the lattice are exchanged with hydroxyl ions from the environment, and the released chlorine depassivates the iron, intensifying the corrosion attack. The mechanism is most effective when water supply is severely restricted. If water is plentiful, e.g. on exposed surfaces above the soil line, the trend is towards washing chlorine away and into the surroundings.

When a buried meteorite, due to seasonal climatic changes, dries up, chlorine-rich akaganeite is reformed, ready, however, to release its chlorine next time, when oxygen and some water become available. - Akaganeite is formed by solid-state diffusion, and the iron-nickel ratio of akaganeite is the same as that of the phase (kamacite or taenite) from which it formed. This also means that the structural relationships of the meteoritic minerals are preserved in the initial stages of the corrosion attack. Troilite, schreibersite and plessitic intergrowths are unchanged, and the process may be seen as a replacement process, "fossilizing" the original structure.

Chlorine from the environment is necessary for the formation of akaganeite. Even under Antarctic conditions there is

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sufficient chlorine in snow and ice for the formation of akaganeite with 5 wt.% Cl. Akaganeite may also incorporate minor amounts of impurity atoms, such as Ca, Al, Si and S. In comparison with akaganeite, maghemite and especially magnetite are very pure iron oxides.

A meteorite which, when transferred from its natural environment (soil, water, ice) to an indoor environment, continues to corrode, contains essential amounts of chlorine. The chlorine is located in akaganeite, but is ready to attack and decompose any adjacent iron. Usually the much higher oxygen concentration of the new surroundings will result in an alarmingly high corrosion rate, especially at normal room temperature and relative humidity (30-70%).

Akaganeite transforms by ageing in situ to microscopic intergrowths of goethite and maghemite in which the iron-nickel ratio is only slightly altered (2). In the ageing process the seasonal amplitudes in temperature and humidity at the location of the meteorite are more significant than time as such. Thus akaganeite is still the major corrosion mineral of many meteorites from the interior Antarctic, while some ageing has taken place on meteorites from the coast-near ranges, e.g. Derrick Peak and Purgatory Peak. In meteorites from temperate climates the corrosion has usually advanced to levels where akaganeite is only found in the active corrosion zone while the major weathering products form exterior shales of the stable oxides goethite, maghemite and magnetite.

In temperate climates the buried meteorite is exposed to pore water, and nickel may be dissolved from the oxides as Ni^{++} and transported to deposition elsewhere. New, secondary minerals are formed, clearly via transport in liquid water solution, such as lepidocrocite, pentlandite, arupite, heazlewoodite etc. Also, in special cases, the metallic phase FeNi_3 is formed.

The final products of disintegration are metal-free shale balls or shales, sometimes reflecting the original octahedral structure of many iron meteorites. The shales consist of chlo-

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rine-free goethite, maghemite and lepidocrocite. The nickel content is low, but distinct, 0,5-2 wt.%, and serves together with the morphology to identify the object as of meteoritic origin.

The ironhydroxychloride, $\text{Fe}_2(\text{OH})_3\text{Cl}$, is the only weathering mineral which contains divalent iron. It is surprisingly rich in chlorine (17-18%) and is found in meteorites from temperate climates (Jerslev, Odessa, Toluca). It is a rather pure olive-green mineral, usually associated with phosphides in thin films or in mm-sized lumps. It is also associated with akaganeite and may represent the initial step in the corrosion process: $\text{Fe}^0 \rightarrow \text{Fe}^{+2} \rightarrow \text{Fe}^{+3}$.

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Table summarizing the corrosion behavior.

Examples	Corrosion behavior in the museum	Because	Chlorine present
1. Cabin Creek Rowton	Stable.	Recovered immediately after the meteorite was seen to fall.	No
2. Morito Navajo Old Woman	Stable.	Found on the surface. Fully exposed to rain, but dries rapidly again in sun and wind.	No
3. Cranbourne, Odessa, Toluca, Mount Joy and many others	Unstable, spalling, akaganeite formation.	Excavated from soil. Most soils contain chlorine. Cl depassivates iron, leading to corrosion. Cl is stored in ion-exchanging akaganeite.	Yes
4. Cape York Quinn Canyon Derrick Peak	Top surface stable. Underside as §: 3	Top surface dries after rain. Underside is always in contact with porewater, leading to akaganeite formation.	Only on underside
5. Some Canyon Diablo and Henbury	Shale balls without metal. Stable.	Fully buried, the corrosion has ended in transforming all iron into various stable iron oxides. No akaganeite.	No
6. Canyon Diablo Shale	Disintegrated shale ball. Stable.	When a shale ball is exposed on the surface, it disintegrates.	No

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OF POOR QUALITY

ARE THERE REAL DIFFERENCES BETWEEN ANTARCTIC METEORITES AND MODERN FALLS?; W.A.Cassidy, University of Pittsburgh

When it began to appear that Antarctic meteorites had accumulated over a long period of time, Rancitelli, Lipschutz and Cassidy developed the idea that they might be used to test for variations in relative abundances of meteorite types arriving at the Earth. The time period represented by the Antarctic collection turned out to be $\approx 10^6$ y, but the effective time period is closer to 0.3×10^6 y, because specimens in the range 0.3 to 1.0×10^6 y are relatively rare. This, however, is still 1000X longer than for modern falls. If the infall rate of Antarctic meteorites were found to fluctuate during their 0.3×10^6 y accumulation time, any variations in the arrival rates of single types have been integrated over 0.3×10^6 y.

It would be important for two reasons to know if such variations occurred: (1) it would require the existence of mechanisms, possibly meteoroid streams, that operate to produce the variations, and (2) it would indicate that the Antarctic collection potentially is more useful in estimating the relative abundances of meteorite types than is the modern falls collection. Raw data on mass abundances do make the Antarctic meteorites look different (see Table 1), but are these differences real?

Every occurrence during the existence of a meteorite-sized body tends to reduce its size, usually by fragmentation: collisions in space between meteoroids, fragmentation during atmospheric entry, fragmentation upon impact, and fragmentation after impact. Chemical weathering that may occur probably mimics the effects of impact. After a long enough accumulation time, an Antarctic stranding surface should harbor a spectrum of different meteorite types, with the most common types each having attained an equilibrium distribution of sizes. In such a framework, the total mass of each type should be proportional to its relative abundance. Figure 1a illustrates such a distribution for the Antarctic meteorites of Table 1. If one allows for preferential loss of small specimens the distribution appears to be lognormal.

Figures 1b-f illustrate distributions for the five meteorite types of Table 1. Stony irons and irons appear not to offer useful data, probably because the sample size of each is too small. By examination, the remaining three types cannot be shown to be unreliable. Table 2 contains a comparison of the three major types of stony meteorites in the Antarctic and modern falls collections. Both sets of data are recalculated to 100%. The two collections continue to yield different abundance estimates, thus we cannot show that the frequency distributions over the two time periods have been the same.

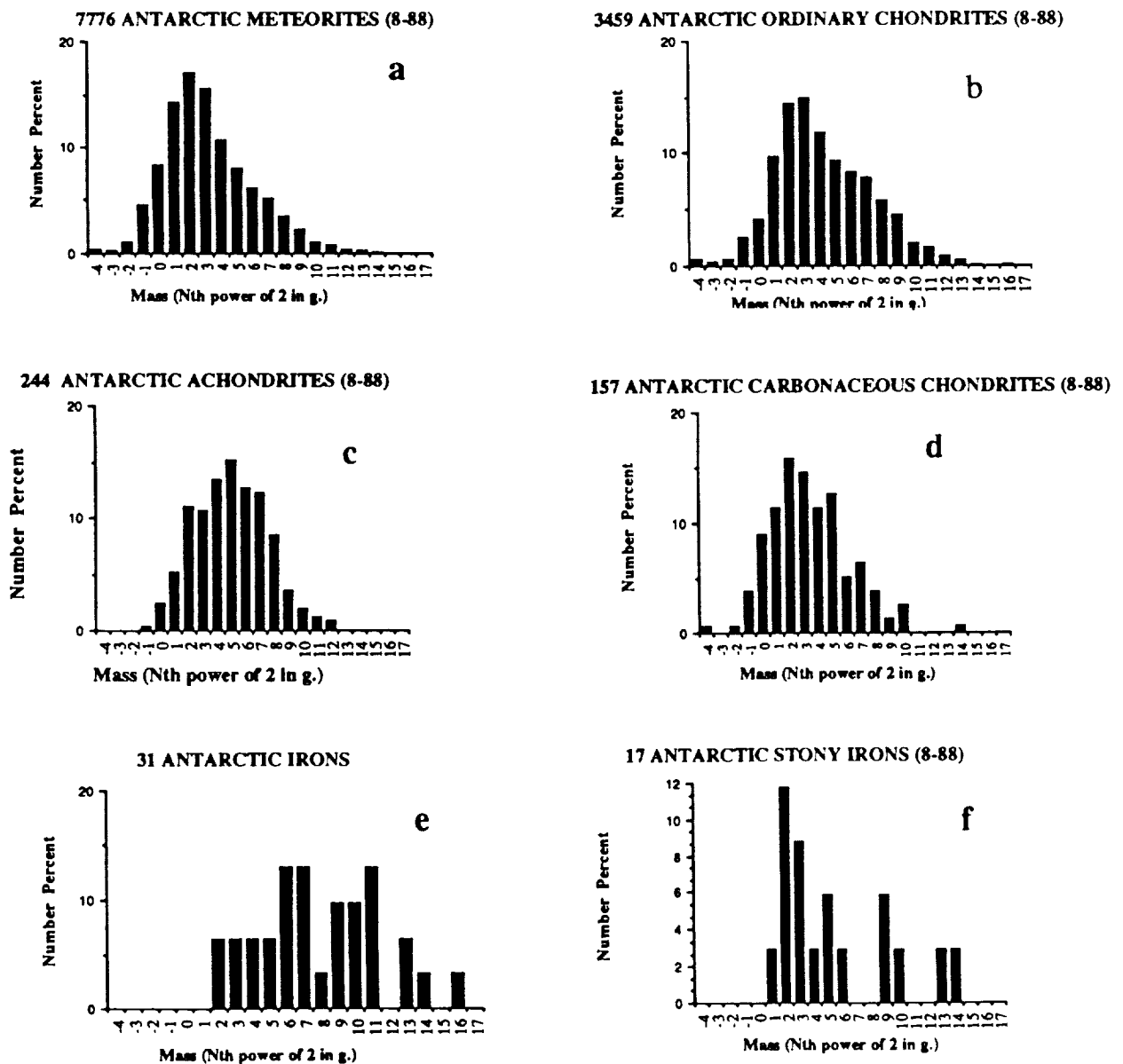
Can these estimates be refined? I assumed the frequency distribution curves for Antarctic meteorites are lognormal and plotted the data for ordinary chondrites, achondrites, and carbonaceous chondrites of Figure 1 against a probability scale. On such a scale a perfect normal distribution plots as a straight line. Each plot had an apparent straight-line segment, which I

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matched by eye. Reading "normalized" values off the straight line, I produced "normalized masses" for the Antarctic meteorites, as shown in Table 3. When the "normalized" estimates are compared to the modern falls collection, they suggest that achondrites and carbonaceous chondrites are present in the modern falls and Antarctic collections in the same proportions relative to each other, but not to ordinary chondrites. These numbers could be explained if ordinary chondrites are arriving 10% less frequently at this instant in time than has been normal for them over the last 0.3×10^6 y.

Conclusions: (1) fluctuations in the supply of meteoroids to the Earth may indeed occur, and (2) perhaps the relative abundance estimates for achondrites and carbonaceous chondrites as derived from modern falls should be reduced by a factor of 3.

Figure 1. Mass frequency distributions for 6 groups of Antarctic meteorites.



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Table 1. Comparison of masses and abundance estimates of antarctic meteorite (AM) and modern falls (MF). *"ord. chond." here includes H, L, LL, and E chondrites. **SNC meteorites and lunar meteorites omitted. ***Irons and stony irons NOT found on stranding surfaces omitted.

Types	Masses (kg)		Abundances (wt %)		$f \left(\frac{MF}{AM} \right)$
	AM	MF	AM	MF	
Ord. chond.*	1434.0	10725.5	88.6	72.0	0.81
achond.**	50.8	1405.0	3.1	9.4	3.03
carb. chond.	39.8	456.9	2.5	3.1	1.24
stony iron***	9.9	619.5	0.6	4.2	7.00
iron***	83.5	1698.0	5.2	11.4	2.19
Totals	1618.0	14904.9	100.0	100.1	

Table 2. Comparison of masses and relative abundance estimates within stony meteorites for antarctic meteorites (AM) and modern falls (MF)

Types	Masses (kg)		Abundances (wt %)		$f \left(\frac{MF}{AM} \right)$
	AM	MF	AM	MF	
ord. chond.*	1434.0	10725.5	94.1	85.2	0.91
achond.**	50.8	1405.0	3.3	11.2	3.39
carb chond.	39.8	456.9	2.6	3.6	1.38
Totals	1524.6	12587.4	100.0	100.0	

Table 3. Comparison of "normalized" masses of antarctic stony meteorites with modern falls masses

Types	Masses (kg)		Abundances (wt %)		$f \left(\frac{MF}{AM} \right)$
	AM	MF	AM	MF	
ord. chond.*	1242.6	10725.5	95.0	85.2	0.90
achond.**	50.2	1405.0	3.8	11.2	2.95
carb chond.	15.1	456.9	1.2	3.6	3.00
Totals	1307.9	12587.4	100.0	100.0	

OXYGEN ISOTOPIC COMPOSITION OF ANTARCTIC METEORITES; Robert N. Clayton^{1,2,3} and Toshiko K. Mayeda¹. ¹Enrico Fermi Institute, ²Department of Chemistry, ³Department of the Geophysical Sciences, all at the University of Chicago, Chicago, IL 60637, USA.

The first concern in the application of oxygen isotope techniques to Antarctic meteorites is the degree of alteration in the polar environment. The Antarctic ice and water are so strongly depleted in heavy isotopes that even 1-2% of contamination (in the form of rust or other terrestrial products) causes unacceptably large perturbation of the isotopic composition. The effects of weathering have been documented by Onuma et al. (1983), Clayton et al. (1984), and Scott et al. (1988) for ordinary chondrites and by Clayton and Mayeda (1988) for ureilites.

The principal scientific questions to be addressed in comparing Antarctic with non-Antarctic samples are: (1) What new meteorite types have been found simply as a consequence of a larger number of specimens? and (2) What new meteorite types have been found due to systematic differences in the Antarctic specimens in sizes of stones, terrestrial age, etc.? and (3) What known species are overabundant or underabundant due to these systematic Antarctic characteristics? The studies applying oxygen isotope measurements to Antarctic meteorites have not been designed to search for specific Antarctic effects, but have focussed on new and unusual meteorites. As a consequence, there are not many analyses of ordinary chondrites or of common types of achondrite, such as eucrites. Most of the interesting results have been found in rare achondrites and in carbonaceous chondrites.

Among the ureilites, the wide range of chemical and isotopic variations was not known until Antarctic samples were found. The low FeO ureilites (Group 3 of Berkley et al., 1980) are all Antarctic meteorites. They also have oxygen isotopic compositions in a field separated from the Group 1 ureilites. This correlation between isotopic composition and major element chemistry led to the proposal of Clayton and Mayeda (1988) that the major element differentiation of the ureilites was a nebular process rather than a planetary igneous process.

The carbonaceous chondrite classes C1 and C2 or CI and CM are redundant for the non-Antarctic meteorites: all C1 are CI and all C2 are CM. This is not the case for Antarctic meteorites. Rocks which do not fit unambiguously into older categories include B-7904, EET 83334, Y 82042, Y 82162, and Y 86720 (Clayton and Mayeda, 1989). A refined classification scheme is required which takes into account the chemical composition, mineralogy, texture, and isotopic composition. There are not yet enough examples of these meteorites to permit a new scheme with useful genetic connotations.

The carbonaceous chondrite ALHA 85085 appears to be related to the CR (Renazzo) subgroup, but has many unique features. There are many Antarctic representatives of the C4-C5 categories; these do not differ isotopically from their non-Antarctic counterparts (Clayton and Mayeda, 1989).

An obvious example of a meteorite type so far found only in the Antarctic is the group of lunar meteorites. Their oxygen isotopic compositions are indistinguishable from Apollo lunar samples (Mayeda et al., 1983; Mayeda et al., 1987).

There are several examples of previously unique or unclassified meteorites for which one or more Antarctic equivalents have been found: (1) Carlisle Lakes 001 and ALHA 85151 (Weisberg et al., 1989); (2) Angra dos Reis and LEW 86010; Winona and Y 75300 (Mayeda and Clayton, 1989); Sombroete and Y 8002 (Mayeda and Clayton, 1989); Brachina and ALH 84025. Oxygen isotopic compositions are given in Table 1.

Among the few oxygen isotopic analyses available for ordinary chondrites, there is no suggestion of a systematic difference between Antarctic and non-Antarctic specimens as has been found in trace-element abundances (Lingner et al., 1987; Dennison et al., 1987). The most interesting ordinary chondrite is ALH 76004, which is highly unequilibrated and contains the widest range of ¹⁶O variations yet seen in an ordinary chondrite (Mayeda et al., 1980).

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Table 1
 Oxygen Isotopic Compositions of Ungrouped Meteorites

Meteorite	$\delta^{18}\text{O}$	$\delta^{17}\text{O}$
Carlisle Lakes 001	5.0	5.4
ALHA 85151	4.5	5.2
Angra dos Reis	3.60	1.64
LEW 86010	3.55	1.70
Acapulco	3.73	1.00
ALH 77081	3.57	0.73
ALH 78230	3.97	1.07
Y 74063	3.01	0.76
Winonaites	5.07	2.19
Y 75300	5.20	2.22
Sombrerete	3.36	0.36
Y 8002	3.36	0.35
Brachina	3.48	1.61
ALH 84025	3.67	1.64

DEPTH-PROFILES OF HALOGEN ABUNDANCE AND INTEGRATED INTENSITY OF HYDRATION BAND NEAR $3\mu\text{m}$ IN ALH 77231, ANTARCTIC L6 CHONDRITE; Mitsuru Ebihara, Taeko Shinonaga, Hiromichi Nakahara, Dept. Chemistry, Tokyo Metropolitan University, Setagaya Tokyo 173, Japan, Atsushi Kondoh, Masatake Honda, Dept. Chemistry, Nihon University, Setagaya, Tokyo 156, Japan, Masamichi Miyamoto, Collage of Arts and Sciences, University of Tokyo, Meguro, Tokyo 153, Japan, Hideyasu Kojima, Natl. Inst. Polar Res., Itabashi, Tokyo 173, Japan.

1. Introduction

The Antarctic meteorite collection made it possible for us to study a wide variety of meteorite specimens for their chemistry and petrology. Being different from the case for the falls, however, an effect of terrestrial weathering should always be taken into consideration in evaluating analytical results of Antarctic meteorites. Of elements, halogens and alkali elements could be the most easily influenced by alteration due to terrestrial weathering.

Dreibus et al. (1985) analyzed a number of Antarctic meteorites for halogens by means of radiochemical neutron activation analysis (RNAA) and found that iodine was extraordinarily enriched in some Antarctic meteorites. Among meteorite groups, eucrites were found to show the most anomalous abundances of iodine. Such an overabundance of iodine in Antarctic meteorites was later confirmed by Heumann et al. (1987) by using a mass spectrometric isotope dilution technique. They also found that iodine was more abundant in the surface than in the center of terrestrial rock collected in Antarctica and deduced that the overabundance of iodine observed in some Antarctic meteorites was caused by the terrestrial contamination.

We have determined by RNAA two halogens, chlorine and iodine, in samples taken at the different depth from the surface for an Antarctic ordinary chondrite. We also measured the spectral reflectance for an aliquot of each sample by using a Fourier transform infrared (FT-IR) spectrometer and calculated the integrated intensity of absorption band near $3\mu\text{m}$ (hydration band). As discussed in Miyamoto (1988), absorption band near $3\mu\text{m}$ is sensitive to the presence of hydrates or hydroxyl ions having OH groups, hence the intensity of absorption band can be an indicator in evaluating how much hydrous minerals were produced by alteration due to terrestrial weathering. In this study, we describe depth-profiles of halogen (chlorine and iodine) abundance and absorption intensity near $3\mu\text{m}$ in the Allan Hills (hereafter ALH-) 77231 (L6) chondrite and compare with each other. Based on these data, we consider the possible cause to make the overabundance of iodine in Antarctic meteorites and discuss how deeply the terrestrial weathering affects chemistry and mineralogy of meteorites collected in Antarctica.

2. Sample preparation

An Antarctic meteorite, ALH-77231 (L6) was used in this study. This meteorite originally weighs 14kg, of which 4.6kg of specimen is preserved at the National Institute for Polar Research (NIPR), Japan. A weathering index of A/B is assigned to this meteorite. A meteorite specimen, of which the original surface is covered with fusion crust, was at first sawn into two portions. The section is shown in Fig. 1(a). The lower part missing is preserved in U.S. Two fragments, A and B, located near the Japan - U.S. boundary were separated from this half-sawn meteorite specimen. The fragment A was taken from the outer part of the specimen and was adjacent to the main fragment B. These two fragments were finally divided into a total of 13 samples (named A1 to A4 for fragment A and B1 to B9 for fragment B) by

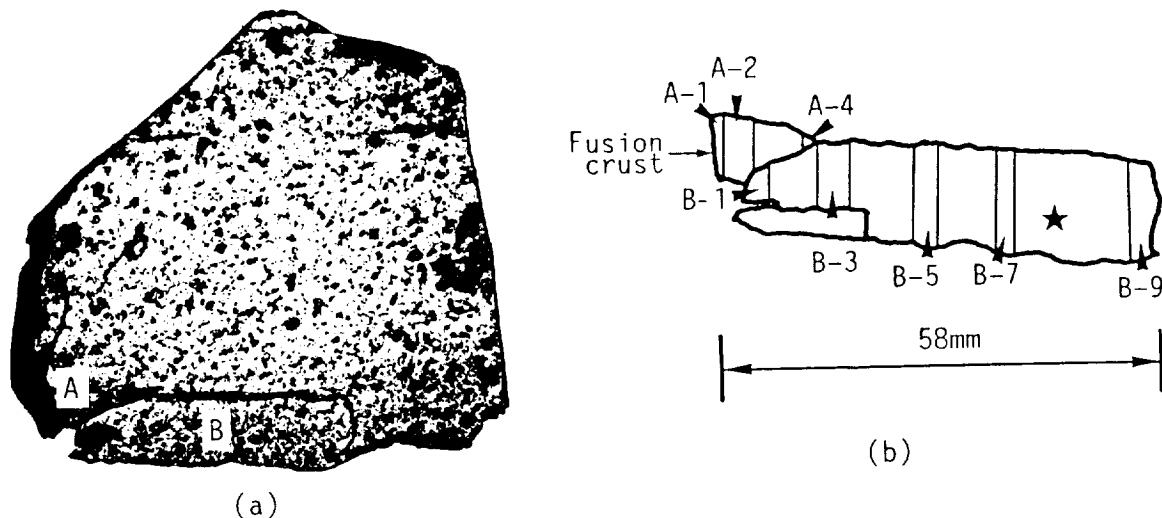


Fig. 1. The section of ALH-77231 (L6) (a) and sampling position (b). The center of meteorite is marked by a star.

cutting with a diamond-pasted chain saw. Sampling position is shown in Fig. 1(b). The Sample A1 was taken from the outermost part and contains fusion crust. The center of meteorite is marked by a symbol of star. The fraction B9 is beyond the center and is rather near to the opposite surface.

Each sample fractionated (0.16 to 4.43g) was at first ground in a clear agate mortar. The fraction sticking to a hand magnet was separated and the remaining fraction was further ground to become uniform compositionally. 'Non-magnetic' fraction thus prepared was used in this study. Out of 13 samples, only 8 samples (A1, A2, A3, B1, B3, B5, B7 and B9) were analyzed for halogens and intensity of hydration band.

3. Experimental

(1) Determination of halogens

Radiochemical neutron activation analysis (RNAA) was applied to determine chlorine and iodine contents in each separated sample. To determine the iodine, about 100mg of each sample was taken into a clean plastic vial (6mm ϕ x 30mm) and irradiated at a neutron flux of $1.5 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ for 5 to 10 min in a TRIGA II reactor of the Institute for Atomic Energy, Rikkyo University. To enhance the relative activity of ^{128}I produced by (n, γ) reaction from ^{127}I , a cadmium can was used for the irradiation of samples. After irradiation was ceased, radiochemical separation of iodine immediately started. The detailed analytical procedures for iodine was reported elsewhere (Ebihara et al., 1986).

To determine the chlorine content, an aliquot of about 30 mg for each sample was used. Sample was irradiated in the same manner (but without a Cd can) at the same conditions as those used for the determination of iodine. Being cooled for about 10 min, samples were subjected to radiochemical separation of chlorine. Analytical procedures will be reported elsewhere.

(2) Measurement of spectral reflectance

Spectral reflectance measurements were performed for the range of 3950 to 400 cm^{-1} in a dry air atmosphere with a JASCO FT/IR-3 Fourier transform

infrared spectrophotometer equipped with a diffuse reflectance attachment. Before being processed to a spectrometer, powdered samples were dried at 100° for 24h to remove adsorbed water from the grain surface. Scan was repeated 500 times and signal intensity was accumulated. To obtain the integrated intensity of hydration band, the area from 3800 to 3000cm⁻¹ was numerically integrated. The reflectance at 3800cm⁻¹ was used for normalization. Details of measurement and a calculation method for the integrated intensity of absorption band are described in Miyamoto (1988).

4. Results and discussion

4.1 Depth-profile of halogen abundances

Analytical results of chlorine and iodine for separated samples are tabulated in Table 1, along with errors due to counting statistics (1σ).

Table 1. Analytical results of chlorine and iodine in separated samples

sample name	chlorine (ppm)	error (%)	iodine (ppb)	error (%)	I/Cl* (x10 ⁶)
A-1	150	5.5	11200	2.1	21000
A-2	141	6.4	4700	1.8	9300
A-4	72	6.3	110	15.0	430
B-1	137	4.9	700	6.0	1430
B-3			14	41	
B-5	100	5.9	20	12	55
B-7	63	6.2	5	32	22
B-9	95	9.6	78	20	230
C1**	704		433		172
L***	76 (27-212)		53 (30-76)		195

*atomic ratio.

**C1 chondrite (Anders and Grevesse, 1989).

***L chondrite (Values in parentheses show ranges) (Mason, 1979).

Literature values (averages) for these two halogens in C1 and L chondrite groups also are given in this Table. In addition, elemental ratios of iodine to chlorine are listed at the 6th column of Table 1.

Chlorine contents seem to be rather constant within a factor of two, ranging from 63ppm to 150ppm. Samples taken near the surface (A1, A2, B1) show somewhat higher content (137 to 150ppm). On the contrary, iodine contents were found to vary more than three orders of magnitude: the sample taken from the outermost portion (A1) has the highest content (11.2ppm), whereas the sample taken from nearest to the center yields the lowest value of 5ppb. Obviously the iodine content has a steep negative gradient from the surface to the center. Iodine contents of B3 to B9 are not identical but seem to be not inconsistent with a literature value for L chondrite. The sample B7 shows an exceptionally low iodine content of 5ppb. These suggest that iodine, or halogen in general, is distributed heterogeneously in meteorite. As chlorine contents are much less variable than those of iodine, I/Cl ratios are largely dependent on values of iodine. The ratio of I/Cl

clearly shows that iodine is overabundant in the portions near the surface.

4.2 Depth-profile of intensity of hydration band

Fig. 2 compares FT-IR spectra for B1 and B7 with each other. In both spectra absorption bands due to the presence of OH groups were observed near 3500cm^{-1} . Sample B1 (Fig. 2(a)) shows a larger band than B7 (Fig. 2(b)). Integrated intensities calculated are listed in Table 2. Intensities vary within a factor of two. Samples taken near the surface (A1, A2, B1) show larger intensities than those taken near the center (B5, B7). Samples A4 and B3, which were closely located in a meteorite specimen, give similar values of intensity. The value for sample B9, which is somewhat near the opposite surface, falls between that of the near-surface-sample and that of the near-center-sample. Among samples examined, the gradient of intensity was observed from the surface to the center of meteorite.

Table 2. Integrated intensity of absorption band near $3\mu\text{m}$

sample name	integrated intensity
A-1	197
A-2	201
A-4	116
B-1	197
B-3	110
B-5	102
B-7	102
B-9	149

*See Miyamoto (1988) for method of calculation.

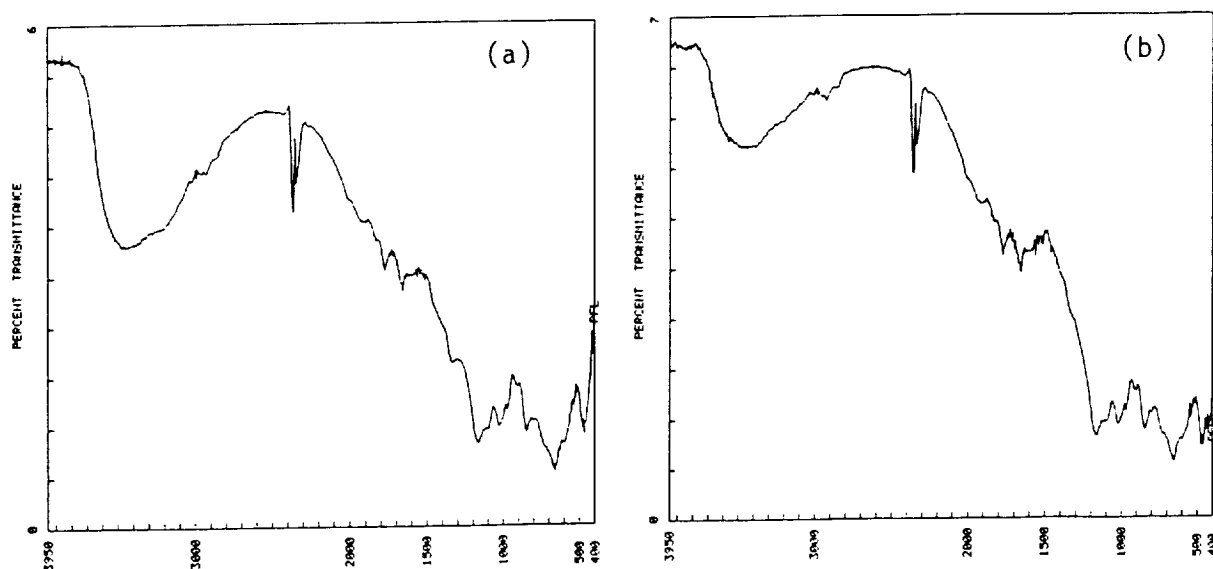


Fig. 2. FT-IR Spectra for samples B1 (a) and B7 (b). In both spectra, absorption bands due to the presence of OH groups were observed near 3500cm^{-1} .

4.3 Correlation between halogen abundances and absorption intensities

As pointed out in the previous sections, both iodine contents and integrated intensities of hydration band show the similar pattern of depth-profiles, even though the former vary more than three orders of magnitude,

while the latter changes only within a factor of two. Fig. 3 shows the relationship between iodine contents and integrated intensities. Note that scales used for two parameters are different from each other. There is an apparent positive correlation between these two variables. Although iodine contents of A1, A2 and B1 vary more than an order of magnitude (0.7 to 11.2 ppm), values of integrated intensity remain almost constant (197 to 201). This suggests that the degree of hydration of silicate minerals due to terrestrial weathering reached to the stage of "saturation". As discussed in Miyamoto (1988), the integrated intensity of hydration band in an IR spectrum can be a good parameter indicating the degree

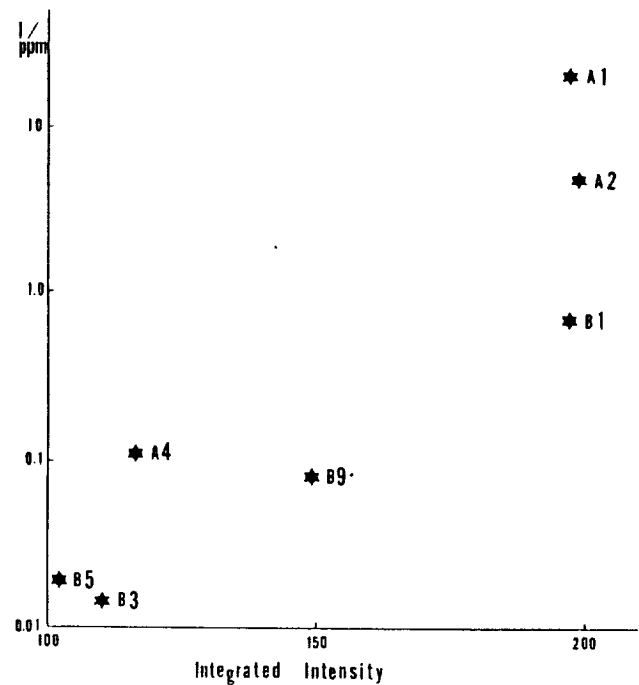


Fig. 3. Relationship between iodine contents and integrated intensities.

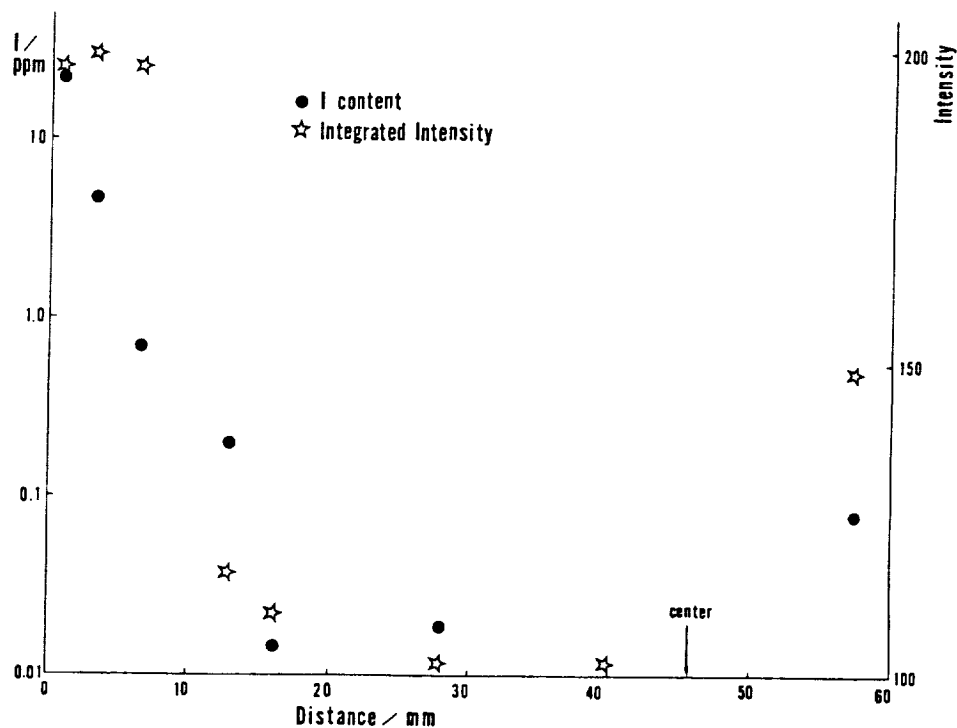


Fig. 4. Comparison of depth-profiles of iodine abundance and integrated intensities.

of terrestrial weathering on meteorites. A positive correlation between iodine contents and integrated intensities as shown in Fig. 3 clearly suggests that the over-abundance of iodine was caused by terrestrial weathering in Antarctica.

In Fig. 4, we compare depth-profiles of iodine abundance and integrated intensity with each other. The iodine content drastically changes from the surface towards the center and reaches to some "normal" range at the depth of 1.6cm from the surface. Such a pattern showing 'sharp decrease - plateau' was also observed for the depth-profile of intensity of hydration band, which reaches to the plateau at 2.0cm. A value of integrated intensity at the plateau region, however, is fairly high compared with those measured for other Antarctic meteorites (Miyamoto, 1988), suggesting that this meteorite was altered rather severely even in the portion near the center, although a weathering index is A/B.

At the center of meteorite, a value of iodine content reaches to the normal range, whereas the integrated intensity is still fairly high. This 'inconsistency' can be explained as follows: iodine must be transported (in the form of aerosol?) from the remote source region to the ice field where meteorites were found and stuck on the meteorite surface. Iodine is then migrated towards the center of meteorite, possibly by liquid water. Because porosity of chondritic meteorites is fairly high, liquid water must penetrate rather easily into meteorite. Water can be dispersed more easily into meteorite, if there are cracks. Iodine, on the other hand, must be trapped easily with mineral grains. If iodine is present in the form of molecule (I_2), physical adsorption can be the mechanism for trapping, while chemical absorption (or ion exchange) must be important if iodine is present as iodide and iodate.

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COMPARISONS BETWEEN ANTARCTIC AND NON-ANTARCTIC METEORITES BASED ON CARBON STABLE ISOTOPE GEOCHEMISTRY. Monica M. Grady, I.P. Wright and C.T. Pillinger, Planetary Science Unit, Dept. Earth Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, U.K.

Over the past two decades, the Antarctic meteorite collection has grown to over ten thousand fragments, which may represent *ca.* 2000 individual meteorite falls (1). This compares with a non-Antarctic meteorite collection of *ca.* 2500, amassed over the last two centuries (2). Break-down of the Antarctic collection by meteorite type shows a completely different distribution of the various sorts of meteorite from that in the non-Antarctic set (*e.g.* in the ordinary chondrite class, the ratio of H/L-group chondrites is ~ 3 times that of the non-Antarctic dataset; ref. 3). Antarctic meteorites have much older terrestrial ages than non-Antarctic samples, (10^4 to 10^6 years, compared to *ca.* 200; ref. 4). This has led to the suggestion that Antarctic and non-Antarctic meteorites might sample two different populations of parent-body material. Differences in trace element geochemistry have also indicated that, not only were there two populations in time, but that these were also genetically distinct (3).

Whilst the hypothesis that Antarctic and non-Antarctic meteorites sample different populations is interesting, the environment in which meteorites are collected/found must also be considered. Terrestrial weathering processes take place globally, in both hot and cold climates. The almost ubiquitous occurrences of evaporite minerals on Antarctic morainal deposits is testament to the action of weathering in sub-zero, desert conditions. Any study which differentiates between Antarctic and non-Antarctic meteorite populations must satisfactorily subtract weathering/contamination effects from the observations. This report addresses the carbon stable isotope geochemistry of Antarctic and non-Antarctic meteorites, with a view to recognizing similarities and differences between the two populations, once weathering effects have been taken into account. The most common weathering products which occur on the surface of Antarctic meteorites are evaporites: mainly sulphates, carbonates and bicarbonates (5). Contamination of non-Antarctic *finds* by similar materials is also possible. In general however, the interfering species in non-Antarctic meteorites, which occurs in both *finds* and observed *falls*, is terrestrial organic material, added during collection, curation and laboratory handling: non-Antarctic meteorites are not subject to the rigorous clean-room techniques used for storage of the Antarctic meteorite collections, and indeed may have been vulnerable for many years.

The effects of contamination (weathering products and organics) can be removed in either of two ways. Stepped combustion in increments above room temperature to 1200°C allows the

separation of indigenous carbon ($T_{\text{comb}} > 450^{\circ}\text{C}$) from terrestrial organics and evaporite weathering products ($T_{\text{comb}} < 450^{\circ}\text{C}$) (6). Table 1 gives a broad outline of the temperature ranges across which different components combust, or breakdown. These limits are not immutable, since factors such as grain-size and matrix effects also influence combustion temperature. Washing with acid provides an alternative way to remove most evaporites whilst not affecting indigenous elemental or stable compounds of carbon. However, for the groups which contain meteoritic carbonate, this method is unsuitable. In meteorites with high carbon abundances, such as C1 and C2 carbonaceous chondrites, the indigenous carbon content is so large that any contribution by terrestrial contaminants is swamped by the native material. In these cases, it is possibly unnecessary to correct for contaminants, and the observed data may be taken at face value.

Ordinary chondrites

Carbon abundance in ordinary chondrites decreases systematically with increasing petrologic type (0.1 - 1% in type 3, down to $\sim 0.01\%$ in type 6; 7), with the majority having relatively low carbon concentrations of 0.1 wt% and less. Bulk samples show no significant variation in whole-rock $\delta^{13}\text{C}$ with either petrologic type or chemical group (7), indicating that H-, L- and LL-group ordinary chondrites were formed in neighbouring localities where the same starting materials were available for incorporation during accretion. Notwithstanding this, as Fig. 1a indicates, there is, on the face of it, a difference in whole-rock $\delta^{13}\text{C}$ between the Antarctic (open symbols) and non-Antarctic chondrites. Stepped combustion, however, allows resolution of carbon into various components: at its simplest, low temperature carbon is often exogenic, high temperature is indigenous. Fig. 1b shows variation of $\delta^{13}\text{C}$ with yield of carbon released in the first temperature increment (room temperature to 200°C) of a stepped combustion: Antarctic ordinary chondrites are clearly distinguished from non-Antarctic. This reflects the release of thermally labile, loosely-bound material from the Antarctic chondrites, presumably from salt-like weathering products, and characterized by slightly ^{13}C -enriched isotopic signatures ($\delta^{13}\text{C}$ ca. $0 \pm 5\text{‰}$). In Fig. 1c, stepped combustion has progressed to 500°C . Again, Antarctic meteorites may be distinguished from non-Antarctic - the influence of weathering is pervasive, and not fully removed until these temperatures, even though the samples selected were interior chips, free from obvious alteration. Figure 1d plots the genuinely "indigenous" carbon, that which combusts above 500°C . Weathering products and any terrestrial organic materials have been removed, leaving a dataset in which there is variable $\delta^{13}\text{C}$. This variation, however, is due to inherent differences in the make-up of the ordinary chondrites, variable proportions of elemental carbon, carbides, *etc.* - there is no

obvious distinction in either carbon abundance or isotopic composition between Antarctic and non-Antarctic ordinary chondrites. Unfortunately, the identity, distribution and isotopic compositions of the several carbonaceous components in ordinary chondrites are not well-known, therefore comparison of individual components is problematic.

Carbonaceous chondrites

There are several carbon-bearing components in carbonaceous chondrites (Table 2), the dominant of which is a complex, acid-insoluble macromolecular material, although minor amounts of solvent-extractable organic compounds also exist. The most abundant accessory phase containing carbon is carbonate; minor "exotic" components: diamond, silicon carbide and other unidentified species, are also present. Each component has its own characteristic isotopic composition (*e.g.* insoluble organics: $\delta^{13}\text{C}$ *ca.* -17 to -15% ; carbonates: $\delta^{13}\text{C}$ *ca.* $+23$ to $+80\%$; minor components in the range -300 to $+7000\%$; 8-11), hence the total $\delta^{13}\text{C}$ of an individual carbonaceous chondrite is dependent on the relative proportions of the various components present. In addition, since the components are heterogeneously distributed within each meteorite, specimens of a single meteorite may exhibit a range of $\delta^{13}\text{C}$, *e.g.* the influence of ^{13}C -enriched carbonate on the total $\delta^{13}\text{C}$ of Murchison has been demonstrated (9). If total $\delta^{13}\text{C}$ of a carbonaceous chondrite is so dependent on its quota of individual components, it is perhaps more instructive to compare $\delta^{13}\text{C}$ of the individual components in Antarctic and non-Antarctic meteorites, in order to assess whether or not they are different. This is possible for carbonaceous chondrites, where it was not for the ordinary chondrites, since the composition of individual components is better understood in the former group of meteorites.

Dissolution in orthophosphoric acid identifies abundances and $\delta^{13}\text{C}$ of meteoritic carbonates. Analysis of carbonates in C1 and C2 chondrites (9) show that whilst there is no apparent difference in carbon and oxygen isotopic composition between Antarctic and non-Antarctic carbonaceous chondrites (Fig. 2a), the Antarctic meteorites contain, on average, almost twice as much carbonate carbon as the non-Antarctic chondrites (Fig. 2b). The significance of this observation is unknown, but might indicate a higher incidence of pre-terrestrial aqueous alteration in the Antarctic carbonaceous chondrite population than in the non-Antarctic.

High resolution stepped combustion allows differentiation of various minor phases on the basis of release temperature and isotopic composition; initial work in this area was reported by (12). Stepped combustion above 1000°C of several Antarctic and non-Antarctic CM2 chondrites revealed a difference in $\delta^{13}\text{C}$ of the two populations: $\delta^{13}\text{C}$ of the Antarctic chondrites was gener-

ally lower than that of the non-Antarctic chondrites. This was taken to indicate that the budget of "exotic" components in Antarctic CM2's was perhaps different from that in non-Antarctic CM2's, reflecting separate environments of formation. However, this study was based on the analyses of HCl-resistant meteorite residues, in which the action of HCl on whole-rock meteorites is unknown. Careful analysis of more fully demineralized HF/HCl-resistant residues (prepared as reproducibly as possible) of two CI1 and three CM2 chondrites fails to verify this apparent difference between Antarctic and non-Antarctic populations. Fig. 3 depicts the variation in $\delta^{13}\text{C}$ with combustion temperature above 600°C for typical Antarctic and non-Antarctic CM2 chondrites. It is readily observed that both specimens contain abundant ^{13}C -enriched carbon, but that in the Antarctic meteorite combusts at a temperature approximately 100°C lower than in the non-Antarctic specimen. This is taken to be a result of preterrestrial aqueous alteration, which has reduced the resistance of the SiC component to oxidation.

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Table 1

T < 200°C	Surficially-absorbed gases Loosely-bound bicarbonates
200 - 500°C	Organics
500 - 700°C	Carbonates Elemental carbon
T > 700°C	Graphite Diamond Carbides

Table 2

Organics: soluble	$\delta^{13}\text{C} > -10\text{‰}$
insoluble	$\delta^{13}\text{C} < -15\text{‰}$
Carbonates	$\delta^{13}\text{C} > +20\text{‰}$
Diamond	$\delta^{13}\text{C} < -30\text{‰}$
Silicon carbide	$\delta^{13}\text{C} > +1000\text{‰}$

Figure 1 Stepped combustion of Ordinary Chondrites

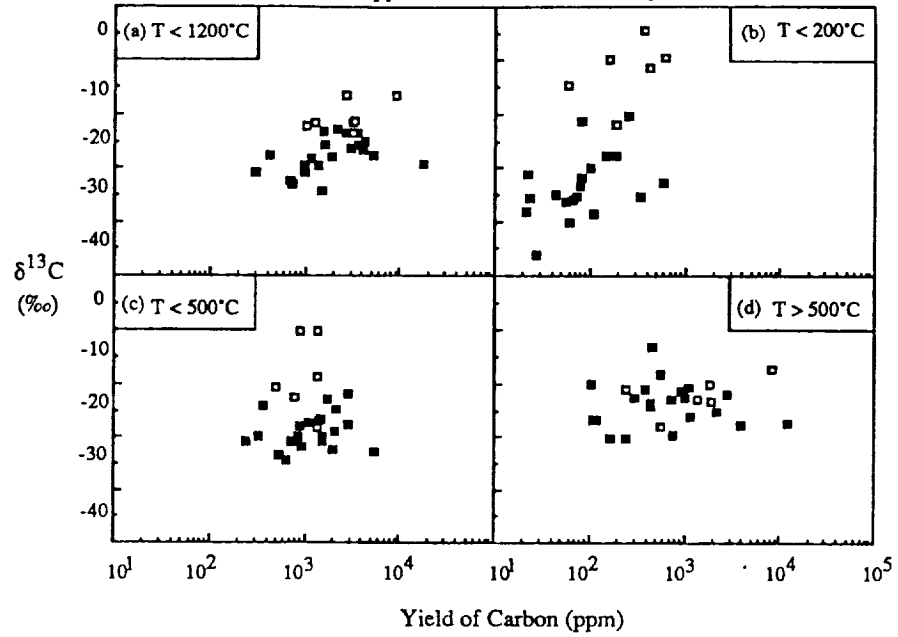


Figure 2

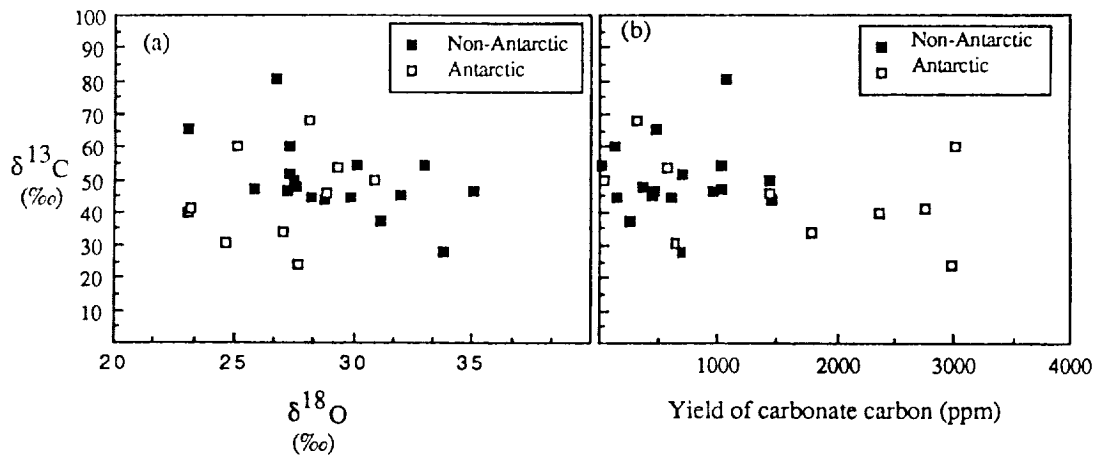
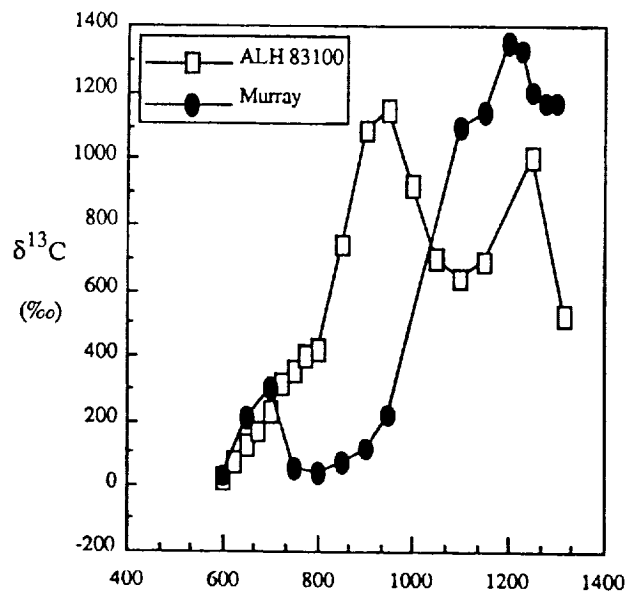


Figure 3: Combustion of CM2 chondrites above 600°C



STATISTICAL DIFFERENCES BETWEEN ANTARCTIC FINDS AND MODERN FALLS: MASS FREQUENCY DISTRIBUTIONS AND RELATIVE ABUNDANCE BY TYPE.

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The relative abundance of different compositional types and mass frequency distributions are presented for four meteorite samples (the modern falls, Antarctic finds, Yamato finds and Allan Hills Main Icefield finds). The modern falls sample represents continuous collection of a known number of falls over a short timespan, while the Antarctic samples represent a longer timespan and an unknown number of falls. A retabulation of the modern falls has been done to create a sample with characteristics similar to those of Antarctic finds, allowing a direct comparison of the two. Because it has been completely collected and reported, with no known bias towards large or unusual specimens, The Allan Hills Main Icefield sample is used in statistical comparisons to represent Antarctic meteorites.

The mass frequency distributions of Antarctic samples exhibit a tail toward the larger sizes and thus differ from that of the modern falls (which approximates a normal curve) (figure 1). Using non-parametric statistical tests at reasonable significance levels, normal and power law models inadequately explain the observed mass frequency distributions. In addition, the four samples are also shown to be distributed in distinct ways.

Relative frequency of meteorites of specific compositions also differ between the samples. Table 1 shows the mass and number of recovered meteorites from the four collections within several levels of compositional groupings. Non-parametric tests comparing numbers and masses within compositional types for the Allan Hills Main Icefield finds and the modern falls indicate they are not distributed in the same fashion. Based on the non-parametric statistics of relative frequency by type and by mass, it is unlikely that these two are both good samples of a single steady-state meteoritic complex.

A common argument used to explain these differences involves the Allan Hills Main Icefield (and other icefields) having been the site of several showerfalls which misrepresent the expected numbers of fragments of specific classifications. This hypothesis is invoked to explain the excess numbers of small H chondrites found on the Allan Hills Main Icefield (figure 2). However, if modern rates of showerfall occurrence are representative (roughly 1 out of 10 falls is a shower, and 35% of falls are either H or L chondrites), the excess numbers of small H chondrites in Allan Hills Main Icefield finds relative to modern falls can only be explained by making extreme assumptions as to the average number of specimens per fall (i.e., very few falls).

REFERENCES: (1) Harvey, R.P. and Cassidy, W.A. (1989) Meteoritics, 24, in press.

STATISTICAL DIFFERENCES: R. P. Harvey

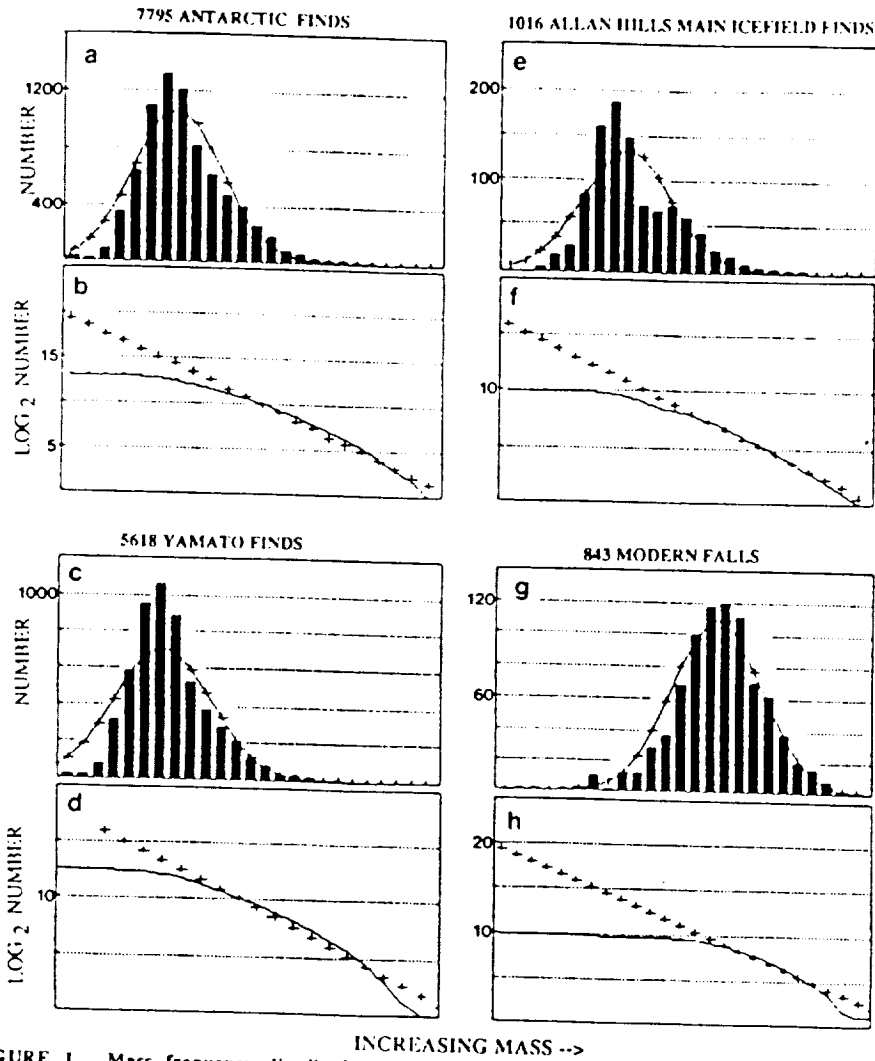


FIGURE 1. Mass frequency distributions for 4 meteorite samples: A, c, e, and g are plotted in number collected, with best fit normal curves superimposed. B, d, f, and h are plotted in log base 2 of the number collected, and the best fit power law is superimposed. In all cases the bottom axis is a series of mass ranges, starting with 0.0625 to 0.125 g, and doubling with each increment towards the right. Thus the second mass range shows the number of meteorites between 0.125 and 0.250 g, etc. (from Harvey and Cassidy, 1989).

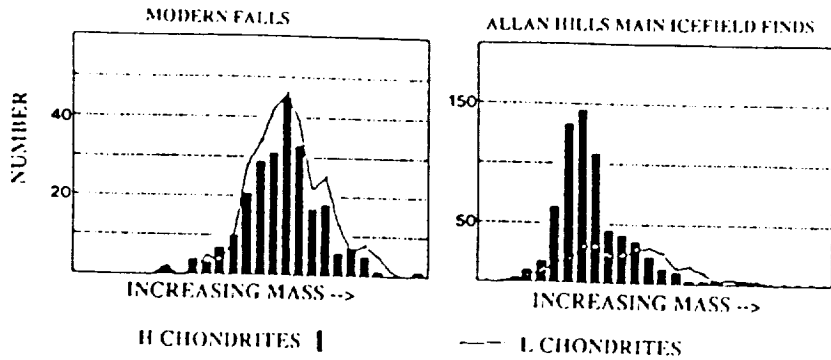


FIGURE 2. Mass Frequency distributions of H and L chondrites compared for modern falls and Allan Hills Main Icefield finds (from Harvey and Cassidy, 1989).

TABLE 1. Numbers and masses of 4 meteorite samples (from Harvey and Cassidy, 1989).

:ALL ANTARCTIC		:YAMATO		:ALLAN HILLS MAIN ICEFIELD		:RETABULATED MODERN FALLS	
MASS (g)	NUMBER	MASS (g)	NUMBER	MASS (g)	NUMBER	MASS (g)	NUMBER
TOTALS	2080000	7795	5618	671500	1016	15060000	843
DIVISION							
CHONDRITE	1434000	72.1	1529	625800	961	10750000	676
CARBON	39790	2	71	1572	13	456900	30
ACHONDRIT	59180	2.98	146	8460	29	1405000	63
ST. IRON	41580	2.09	6	637.1	1	619500	8
IRON	414300	20.83	7	35020	12	1698000	50
TOTAL:	1988850	3930	1759	671489.1	1016	14929400	827
ORD. CHONDRITES							
H CHON	540300	37.72	2009	182500	901	93510	647
L CHON	846900	59.13	1228	156800	535	528900	277
LL CHON	43130	3.01	166	33110	64	3211	30
E CHON	1968	0.14	27	773.2	4	161.5	3
TOTALS:	1432298	3430	1504	625782.5	957	10725500	651
H CHONDRITES							
H3	26460	5.04	51	10880	39	15360	5
H4	127800	24.33	318	39530	175	43420	91
H5	261500	49.78	982	57330	349	19860	408
H6	109500	20.85	638	59840	323	14810	138
TOTALS:	525260	1989	886	167580	886	93450	642
L CHONDRITES							
L3	28950	3.52	143	6965	23	15870	3
L4	18590	2.26	75	9205	37	2869	9
L5	50523	6.14	91	21160	34	2332	14
L6	724800	88.08	901	95510	425	507800	161
TOTALS:	822863	1210	519	528871	275	5543570	278

COSMOGENIC RADIONUCLIDES AND NOBLE GASES IN ALLAN HILLS C-CHONDRITES;
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Introduction: Cosmogenic nuclides in meteorites represent a record of the history of the cosmic radiation as well as of that of the meteorites themselves. Important information about the irradiation history of meteorites can be obtained from their exposure ages derived by measuring the concentrations of cosmogenic nuclides. With respect to Antarctic meteorites, chemical and petrological similarities as well as identical cosmic ray exposure and terrestrial residence times are criteria that two meteorites are possibly paired. We therefore measured the radioisotopes ^{10}Be and ^{26}Al as well as noble gases in carbonaceous chondrites from the Allan Hills area.

Experimental: The determination of ^{26}Al via gamma-gamma coincidence techniques is non-destructive and accurate to about $\pm 5\%$. The technique is described in detail elsewhere [1]. Samples of 10 - 15 g were used. ^{10}Be was separated by ion exchange, solvent extraction as well as classical precipitation methods as described in [2]. To insure bulk meteorite composition, 300 - 400 mg sized samples were used, taken from the same chunks on which ^{26}Al had been determined. The $^{10}\text{Be}/^9\text{Be}$ ratios were measured with the 6 MV Tandem Van de Graaff accelerator at ETH-Zürich [3]. For isotopic ratio measurements, detection limits down to $1 \cdot 10^{-14}$ were achieved.

He, Ne, and Ar were analyzed mass-spectrometrically as described in [4] on 120 - 150 mg sized aliquots of the respective ^{10}Be samples.

Results: ^{10}Be and ^{26}Al data are given in Table 1. The errors stated include statistical as well as systematical uncertainties. ^{26}Al in adjacent samples of ALH 83100.94 and ALH 77307.59 also was measured by AMS. The results show a relatively wide range of variation. Our value for ALH 77003 is in excellent agreement with the 45 ± 5 [dpm/kg] reported in [5]. For ALH 83100, a ^{26}Al value of 13 [dpm/kg] is cited in [6]. This value supports the low ^{26}Al activity given here. ^{26}Al in ALH 84029 was determined twice. Both analyses yielded the same very low activity.

He, Ne, and Ar data are given in Table 2. Errors of gas concentrations are $\pm 5\%$, isotope ratios have an uncertainty of $\pm 1.5\%$. Concentrations of cosmogenic ^{21}Ne ($^{21}\text{Ne}_c$) and $^3\text{He}_c$ in Table 2 should be accurate to within $\pm 7\%$, except for the $^{21}\text{Ne}_c$ values $< 0.05 \cdot 10^{-8} \text{ cm}^3\text{STP/g}$. In these cases, the uncertainties of the composition of trapped Ne lead to errors for the concentrations of cosmogenic Ne of about $\pm 15\%$. Exposure ages given in Table 2 are calculated with the production rates given in [7]. These are "nominal" exposure ages, assuming "average" shielding for our meteorites, since no shielding correction is possible.

Discussion: Except for ALH 84033, the ^{21}Ne exposure ages of the C2 chondrites are on the order of 100'000 - 200'000 years. These very low values make it clear that the radionuclide concentrations of these meteorites are not in saturation. The exposure ages of the other meteorites are high enough to ensure that the radionuclide activities were in saturation at the time of fall, with the possible exception of ^{10}Be in ALH 84033.

Exposure ages of C2 chondrites generally tend to be low and even exposure times as short as those reported here are rather common for this class [cf. 8]. Pairing of C2 chondrites can thus not be postulated based on a very low $^{21}\text{Ne}_c$ concentration alone. A common parent meteoroid for all five C2 chondrites in Table 2 having exposure ages less than 200'000 years is in fact clearly excluded by the ^{26}Al activities which differ by a factor of six in two meteorites (ALH 83102, ALH 84029) having $^{21}\text{Ne}_c$ concentrations equal within 30%. Radionuclide and noble gas data together suggest a possible pairing of ALH 84044 with ALH 83102 and perhaps also of ALH 84042 with ALH 83100. At present we have no explanation for the extremely low ^{26}Al activity in ALH 84029. A very long terrestrial age of this meteorite is not supported by its ^{10}Be activity which is at the upper bound of those found in the five C2 chondrites with low exposure age.

All four ^3He ages in Table 2 are higher than the corresponding ^{21}Ne ages by about 15 - 25%. Systematic errors of this magnitude either in the analysis of gas concentrations or in the corrections for trapped gases can be excluded. The discrepancy might reflect the fact that antarctic meteorites are on average smaller than the meteorites used in [7] to determine production rates. The production rate ratio $P(^{21}\text{Ne})/P(^3\text{He})$ is lower in small meteorites than in large ones [9].

Acknowledgements: Work supported by the Deutsches Bundesministerium für Forschung und Technologie and by the Swiss National Science Foundation.

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Tab.1: ^{10}Be - and ^{26}Al -concentrations in Allan Hills C-chondrites

Meteorite	Class	Sample	^{26}Al [dpm/kg]	Sample	^{10}Be [dpm/kg]
ALH 83100	C2	.94	6.9+0.3		
		.95	10.2+0.9*	.95	1.8+0.1
ALH 83102	C2	.43	13.8+0.8	.44	2.9+0.2
ALH 84029	C2	.16	2.2+0.3	.15	3.1+0.2
ALH 84033	C2	.9	56.8+4.2	.10	21.7+1.3
ALH 84042	C2	.6	8.6+0.6	.07	2.5+0.2
ALH 84044	C2	.8	12.1+0.5	.07	3.1+0.2
ALHA77307	C3	.59	24.3+1.3		
		.61	18.3+1.5*	.61	7.6+0.4
ALHA77003	C30	.6	46.6+1.9	.83	17.3+1.3
				.84	16.5+0.9
ALH 84028	C3V	.26	42.1+1.8	.30	17.6+1.0

* measured by AMS

Classification according Antarctic Meteorite Newsletter 9, No.4, September 1986

Tab. 2: Noble gases in Allan Hills C-chondrites

	^3He	4/3	^{20}Ne	^{21}Ne	20/22	^{36}Ar	36/38	^{40}Ar	$^{21}\text{Ne}_c$	$^3\text{He}_c$	A-21	A-3
ALH 83100	.571	5510	12.51	.089	8.15	55.3	5.31	537	.042	--	0.17	--
ALH 83102	.800	4570	15.34	.095	8.96	63.4	5.31	764	.043	--	0.17	--
ALH 84029	--	--	15.86	.082	9.64	47.1	5.30	405	.032	--	0.12	--
ALH 84033	2.80	1197	17.70	1.141	5.40	216.0	5.29	234	1.08	--	4.2	--
ALH 84042	.661	4480	13.32	.087	9.09	41.2	5.31	430	.043	--	0.17	--
ALH 84044	.676	4490	13.28	.087	8.52	51.7	5.31	498	.039	--	0.15	--
ALH 77307	32.5	98.7	20.14	4.88	2.69	284.5	5.26	351	4.81	32.1	15.0	20.0
ALH 77003	22.4	66.4	5.50	3.55	1.201	129.0	5.18	2550	3.53	22.4	11.0	14.0
ALH 77003	22.9	64.6	5.72	3.66	1.217	133.5	5.18	2620	3.64	22.9	11.4	14.3
ALH 84028	41.6	64.8	9.98	7.11	1.171	16.6	4.01	2360	7.09	41.3	22.1	25.8

Gas concentrations in [10^{-8} cm 3 STP/g]. Cosmogenic ^{21}Ne and ^3He ($^{21}\text{Ne}_c$, $^3\text{He}_c$) calculated as described in the text. ^{21}Ne and ^3He exposure ages (A-21, A-3) calculated with production rates given in [7].

METEORITE MASS DISTRIBUTIONS AND DIFFERENCES BETWEEN ANTARCTIC AND NON-ANTARCTIC METEORITES

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Possible differences between Antarctic and non-Antarctic meteorites fall into two classes: I) those resulting from differences in terrestrial history and/or collection procedures, which produce distinct samples of the same infalling material, and II) those that result from changes in the mix of material striking the earth as a function of position or time. An interpretive framework must be set up to place observations into the appropriate class. I will assume the following: 1) Meteorites of all classes fall randomly over the earth with no systematic variation with position or time. Relative proportions of meteorite types may differ as a function of mass, but are assumed to be constant with time and position. 2) Infalling meteorites have a power-law mass distribution with a slope of -0.833 on a log-number vs log-mass plot [1,2]. Most published values lie between -0.6 and -0.9 and none of my conclusions depend significantly on the precise value chosen. Such distributions contain many more small objects than large ones. 3) Meteorites often break in the air as they fall, to a degree that increases with mass [1,3]. Observed differences that cannot be explained within this framework may be examples of class II.

Antarctic meteorites are smaller than non-Antarctic meteorites. Antarctic meteorites have mass distributions that peak at about 10 grams, compared to about 5 kilograms for witnessed falls (Fig. 1). Non-Antarctic finds, as reported in the Catalogue of Meteorites [4] have a distribution like that for witnessed falls. Although the Antarctic distributions have not been corrected for pairing, this cannot explain the observed size difference. There is only enough mass in each Antarctic distribution (Fig. 1) to make up a handful of meteorites the size of a typical witnessed fall, yet we know that hundreds of falls are present.

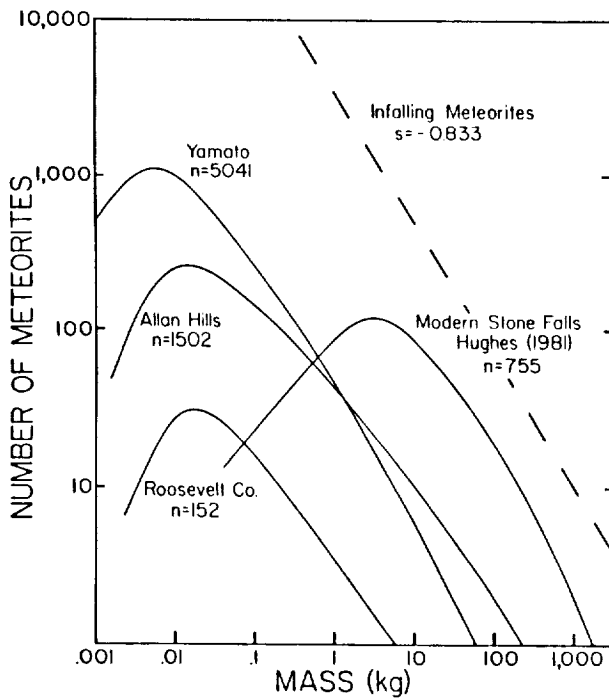


Figure 1

Antarctica is uniquely favorable for the recovery of meteorites. Meteorites survive for thousands of years in the dry, cold environment. On the blue ice where meteorites are found, it is easy to spot meteorites down to about ten grams (a ten gram meteorite is about two cm in diameter), and on many ice fields there are no terrestrial rocks to confuse the issue. Even when terrestrial rocks are present, it is easier to find the meteorites in Antarctica than it is in most of the rest of the world. Under these conditions, collection is more complete and complete recovery extends to smaller masses than almost anywhere else on earth.

Several authors have noted that the high-mass portion of the mass distribution for witnessed falls is similar to that expected for material hitting the earth's atmosphere [5,6]. Fig. 1 shows that the high-mass portion of the distributions of Antarctic meteorites also resembles that of infalling meteorites. This similarity,

combined with highly favorable collecting conditions, suggest that Antarctic meteorites represent a different portion of the mass distribution of infalling meteorites than do witnessed falls or most non-Antarctic finds.

This is not simply an Antarctic phenomenon. In Roosevelt County, New Mexico, a group of 154 meteorites with a mass distribution similar to those of Antarctic meteorites have been collected by systematically searching area where the soil has blown away, leaving meteorites lying, easily visible, on the surface [1,7]. The arid climate and vertical concentration of meteorites from a meter or more of soil onto a 'hardpan' surface, makes Roosevelt County a reasonable analogue to Antarctica. It appears that wherever conditions are suitable for preservation of meteorites and complete collection of the meteorites present, a mass distribution resembling that expected for infalling meteorites will be seen.

In summary, Antarctic meteorites are smaller than most non-Antarctic meteorites because collecting conditions allow for more complete collection of the material that has fallen. Any property that correlates with meteorite size will show up as a difference between Antarctic and non-Antarctic meteorites. Because small meteorites fall at a much higher rate than large meteorites, direct infall can produce the observed meteorite concentrations in a few tens to a few hundreds of thousands of years [1], contrary to expectations based on infall rates determined from witnessed falls [5,6]. Complete collection and the very large number of small meteorites has resulted in the recovery of numerous rare meteorites and the discovery of several unique meteorites, most of which are small. This is primarily because we now have large enough numbers of meteorites to begin to see the low-abundance types.

The H-chondrite/L-chondrite ratio among Antarctic and non-Antarctic meteorites. It has been widely reported in the literature that Antarctic meteorites have a higher H/L ratio than non-Antarctic meteorites and this supposed difference has been assigned to class II [8,9]. Table 1 shows H/L ratios and some related parameters for five Antarctic ice fields where classification has been largely completed, for Roosevelt County, and for witnessed falls and non-Antarctic finds as reported in the Catalogue of Meteorites [4].

Table 1: Selected data on relative abundances of chondrites.

Data Set	% Specimens	H + L		
	Classified	Specimens	H/L	H4 : H5 : H6
Allan Hills Main	96	893	2.63 (3.27) ^{1,2}	0.65 : 3.1 : 1.0
Allan Hills Near West.	94	112	4.89 (3.68) ^{1,3}	3.2 : 4.3 : 1.0 (1.1 : 4.3 : 1.0) ^{1,3}
Allan Hills Mid. West.	100	45	1.25	0.33 : 2.7 : 1.0
Allan Hills Far West.	93	217	1.21	0.13 : 1.9 : 1.0
Elephant Moraine	92	190	0.62	0.27 : 1.4 : 1.0
Roosevelt County	51	73	1.52 (1.21) ¹	3.0 : 15.5 : 1.0 (2.5 : 10.0 : 1.0) ¹
Modern Falls		599	0.87	0.64 : 1.5 : 1.0 ⁴
Non-Antarctic Finds		617	1.24	1.6 : 2.2 : 1.0 ⁴

¹ Ratio corrected for known pairing.

² Correction dominated by large L3 shower fall.

³ Correction dominated by H4 shower fall.

⁴ 10-15% of H chondrites not classified by petrologic type.

H/L ratio is apparently confined to the Allan Hills Main and Near Western ice fields, which lie within a few kilometers of each other, and is accompanied by an excess of H5's compared to other H chondrites. This data suggests an H5 shower fall and further investigation seems to confirm this interpretation.

Fig. 2 shows mass distributions for H5, H6, and L6 chondrites from the Allan Hills Far Western ice field, a field that has a 'normal' H/L ratio. Weathering, dominated by fragmentation, combines with the wind to remove meteorites from the ice, and the slope of the mass distributions becomes shallower with time [1]. The three classes shown in Fig. 2 have similar mass distributions, as would be expected for a group of meteorites that have experienced similar conditions for a similar period of time. Compare Fig. 2 with Fig. 3, which shows similar data for the Allan Hills Main ice field. Here the H5's have a strikingly different slope,

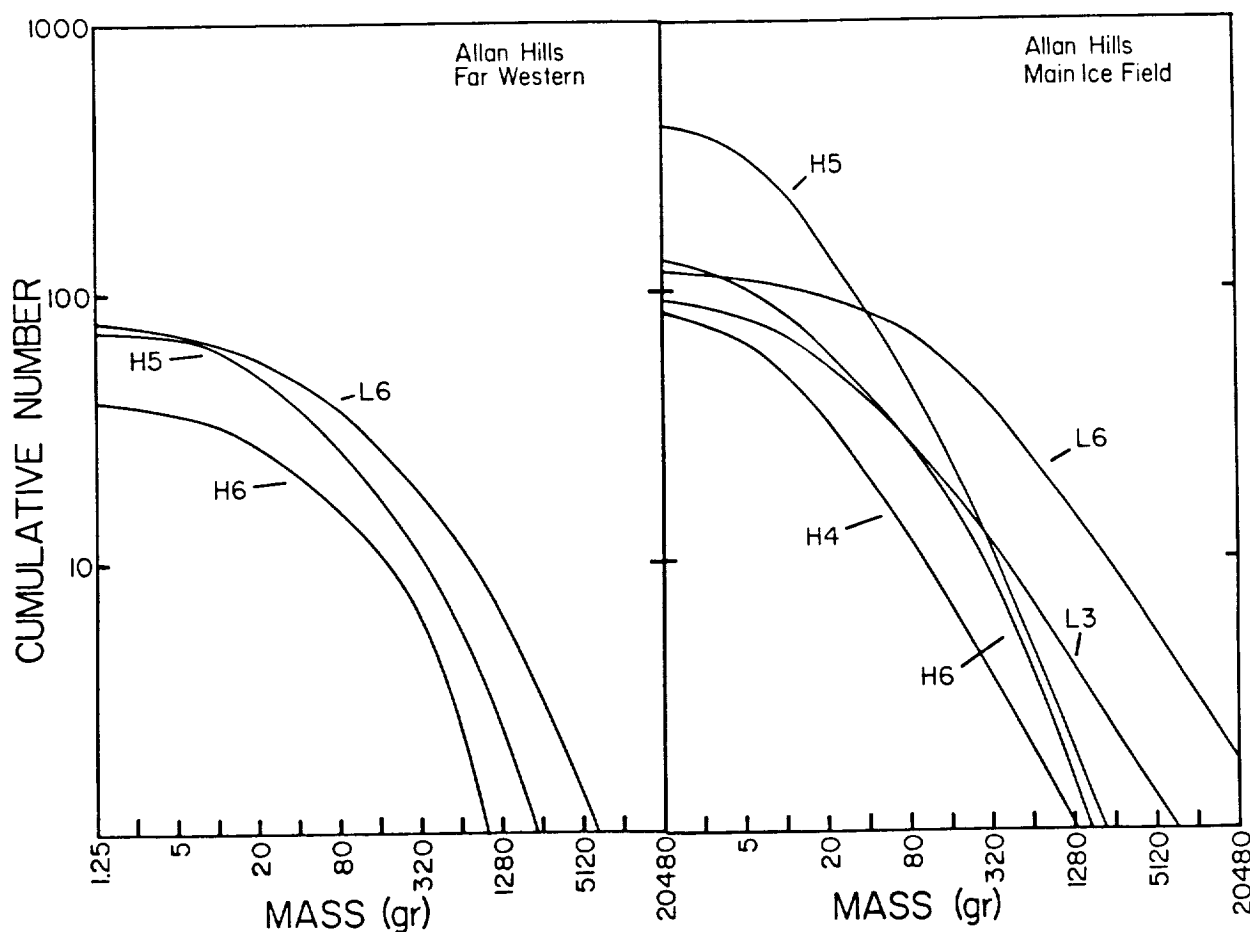
METEORITE MASS DISTRIBUTIONS. . .
G. R. Huss

much steeper than those of other classes of meteorites. This indicates the recent addition of a large number of small H5 chondrites.

As a further exercise, consider Fig. 4, in which a curve for the H5 chondrites (dashed line) has been drawn arbitrarily in a position (relative to the other curves) similar to that for H5 chondrites at the Allan Hills Far Western ice field. If I take the difference between the H5 curves in Figs. 3 and 4 and plot the result on a histogram (Fig. 5), the resulting mass distribution is similar to that of the Holbrook, Arizona shower fall. The interpreted shower consists of more than 300 stones and totals around 7,700 grams. The real shower may be somewhat larger since it apparently covers both the Allan Hills Main and Near Western ice fields. The slightly steeper slope for H6's (Fig. 2) might indicate a separate shower fall, but more likely reflects some misclassified H5 specimens.

Elephant Moraine seems to have an anomalously low ratio H/L ratio (Table 1). L6's are overabundant compared to other classes (e.g., Fig. 2) and have a steeper mass distribution than do the other classes (Fig. 6). The low H/L ratio at Elephant Moraine is most likely explained by a recent (or recently exhumed) L6 shower fall.

Thus there is no evidence of a grossly abnormal H/L ratio among Antarctic meteorites. Only limited pairing has been done among Antarctic meteorites, and this has concentrated on the rare and unusual meteorites. Until someone actually does the work to pair the 'uninteresting' H5's and L6's, as well as all other types of meteorites, there is no way to clearly identify possible subtle differences in ratios of meteorite types between Antarctic and non-Antarctic meteorites.



Figures 2 (left) and 3 (right) plot cumulative number larger than a given mass against the mass for several class of meteorites from each ice field.

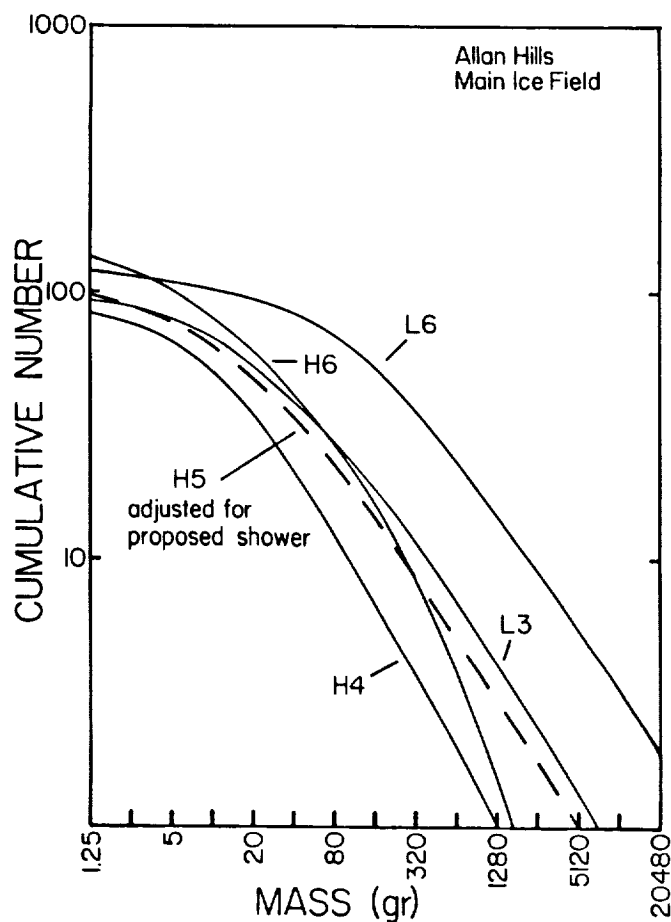


Figure 4: Same plot as Fig. 3 except that the curve for H5 chondrites has been replaced with an arbitrary curve (dashed line) in a position similar to that for H5's in Fig. 2.

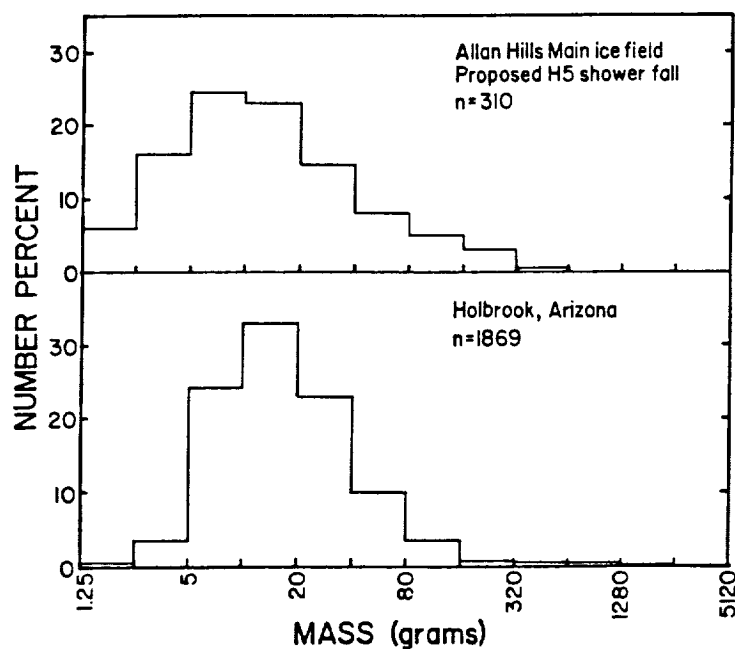


Figure 5: Histograms showing the mass distribution of specimens recovered from the Holbrook shower fall (after Harvey and Cassidy, 1989) and the mass distribution produced by taking the difference between the distributions for H5 chondrites in Figs. 3 and 4.

METEORITE MASS DISTRIBUTIONS. . .
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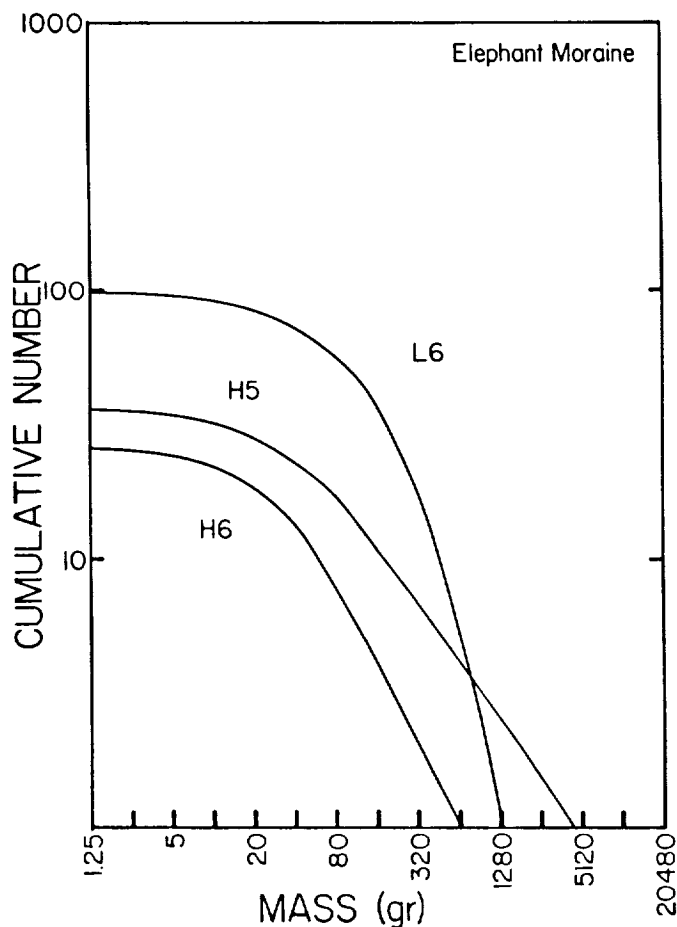


Figure 6: Cumulative mass distributions of three classes of meteorites from Elephant Moraine.

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CHEMICAL COMPOSITION OF ANTARCTIC AND
NON-ANTARCTIC CHONDRITES: A COMPARISON.

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The discovery of large quantities of meteorites in Antarctica provides an abundance of new material for research. Since some Antarctic meteorites may represent a different sample population from non-Antarctic meteorites, a comparison of petrology, mineralogy and chemical composition in the study of these meteorites is of interest. There is general agreement that Antarctic and recent meteorites may differ in their distribution patterns [1]. Also, it has been suggested that the trace elements composition of Antarctic and non-Antarctic H-chondrites differ [2]. A perceptible difference of any other features of these meteorites would help to establish clearer differences.

The author analyzed 151 ordinary chondrites, including 19 from Antarctica, for major and minor elements, Table 1. The average composition is given for Antarctic and non-Antarctic meteorites separately for finds and falls in order to distinguish the differences more clearly. Six L-3 and two L-6 paired chondrites were analyzed prior to having been identified as paired (Remarks, Table 1). These meteorites were included in the average as single analyses.

The data show good agreement of each of the three groups except for Fe(tot) and H₂O of H-chondrites. Other components within each of the three groups of chondrites agree rather well. The results are within one standard deviation. Although the agreement is good within each group, there are distinct trends within Fe(tot) and Fe(met) values, highest for finds and lowest for the Antarctic meteorites. It is worth noting that sulfur is lowest in the Antarctic meteorites. Some of these differences can be explained by weathering and leaching of iron and sulfur from the sample. Since only two LL-finds were analyzed and one of them, Ragland, is a unique type with unusual composition, the average results for Fe(met) and S may not reflect the true composition of LL-finds.

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CHEMICAL COMPOSITION: E. Jarosewich

TABLE 1

CHEMICAL COMPOSITION OF ANTARCTIC AND
NON-ANTARCTIC METEORITES: A COMPARISON

	H-CHONDRITES						L-CHONDRITES					
	falls(26)		finds(19)		Antarctic(4)		falls(54)		finds(12)		Antarctic(11)	
	s.d.		s.d.		s.d.		s.d.		s.d.		s.d.	
SiO ₂	36.60	0.55	36.96	0.81	36.90	0.64	39.72	0.55	39.68	0.53	39.65	1.11
TiO ₂	0.12	0.01	0.12	0.01	0.12	0.01	0.12	0.01	0.13	0.01	0.13	0.01
Al ₂ O ₃	2.14	0.15	2.18	0.15	2.20	0.13	2.25	0.15	2.29	0.07	2.30	0.10
Cr ₂ O ₃	0.52	0.03	0.52	0.03	0.49	0.06	0.53	0.04	0.51	0.06	0.53	0.03
FeO	10.30	1.16	9.93	1.95	10.86	2.44	14.46	1.07	14.40	2.11	15.77	1.64
MnO	0.31	0.02	0.32	0.02	0.31	0.02	0.34	0.02	0.34	0.01	0.32	0.03
MgO	23.26	0.38	23.34	0.53	23.19	0.43	24.73	0.41	24.63	0.43	24.69	0.63
CaO	1.74	0.09	1.72	0.11	1.75	0.09	1.85	0.10	1.86	0.11	1.64	0.09
Na ₂ O	0.86	0.04	0.69	0.16	0.88	0.13	0.95	0.05	0.86	0.13	0.88	0.08
K ₂ O	0.09	0.01	0.08	0.02	0.10	0.02	0.11	0.01	0.10	0.02	0.10	0.02
P ₂ O ₅	0.27	0.03	0.26	0.05	0.25	0.04	0.22	0.04	0.23	0.04	0.22	0.03
H ₂ O+	0.32	0.44	1.57	0.13	1.09	0.82	0.37	0.45	0.84	0.60	0.51	0.60
H ₂ O-	0.12	0.11	0.07	0.01	0.41	0.13	0.09	0.07	0.27	0.21	0.26	0.15
Fe(met)	15.98	1.53	15.08	1.93	14.35	1.79	7.03	0.95	6.39	1.50	5.66	1.55
Ni	1.74	0.09	1.62	0.13	1.75	0.07	1.24	0.10	1.20	0.09	1.19	0.10
Co	0.08	0.02	0.08	0.01	0.08	0.01	0.06	0.01	0.06	0.01	0.06	0.01
FeS	5.43	0.38	5.35	0.76	4.90	0.54	5.76	0.80	6.01	0.52	5.41	1.11
C	0.11	0.18	0.12	0.08	0.16	0.15	0.12	0.10	0.14	0.12	0.11	0.29
Total	99.99	0.30	100.00	0.00	99.77	0.35	99.99	0.29	99.94	0.35	99.65	0.18
Fe(tot)	27.45	0.84	26.19	1.25	25.63	0.85	21.93	0.80	21.42	0.93	21.36	1.26

LL-CHONDRITES												
	falls(12)				finds(2)				Antarctic(4)			
	falls		s.d.		falls		s.d.		falls		s.d.	
	s.d.		s.d.		s.d.		s.d.		s.d.	s.d.		
SiO ₂	40.60	0.54	40.73	0.61	41.18	0.61	P ₂ O ₅	0.22	0.04	0.22	0.24	0.08
TiO ₂	0.13	0.02	0.12	0.01	0.13	0.01	H ₂ O+	0.51	0.55	1.72	0.53	0.43
Al ₂ O ₃	2.24	0.08	2.23	0.10	2.36	0.10	H ₂ O-	0.20	0.14	0.41	0.23	0.10
Cr ₂ O ₃	0.54	0.03	0.54	0.03	0.54	0.03	Fe(met)	2.44	1.61	5.53	2.21	0.90
FeO	17.39	2.06	16.10	1.34	17.69	1.34	Ni	1.07	0.13	0.90	0.71	0.29
MnO	0.35	0.02	0.34	0.01	0.35	0.01	Co	0.05	0.01	0.04	0.05	0.01
MgO	25.22	0.44	24.46	0.71	25.08	0.71	FeS	5.79	1.04	3.58	5.04	1.27
CaO	1.92	0.11	1.95	0.07	2.02	0.07	C	0.22	0.21	0.35	0.05	0.07
Na ₂ O	0.95	0.06	0.62	0.07	0.93	0.07						
K ₂ O	0.10	0.02	0.08	0.00	0.10	0.00	Total	99.92	0.24	99.93	99.42	0.14
							Fe(tot)	19.63	0.68	20.38	19.16	0.74

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CHEMICAL COMPOSITION: E. Jarosewich

Remarks:

L-Antarctic: L-3: ALHA 77011, 77015, 77167, 77214, 77249, and 77260 are paired as are L-6: ALHA 77296 and 77297. Only the average of each type was included in the average L-chondrites.

Based on the data presented in Table 1, no statistically significant difference between falls, finds, and Antarctic meteorites of major and minor elements can be discerned, except for minor differences noted above. Other more sensitive diagnostic methods would have to be used to determine if differences do exist.

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CHEMICAL COMPOSITIONAL COMPARISON OF ANTARCTIC AND NON-ANTARCTIC METEORITE POPULATIONS. M. E. Lipschutz, Dept. of Chemistry, Purdue University, W. Lafayette, IN 47907 USA

After noting peculiarities in the Antarctic meteorite sampling relative to contemporary falls, Dennison et al. (1986) carried out a comparative, volatile/mobile trace element study of H5 chondrites from both populations. They suggested that the statistically significant compositional differences are too numerous to be attributed to chance or other trivial cause and are of such a nature as not to be attributable to Antarctic weathering. Dennison et al. (1986) concluded that the differences are preterrestrial in origin, reflecting differences in average thermal histories of the parent populations.

This study (and subsequent ones) then raised the 3 major questions being considered by this Workshop.

- 1) Do Antarctic and non-Antarctic meteorite populations differ significantly?
- 2) If so, are the differences terrestrial in origin?
- 3) If not, what preterrestrial processes do the differences reflect?

Chemical differences are among the many differences evident between Antarctic and non-Antarctic meteorite populations (Lipschutz, 1989). Mainly, volatile/mobile trace element contents are higher in Antarctic H chondrites (Dennison et al., 1986; Dennison and Lipschutz (1987)) and eucrites (Paul and Lipschutz, 1987) and lower in Antarctic L chondrites (Kaczaral et al., 1989) than in non-Antarctic falls. Antarctic/non-Antarctic differences are also evident on discriminant analysis of H or L chondrites (Samuels and Lipschutz, 1989). During Antarctic weathering and alteration of meteorites to weathering type C, such trace elements are leached out. Hence, even if the meteorites studied of weathering types A and B were affected to any extent by Antarctic processes, L chondrites are the only group that could conceivably reflect such alteration. But this group exhibits shock-history differences between the populations that must be preterrestrial in origin (Haq et al., 1988; Kaczaral et al., 1989). Antarctic Cl,2 chondrites differ compositionally from non-Antarctic samples in ways that must reflect preterrestrial thermal history differences (Paul and Lipschutz, 1988). Hg-siting and -contents in Antarctic achondrites and E4,6 chondrites differ from those in corresponding non-Antarctic samples in ways that could not reflect Antarctic weathering (Jovanovic and Reed, 1988).

It should be noted that McSween (1987) and Zolensky et al. (1989b) found that the matrix compositions of Antarctic and non-Antarctic Cl,2 chondrites are very similar. As noted above, trace element trends and other data from these meteorites - oxygen isotopic composition (Mayeda et al., 1988; Clayton and Mayeda, 1989) and petrologic properties (Grady et al., 1987; Tomeoka et al., 1988; Zolensky et al., 1989a) - differ so much in the two populations as to call into question previous classification schemes based upon non-Antarctic samples.

CHEMICAL COMPOSITIONAL COMPARISON: Lipschutz M. E.

The differences that exist involve labile elements and are ascribable to thermal fractionation during solid-state transformation of meteoritic material. Refractory element contents are insensitive to solid-state processes and are not expected to differ in Antarctic and non-Antarctic chondrite populations. Such differences could occur during solid-liquid transformations, hence might be evident in achondrites. The systematically lower siderophile element contents in Antarctic ureilites relative to non-Antarctic ones may reflect such an effect (Spitz and Boynton, 1988).

Acknowledgements. This research was sponsored by the U. S. National Science Foundation (grant DPP-8715853) and the National Aeronautics and Space Administration (grant NAG 9-48).

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DIFFERENCES BETWEEN ANTARCTIC AND NON-ANTARCTIC METEORITE POPULATIONS,
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Summarized below is an up-to-date list of properties that do and do not differ significantly in specific meteorite types of Antarctic and non-Antarctic meteorite populations and the references in which these results are reported. I also list additional evidence pertinent to the question of whether meteorites "remember" their launch parameters: the contemporary picture obtained by statistical, Monte Carlo calculations of asteroid ejecta indicate that meteorites should be amnesiacs in this regard (Wetherill, 1986).

Differences between Antarctic and non-Antarctic meteorite populations ARE exhibited by:

1. Meteorite type frequencies (Dennison, Lingner and Lipschutz, 1986)
 - Stony-irons
 - Achondrites
 - Aubrites
 - Howardites
 - Ureilites
 - Chondrites
 - H/L chondrite ratio
 - Irons (Clarke, 1985; Wasson, Ouyang, Wang and Jerde 1989)
2. Meteorite mass distributions (Harvey and Cassidy, 1988)
3. Meteorite textures
 - Eucrites (Takeda, Mori, Delaney, Prinz, Harlow and Ishii, 1983; cf. Takeda, 1989)
 - Ureilites (Takeda, 1987; cf. Takeda, 1989)
 - Cl,2 Chondrites (Grady, Graham, Barber, Aylmer, Kurat, Ntaflos, Ott, Palme and Spettel, 1987; Tomeoka, Kojima and Yanai, 1988; Zolensky, Barrett and Prinz, 1989a)
4. Shock histories
 - H,L chondrites
 - thermoluminescence (Haq, Hasan and Sears, 1988)
 - petrography (Dennison and Lipschutz, 1987; Kaczaral, Dodd and Lipschutz, 1989)
5. Trace element contents
 - H chondrites (Dennison and Lipschutz, 1987)
 - L chondrites (Kaczaral, Dodd and Lipschutz, 1989)
 - Cl,2 chondrites (Paul and Lipschutz, 1988)
 - Eucrites (Paul and Lipschutz, 1987)
6. Siderophile element contents
 - Ureilites (Spitz and Boynton, 1988)
7. Hg-siting and retention (Jovanovic and Reed, 1988)
 - Achondrites
 - E4,6 chondrites
8. $^{13}\text{C}/^{12}\text{C}$ ratios
 - Cl,2 chondrites (McGarvie, Wright, Grady, Pillinger and Gibson, 1987)

METEORITE POPULATION DIFFERENCES: Lipschutz M. E.

9. Oxygen isotopic composition
 - Ureilites (*Clayton and Mayeda, 1988*)
 - Cl,2 chondrites (*Mayeda, Clayton and Yanai, 1988; Clayton and Mayeda, 1989*)
10. Cosmogenic ^{53}Mn contents (*Nishiizumi, 1986; Dennison and Lipschutz, 1987*)
 - H chondrites

Differences between the sample populations ARE NOT exhibited by:

1. Matrix composition
 - Cl,2 chondrites (*McSween, 1987; Zolensky, Barrett and Gooding, 1989b*)
2. Cosmogenic ^{53}Mn contents
 - L chondrites (*Nishiizumi, 1986; Dennison and Lipschutz, 1987*)
3. Cosmic ray exposure age distribution
 - H chondrites (*Weber, Schultz and Begemann, 1988*)

A strong contrast is evident in the absence of significant matrix compositional differences for Antarctic and non-Antarctic populations of Cl,2 chondrites and the presence of striking differences in their textures. Trends for cosmogenic ^{53}Mn contents in Antarctic and non-Antarctic L chondrite populations contrast sharply with those in H chondrite populations. The H chondrite exposure age distribution is not completely understood. *Graf and Marti (1989)* report that exposure age distributions of non-Antarctic H chondrites apparently vary with petrographic type but this observation relies upon older, possibly unreliable, data (*Schultz, Weber and Begemann, 1989*).

In commenting on the initial report of *Dennison et al. (1986)*, *Wetherill (1986)* pointed out that a necessary consequence of this would be the existence of meteorite streams in space. Such streams had previously been postulated by *Wood (1982)*. Subsequently, *Oberst and Nakamura (1986)* reported detection of meteorite streams on lunar seismograms (cf. *Oberst, 1989*) and *Dodd (1989)* reported that contemporary fall data indicate such streams for H chondrites. *Halliday, Blackwell and Griffin (1989)* observed putative streams of meteorite-producing asteroidal fragments in photographic data from the U.S. Prairie Network and Canadian Meteorite Observation and Recovery Project in the Earth's Northern hemisphere. *Olsson-Steel (1988)* obtained evidence from radar orbit surveys (at Adelaide in the Southern hemisphere) for such streams from Apollo asteroids. One point that must be settled is whether the otherwise convincing observations of streams by two independent studies using different techniques could reflect a chance effect, since both rely upon the revised discriminant parameter, D' , employed hitherto only for meteor observations.

Most differences observed between Antarctic and non-Antarctic meteorite populations cannot reflect Antarctic weathering processes. [Differences observed in the carbon isotopic composition of ordinary chondrites does seem to reflect weathering according to *Grady, Wright and Pillinger, 1989*.] Rather, the differences reflect substantial thermal history differences in (components of) each population. The most likely cause, in my judgement, for variations in population-components is a time-dependent change in the

Earth's sampling of extraterrestrial sources, although orbital, hence size-dependent variations could be invoked (Huss, 1989; Wasson, Ouyang, Wang and Jerde, 1989).

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MICROMETEORITES FROM THE GREENLAND AND ANTARCTICA ICE SHEETS; PRELIMINARY COMPARISON WITH DEEP SEA MICROMETEORITES, STRATOSPHERIC IDPs, AND PRIMITIVE METEORITES. M. Maurette, Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, Batiment 108, 91406 Campus-Orsay, France. J.P. Bradley, McCrone Associates, 850 Pasquinelli Drive, Westmont, IL 60559. C. Hammer, Institut of Geophysics, University of Copenhagen, Haraldsgade 6, DK-2200 Copenhagen N. M. Pourchet, Laboratoire de Glaciologie, Domaine Universitaire, BP 96, 38402-St Martin d'Hères, France. P. Veyssières, Laboratoire d'Etude des Microstructures, ONERA, BP 72, 92322 Chatillon-sous-Bagneux.

Three "Blue Lake" expeditions (July 1984; July-August 1987; July 1988) have been launched to collect dark sediments ("cryoconite") from the melt zone of the west Greenland ice sheet. A simple mechanical disaggregation of cryoconite on stainless steel sieves with opening of $\geq 50 \mu\text{m}$ yields a minute mineral filtrate (about 0.5 wgt %), that is very much enriched in melted (spherules) and unmelted chondritic micrometeorites (1). In January and February 1988 about 100 tons of blue ice was artificially melted near the margin of the Antarctica ice sheet at "Cap-Prudhomme", at about 6 km from the french station of Dumont d'Urville. The filtering of melt ice water on sieves with openings of $\geq 50 \mu\text{m}$ yielded about 2g of mineral filtrates, that contain ~ 5000 spherules and ≥ 5000 unmelted micrometeorites with a chondritic composition (2).

The great enrichment of micrometeorites in both types of "blue ice" filtrates allows their direct hand-picking under a binocular. The new collections of Greenland and Antarctica micrometeorites are amazingly complementary, with regard to both terrestrial contamination and terrestrial weathering. The comparison of 3 size fractions ($50-100 \mu\text{m}$, $100-400 \mu\text{m}$, and $\geq 400 \mu\text{m}$) indicates that terrestrial contamination in Greenland is related to wind born dust, that heavily contaminates the smallest $50-100 \mu\text{m}$ size fraction, in which micrometeorites can hardly be hand-picked. The cleanest $\geq 400 \mu\text{m}$ size fraction now shows the highest enrichment in micrometeorites (about one third of the grains are extraterrestrial).

In sharp contrast in Antarctica the $50-100 \mu\text{m}$ and the $\geq 400 \mu\text{m}$ fractions are the least and the most heavily polluted, respectively. This results from a different type of contamination, related to a turbulent flow of the ice sheet near margin, that injects coarse moreine debris into a shallow micrometeorite-rich layer of the ice field, found at depths ranging from 20cm up to 1.5m. In this layer the concentration of micrometeorites with size $\geq 50 \mu\text{m}$ ($\sim 100/\text{ton}$) is about 20 times higher than the background value measured at a depth of 5m.

A method was developed to assess the relative extent of terrestrial weathering in any collection of micrometeorites with sizes $\geq 100 \mu\text{m}$ (3). We select chondritic "barred" spherules, which are the most abundant grains in this size range. These spherules

are composed of bars of olivine and interstitial glass. In deep sea spherules the glass bars are preferentially etched out, delineating a typical pattern of etch canals with lengths $\geq 100\mu\text{m}$.

In Greenland this etch pattern extends to much shallower depths ($\leq 10\mu\text{m}$). In Antarctica etch canals can hardly be detected, and in the worst case they extend only up to depths $\leq 1\mu\text{m}$. In both deep sea and Antarctica spherules glass is always etched out at a faster rate than olivine, and this reflects the "ordinary" chemical etching of water. But in Greenland olivine is now etched out at a much faster rate than glass. We have shown (3) that this odd feature is related to biogenic etching in Greenland cryoconite, mostly composed of cocoons of siderobacteria in which all grains are tightly encapsulated. We deduce from these observations that the "cap-Prudhomme" micrometeorites (CPMM) are the least weathered of all, and that they have not been exposed to biogenic activity.

There is no collection of micrometeorites in Space or on Earth which is completely free from artefacts and biases. The Cap-Prudhomme collection looks so far as the best one "returned" to the laboratory, only considering "giant" micrometeorites with sizes ranging from $50\mu\text{m}$ to $200\mu\text{m}$ (But Greenland cryoconite is yet the only available "mine" of coarser micrometeorites, that are extremely rare in space). We outline below a preliminary comparison between this best preserved collection of CPMM, and other collections, outlining differences resulting from: collection techniques, terrestrial contamination and/or weathering, atmospheric entry, dynamical processes in space, nature of parent bodies.

DEEP SEA COLLECTION

In this type of collection, obtained by magnetic raking of deep sea sediments, the proportion of "metallic" spherules (i.e. oxidized Fe/Ni alloys) reaches a high value of $\sim 50\%$, whereas that of unmelted micrometeorites is smaller than $\sim 1\%$ (4). In Antarctica this proportion of metallic spheres drops to $\leq 2\%$, and that of unmelted micrometeorites drastically increases as to reach a value $\geq 80\%$ in the richest $50\text{--}100\mu\text{m}$ size fraction. Such differences are likely related to both the magnetic extraction and the more extensive terrestrial weathering of deep sea particles.

GREENLAND COLLECTION

In Greenland only the $50\text{--}100\mu\text{m}$ size fraction of the richest cryoconite sample (JAK-3) has been investigated yet. The proportion of "metallic" spherules is similar to the low value observed in Antarctica, but the proportion of unmelted grains reaches a smaller value of about 50% . This might reflect the harsher mechanical procedures used to disaggregate cryoconite samples, that preferentially destroy the most friable grains. In both collections the proportion of unmelted micrometeorites with sizes $\geq 100\mu\text{m}$ drops to a much smaller value of $\sim 25\%$, that is rather constant up to sizes of $\sim 1\text{mm}$.

STRATOSPHERIC COLLECTION OF INTERPLANETARY DUST PARTICLES

Automated point count analyses of a few unmelted C-rich CPMMs (see below) were performed at McCrone Associate (5) at a scale of the analyzed volume of $\sim 10^{-3} \mu\text{m}^3$. They suggest that CPMMs are different from the 3 major classes of IDPs, namely hydrated particles, and olivine and/or pyroxene-rich anhydrous particles (6). This is displayed on Si/Mg/Fe ternary diagrams reported in references 5 and 6 for CPMMs and IDPs, respectively, showing a much tighter clustering and higher Fe contents for Antarctica micrometeorites. Such differences between the small and "giant" micrometeorites captured by the Earth might originate from dynamical processes perturbing their orbits in space, and from their hypervelocity impact with the atmosphere, screening peculiar "survivors".

PRIMITIVE METEORITES

We have compared micron-size grains extracted from the fine-grained matrices of either "primitive" meteorites (Orgueil, Allais, Murchinson) or 13 individual unmelted "giant" CPMMs (sizes $\sim 200 \mu\text{m}$). For these analyses several techniques of high voltage transmission electron microscopy were used to investigate: high resolution imaging up to magnification of 800,000X (with the new 400KV microscope at ONERA); electron energy loss spectra, yielding C/O atomic ratios at a scale of $0.2 \mu\text{m}^2$ (with the electron spectrometer of the 1MV microscope at "Laboratoire d'Optique Electronique du CNRS, Toulouse"); thermal degradation upon in-situ pyrolysis up to 1000°C (with the hot stage of the 3MV microscope at Toulouse). We thus found that the "composite-nanophase" material that constitute the fine grained matrices of the CPMM differ again from primitive meteorites. In particular about 20% of the CPMM shows C/O ratios higher than the value measured in Orgueil. Moreover besides the few major minerals usually quoted in the literature, they contains an amazingly high diversity of nanophases, not clearly observed in primitive meteorites, yet.

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EUCRITES: ANTARCTICA VERSUS THE REST OF THE WORLD

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Antarctic eucrites provide a valuable source of material from the HED parent body for petrologic and geochemical interpretations of petrogenesis on asteroids. Differences between Antarctic and non-Antarctic eucrites have been noted previously. The first order difference in proportions of polymict and monomict eucrites may not be as large as it appears because many of the Antarctic polymict eucrites are paired and thus represent only a few falls. In a recent study of volatile/mobile trace elements in HED samples Paul and Lipschutz (1) showed that Antarctic samples are enriched in many of these elements. They attributed this difference to differences in parent population due to HED parent body processes. We have previously noted that many basaltic clast samples of the LEW853xx polymict eucrites have unusual REE patterns that show positive Ce anomalies (2) and suggested the possibility that the anomalies result from weathering processes. Here we apply the results of our eucrite weathering study (3) to literature data in order to evaluate the nature and causes of differences between non-Antarctic and Antarctic eucrites, polymict eucrites and basaltic clasts. In this abstract, we will use the generic term eucrites for eucrites, polymict eucrites and basaltic clasts from HED samples.

The REE data for Antarctic eucrites and non-Antarctic eucrites show distinct differences. The Ce/La ratios for non-Antarctic eucrites are generally more nearly chondritic than those of Antarctic eucrites: 76% of the 51 analyzed non-Antarctic eucrites are within the range 0.9-1.1x CI. In contrast, only 40% of the 76 analyzed Antarctic eucrites are within the same range. In Figure 1, a plot of La vs. Ce/La, the Antarctic eucrites span the range of La and Ce/La. However, most of the samples with higher than normal Ce/La have low La concentrations. This suggests that the anomalous Ce/La ratios are predominantly due to low La in the samples and not high Ce. Ratios of Ce/La reach a maximum of 2.5 x CI for one analysis of ALHA78132 (4). The Antarctic eucrites also show high Ce/Sm ratios at low Sm concentration (not shown). Partition coefficients for the +3 REE are smooth functions of ionic radius, and it is unlikely that igneous processes will fractionate Ce from La and Sm. Cerium more easily forms tetravalent species than the other REE, and may be fractionated from the trivalent REE. However, Ce⁺⁴ occurs in significant abundance only in oxidizing conditions such as are found on the earth's surface. Eucrite petrogenesis occurred under low oxygen fugacity near the iron-wustite buffer (5), where it is unlikely that significant Ce⁺⁴ was present. The positive Ce anomalies are more likely to have developed in terrestrial weathering than during HED petrogenesis.

Our analyses of ALHA76005 and ALHA78040 show pronounced LREE depletions and positive Ce anomalies in exterior samples and little or no Ce anomalies in interior samples (3). Schimizu et al. (4) similarly measured interior and exterior samples of ALHA78132. Their exterior samples showed positive Ce anomalies while the interior sample exhibited a negative Ce anomaly. We have found a negative Ce anomaly in the exterior sample of EETA79005 (3). Schimizu et al. (4) have concluded based on their Ce isotopic analyses that the anomalies in Ce concentration are a result weathering while on the ice sheet and are not a HED parent body phenomena. We believe that this is probably true.

EUCRITES: D. W. Mittlefehldt and M. M. Lindstrom

We have found one other significant difference between non-Antarctic eucrites and Antarctic eucrites based on literature data and our unpublished data. The Antarctic eucrites are significantly richer in Se than are non-Antarctic eucrites. The mean concentrations in non-Antarctic eucrites and Antarctic eucrites are 200 +/- 50 and 1330 +/- 320 ppb respectively. A histogram of eucrite Se data clearly shows the distinction between the Antarctic and non-Antarctic populations (Fig. 2). Our preliminary Se data for exterior samples of eucrites show Se concentrations above the range for non-Antarctic eucrites, while only upper limits can be calculated for the interior samples. We expect that the final count set will help us determine whether Se is affected by weathering processes.

Previously, it has been suggested based on chondrite studies that weathering in the Antarctic environment results in leaching of trace elements from meteoritic samples (1). We believe that the effects of weathering processes in HED samples are more complex and involve both leaching and enrichment. It is premature to use the observed differences in Antarctic and non-Antarctic eucrites to infer petrologic processes on the HED parent body. Additional studies on exterior and interior samples of HED meteorites are clearly required.

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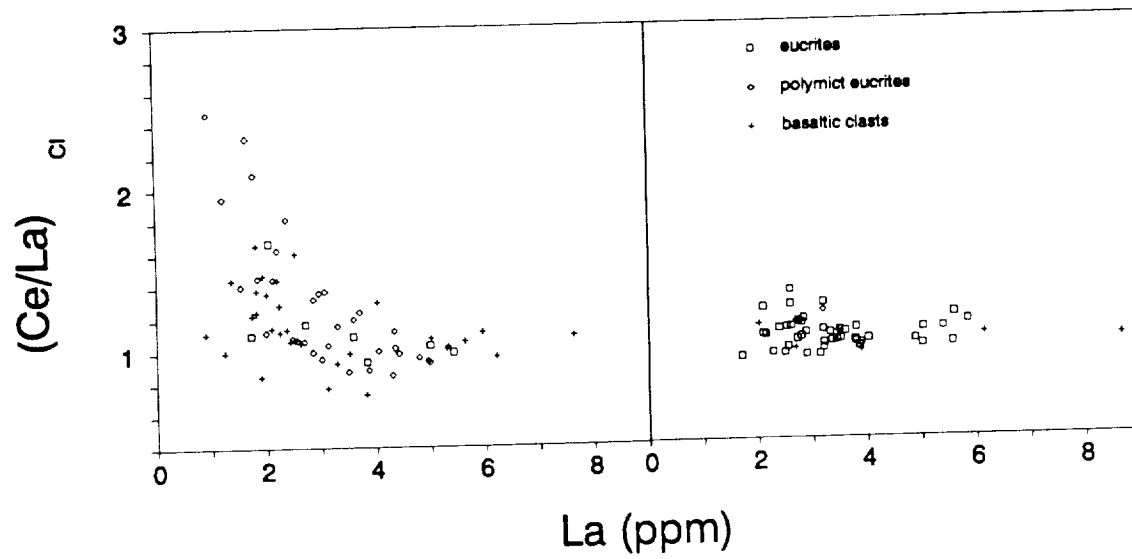


Fig. 1.

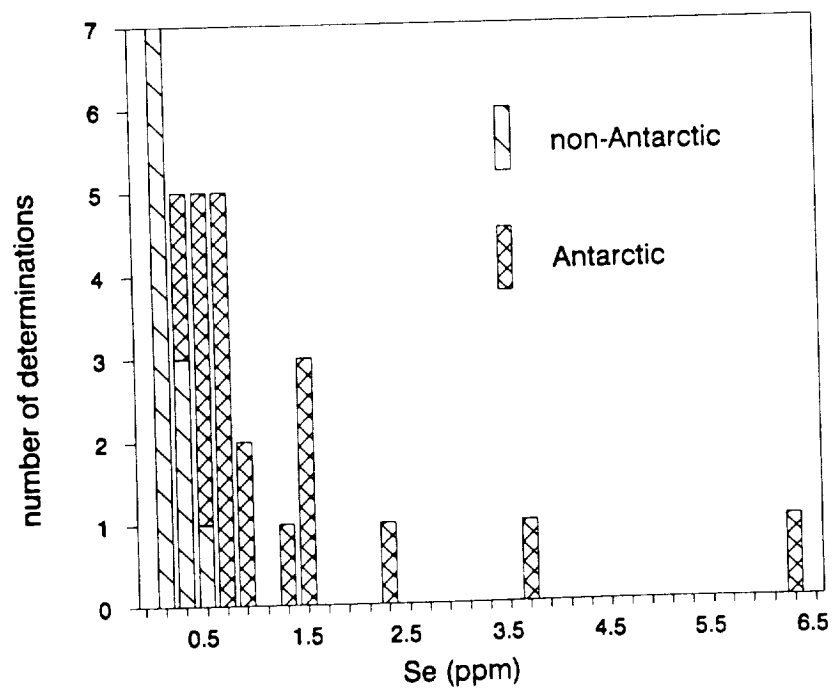


Fig. 2.

DIFFERENCES IN THE DEGREE OF WEATHERING BETWEEN ANTARCTIC AND NON-ANTARCTIC ORDINARY CHONDRITES: INFRARED SPECTROSCOPY

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Introduction: We have studied the degree of terrestrial weathering of Antarctic ordinary chondrites on the basis of the integrated intensity of absorption bands near $3 \mu\text{m}$ of infrared diffuse reflectances (1,2). Absorption bands (hydration bands) near the $3 \mu\text{m}$ wavelength region are caused by OH stretching vibrations of hydrates and/or hydroxyl ions. The integrated intensity of the hydration bands may be dependent on the degree of weathering, because terrestrial weathering produces hydrous minerals. In addition, Antarctic ordinary chondrites usually show weak absorption bands near 1350 cm^{-1} ($7.4 \mu\text{m}$) which are due to weathering-produced hydrated carbonates (3). In this paper, we discuss the degree of terrestrial weathering, contrasting Antarctic and non-Antarctic ordinary chondrites on the basis of the intensities of the 3 and $7.4 \mu\text{m}$ bands.

Samples and Experimental Techniques: Antarctic meteorite samples were supplied by the National Institute of Polar Research and were powders from the cutting of the meteorites. Non-Antarctic ordinary chondrites were crushed and ground in an agate mortar. Spectral reflectance measurements were made in a dry air atmosphere with a Fourier transform infrared spectrophotometer (JASCO FT/IR-3), equipped with a diffuse reflectance attachment. We dried each powder sample in a desiccator for 48 hours to remove adsorbed water from the surfaces of grains. Details of measurements and the method to calculate the integrated intensity of absorption bands near $3 \mu\text{m}$ are described in Miyamoto (1988)(1).

Degree of Weathering: Figures 1 and 2 show absorption features near $3 \mu\text{m}$ of Antarctic and non-Antarctic ordinary chondrites, respectively. Table 1 summarizes the integrated intensity of the $3 \mu\text{m}$ band (1,2). Because terrestrial weathering produces hydrous minerals, a large value of the integrated intensity of the $3 \mu\text{m}$ band means a severely weathered chondrite. Antarctic ordinary chondrites show the wide range of integrated intensities. Non-Antarctic chondrites which are falls show small values of the integrated intensity, whereas non-Antarctic ordinary chondrites which are finds show relatively large values. Some Antarctic chondrites (e.g., Yamato(Y)74647, Y75097, Y790964) are as fresh as non-Antarctic chondrites which are falls. On the other hand, some non-Antarctic chondrites which are finds are as weathered as severely weathered Antarctic chondrites.

For Antarctic chondrites, there is no clear correlation between the integrated intensity and the degree of weathering on the A-B-C scale (2,4). Integrated intensities near $3 \mu\text{m}$ vary widely among Antarctic chondrites whose degree of weathering is reported to be A (2). This apparent discrepancy may be explained by differences in weathering between different portions of a meteorite. In fact, Ebihara et al. (1989)(5)

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examined the depth-profiles of halogen abundance and integrated intensities of hydration bands near $3\ \mu\text{m}$ and showed that integrated intensities of outer portions are larger than inner portions of the ALH77231(L6) ordinary chondrite, that is, an outer portion of the meteorite is more weathered compared with an inner portion. We can easily select less weathered ordinary chondrites from among the Antarctic collection by using infrared spectra.

Weathering-produced Carbonates: Figures 3 and 4 show absorption features near $7.4\ \mu\text{m}$ of Antarctic and non-Antarctic ordinary chondrites, respectively. The $7.4\ \mu\text{m}$ band is probably due to the presence of hydrated Mg-carbonates produced by terrestrial weathering (3,6-9). Because all the Antarctic ordinary chondrites we measured (about 40) show weak absorption bands near $7.4\ \mu\text{m}$, hydrated carbonates produced by terrestrial weathering seem to be ubiquitous in Antarctic ordinary chondrites. Our preliminary examination on the basis of infrared spectra shows that the hydrated carbonates tend to concentrate on the surface portion of an ordinary chondrite (5). We need to take into account the presence of hydrated carbonates produced by terrestrial weathering when we study Antarctic chondrites.

Non-Antarctic ordinary chondrites show relatively weak $7.4\ \mu\text{m}$ bands compared with Antarctic ordinary chondrites. Non-Antarctic ordinary chondrites which are falls do not show $7.4\ \mu\text{m}$ bands, whereas non-Antarctic ordinary chondrites which are finds show faint $7.4\ \mu\text{m}$ bands. In spite of large values of the integrated intensity of hydration bands near $3\ \mu\text{m}$ for non-Antarctic chondrites which are finds (Table 1), they show relatively weak absorption bands near $7.4\ \mu\text{m}$ compared with Antarctic ordinary chondrites (Figs. 3 and 4). Hydrated carbonates may be easily formed on ordinary chondrites in the Antarctic environment.

Conclusion

- 1) Some Antarctic ordinary chondrites are as fresh as non-Antarctic ordinary chondrites which are falls on the basis of the integrated intensity of hydration bands.
- 2) Non-Antarctic ordinary chondrites which are finds usually show large values of the integrated intensity.
- 3) Hydrated carbonates produced by terrestrial weathering seem to be ubiquitous in Antarctic ordinary chondrites and may be easily formed on ordinary chondrites in the Antarctic environment.

Acknowledgments: The author thanks the National Institute of Polar Research for Antarctic meteorite samples, Prof. H. Takeda for non-Antarctic chondrites, and Profs. Y. Ikeda, K. Yanai, H. Kojima, and M. Ebihara for discussion.

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Table 1. The degree of weathering of some Antarctic and non-Antarctic ordinary chondrites.

Meteorite	Class	Degree of weathering		Meteorite	Class	Degree of weathering	
		3 μ m band*	A-B-C ⁺			3 μ m band*	
ALH77299	H3	103	A	Anlung	H5	44	Fell 1971
Y75028	H3	99	-	Bjurbole	L4	47	Fell 1899
Y74156	H4	48	-	Gifu	L6	25	Fell 1909
Y74647	H5	45	A				
ALH77182	H5	104	C				
ALH768	H6	103	B/C				
Y74191	L3	74	A	Wellman (C)	H4	103	Found 1964
Y75097	L6	36	-	Plainview	H5	171	Found 1917
ALH769	L6	87	B	Forrest (B)	L6	191	Found 1980
MET78003	L6	105	B				
Y790448	LL3	112	-				
Y790964	LL	30	-				

* Integrated intensity (cm^{-1}) of absorption bands near 3 μ m (1, 2).

+ Gooding (1986)(4); Yanai and Kojima (1985)(10); Antarctic Meteorite Working Group (1981)(11).

- The degree of weathering by the A-B-C scale not reported.

DIFFERENCES IN WEATHERING: Miyamoto M.

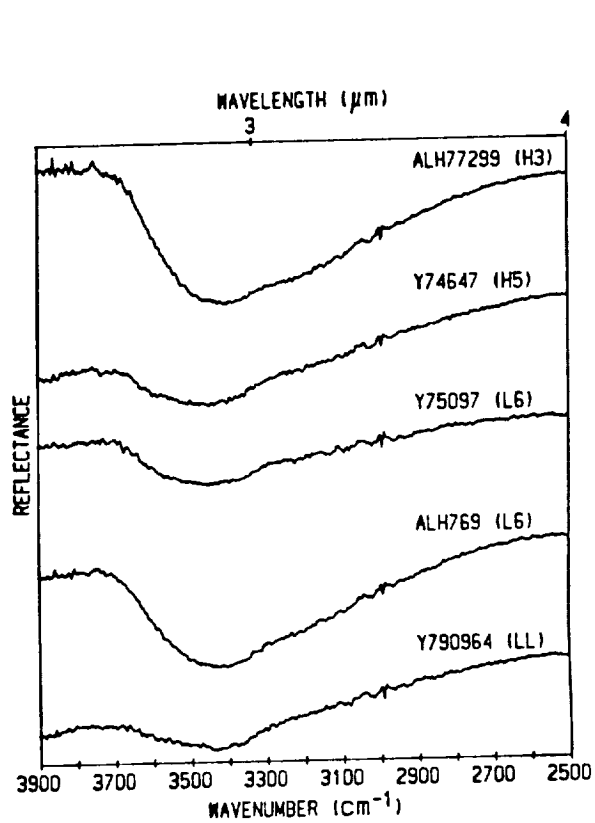


Fig. 1. Diffuse reflectances near 3 μm of Antarctic chondrites.

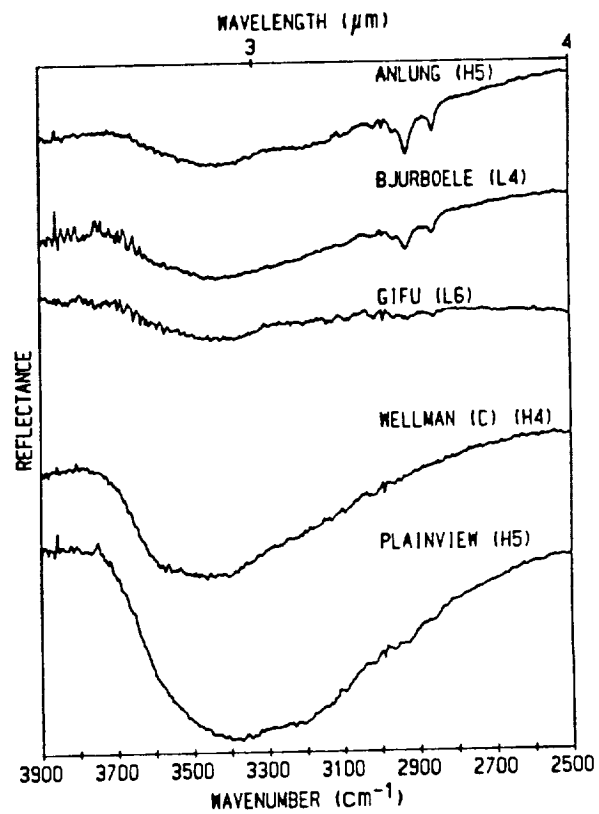


Fig. 2. Diffuse reflectances near 3 μm of non-Antarctic chondrites.

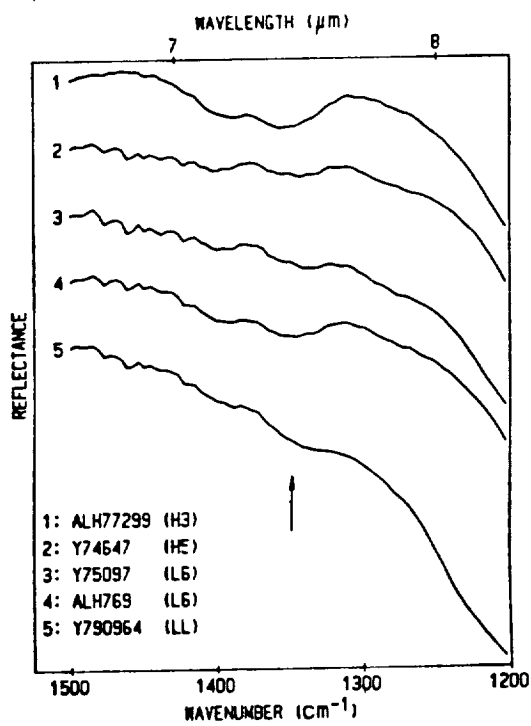


Fig. 3. Diffuse reflectances near 7 μm of some Antarctic chondrites. Arrows indicate the 1350 cm^{-1} band.

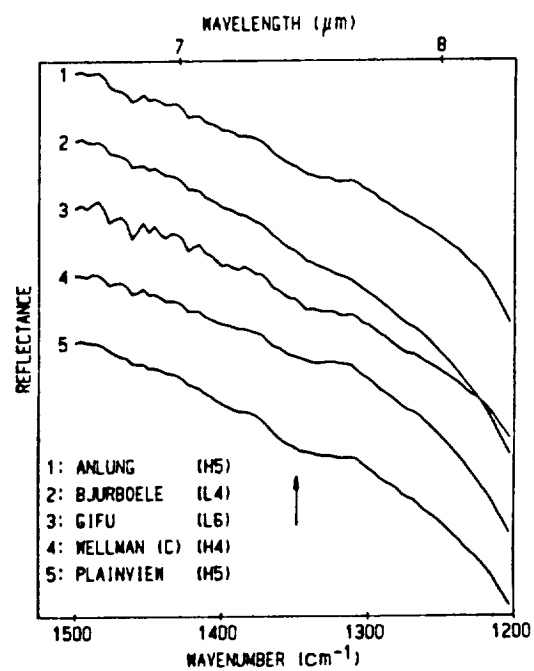


Fig. 4. Diffuse reflectances near 7 μm of non-Antarctic chondrites.

WEATHERING EFFECTS ON AND TERRESTRIAL AGES FROM COSMOGENIC RADIONUCLIDES IN ANTARCTIC AND NON-ANTARCTIC METEORITES

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The concentrations of cosmogenic nuclides in meteorite provides information on their history including; exposure age, preatmospheric size, multi-stage irradiation, and precompaction age, and also on the history of the cosmic rays. Cosmogenic radionuclide data in both Antarctic and non-Antarctic meteorites has been compiled [1]. To use these data to compare Antarctic and non-Antarctic meteorites or to calculate the meteorite exposure ages and the terrestrial ages we have to know how weathering effects the concentrations of these nuclides. The focus of this paper is weathering effects on the cosmogenic nuclide concentrations in Antarctic meteorites and the terrestrial ages of these objects.

Weathering and cosmogenic nuclides : Fig. 1 looks for a relationship between the terrestrial ages of meteorites and their weathering categories [2]. However, none can be seen in these data. One major question is whether or not weathering changes the chemical or isotopic composition in Antarctic meteorites. Gibson and Bogard reported that the noble gas concentrations decreased significantly with increasing "terrestrial age" for the Holbrook meteorite [3]. Although their results can't be directly applied to Antarctic meteorites because of extremely different terrestrial ages (56 years vs. hundred thousand years) and environmental condition (Arizona vs. Antarctica), many Antarctic meteorites do have lower $^3\text{He}/^{21}\text{Ne}$ ratios than expected from their $^{22}\text{Ne}/^{21}\text{Ne}$ ratios, which may indicate ^3He loss due to weathering [e.g. 4]. Weathering effects are also known to influence the ^{14}C concentration in Antarctic meteorites [e.g. 5, 6]. Cosmogenic ^{53}Mn is produced from Fe and Ni. The concentrations of ^{53}Mn in metal, bulk, and non-magnetic fractions in several Antarctic meteorites with various terrestrial ages have been carefully examined [7, 8]. No significant loss or gain of ^{53}Mn was found in either clean or oxidized separates of Antarctic meteorites. If there are any differences in the histograms of ^{53}Mn activities of Antarctic and non-Antarctic meteorites, they are caused by neither weathering nor terrestrial age since the half-life of ^{53}Mn (3.7 Myr) is much longer than most of the terrestrial ages. More than 2/3 of the terrestrial ages of Antarctic meteorites were calculated using the measured ^{36}Cl concentrations [2]. Since the ^{36}Cl is extracted from clean metal, weathering loss of this nuclide is unlikely to have occurred. Other cosmogenic radionuclides such as ^{10}Be and ^{26}Al which are mainly produced in the silicate phase have not yet been carefully examined for weathering effects.

Terrestrial ages : One special characteristic of Antarctic meteorites is their long terrestrial ages, the time period since the date of meteorite fall. These terrestrial ages give vital information not only for studies of Antarctic meteorites but also for Antarctic glaciology and geology. These studies include the influx rate of meteorites, the history of ice sheets, and pairing of meteorites. A detailed study of terrestrial ages of Antarctic meteorites can be seen elsewhere [2]. Even though some non-Antarctic iron meteorites have terrestrial ages of a few million years, the terrestrial ages of non-Antarctic stony meteorites are usually less than a few tens of thousands of years [9, 10]. On the other hand, the terrestrial ages of Antarctic stony meteorites range up to 1 million years [2]. After many studies of Antarctic meteorites, the question has arisen whether Antarctic and non-Antarctic meteorites represent the same

population [e.g. 11]. Figure 2 shows the relationship between terrestrial age and class for Antarctic meteorites. The meteorites are separated into four classes, L and LL, H, Iron, and other. Up to now, only L and LL chondrites have terrestrial ages in excess of 370,000 years. (The 3 iron meteorites, DPR 78001-78009, ILD 83500, and Lazarev, which have more than 1 Myr terrestrial ages are not included in the figure because they were found on bedrock.) Whether this represents statistical uncertainty due to the small number of objects examined or is a weathering effect or has another physical cause is unknown. If the frequency distribution of ages reflects a real time spectrum of meteorite fall during the last 1 million years, it suggests that the proportion of influx from different classes of meteorites changes with time. We need measurements of terrestrial ages for more meteorites to improve the statistics.

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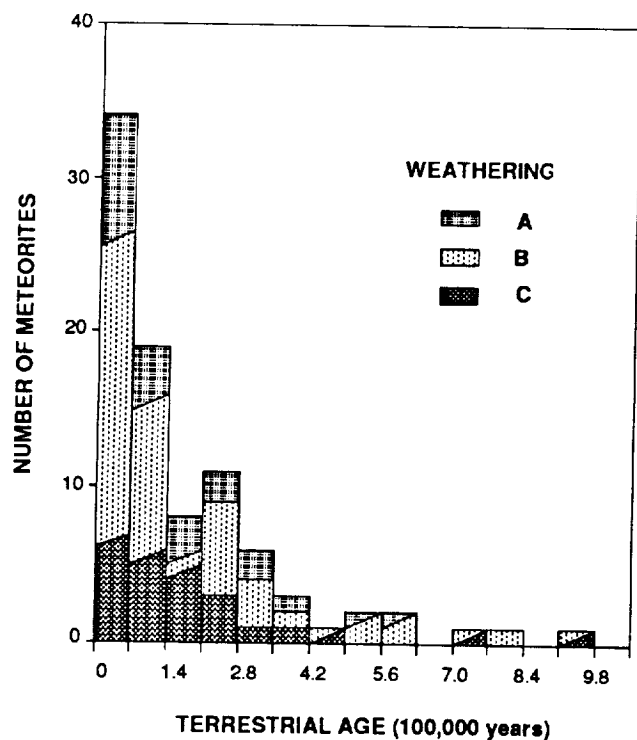


Figure 1. from Nishiizumi, K. et al., (1989)

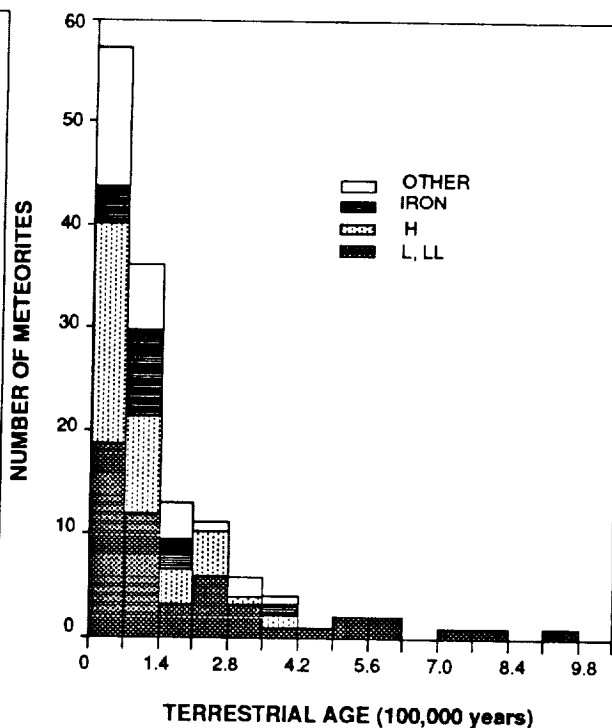


Figure 2. from Nishiizumi, K. et al., (1989)

APPLICATIONS OF STATISTICS TO ANTARCTIC, NON-ANTARCTIC DIFFERENCES.
 Stephen M. Samuels, Dept. of Statistics, Purdue University, W. Lafayette, IN 47907 USA

Two standard statistical procedures—Linear Discriminant Analysis and Logistic Regression—effectively distinguish between Antarctic and non-Antarctic H or L Chondrites solely on the basis of their trace element compositions. This is true both overall and for strongly shocked (> 22 GPa) L4-6 chondrites. As with any statistical analysis of this kind, we conclude only that the data *support* one hypothesis (the hypothesis of a difference), and are *inconsistent* with another (the hypothesis of no difference). Our statistical argument says nothing whatsoever about the *causes* (if any) of such differences.

Linear Discriminant Analysis [1], [2], finds the particular linear combination of variables (here the variables are logs of concentrations of up to 13 trace elements) for which the ordinary two-sample t-statistic has maximal absolute value. So, linear discriminant analysis is like a single super t-test performed simultaneously on all of the variables, rather than individual t-tests on each of them, as in [3]. (Linear discriminant analysis is also equivalent to ordinary multiple regression with a dichotomous response variable.)

The two groups (Antarctic and non-Antarctic) are said to be completely distinguished if the values of this linear combination (called the Discriminant Function) for samples in one group are all larger than the values for samples in the other group. The groups are *almost* completely distinguished if there is slight overlap; for example, if the smallest discriminant function value for an Antarctic sample were larger than all but one of the non-Antarctic values, and only slightly smaller than the largest non-Antarctic value.

Figure 1 shows the contrast between good and bad discrimination, using 18 Antarctic and 20 non-Antarctic H5 Chondrites. The *Pseudo* Discriminant Analysis was carried out by deliberately mis-labelling the samples, calling the odd-numbered ones (1,3,5, . . . ,37) “Antarctic” and the even-numbered ones “non-Antarctic.” In the real discriminant analysis there are only four misclassifications, while in the pseudo discriminant analysis there are 14.

Under rather strict distributional assumptions—normality and equality of covariance matrices—it is valid to compute *significance levels*, that measure the likelihood of obtaining as good apparent discrimination between groups which have identical trace element concentrations. For example, when the 11 strongly shocked Antarctic L4-6 chondrites in [4] were compared with the 18 strongly shocked non-Antarctic L4-6 chondrites (for which data was available for all 13 trace elements) in [5] and [6], the discriminant function values had very slight overlap and the significance level was $.0062 = 1/160$, indicating that identical multivariate normal populations have only about one chance in 160 of looking as different from each other as do these two groups of samples. For the *real* discriminant analysis of H5 Chondrites, the significance level is a highly significant .0031, while in the *pseudo* discriminant analysis it is a far from significant .914. In other words, *identical* populations would yield better discrimination than this 91% of the time.

REAL Discriminant Analysis Using 12 Trace Elements
Co, Sb, Se, Rb, Cs, Te, Bi, Ag, In, Tl, Zn, Cd

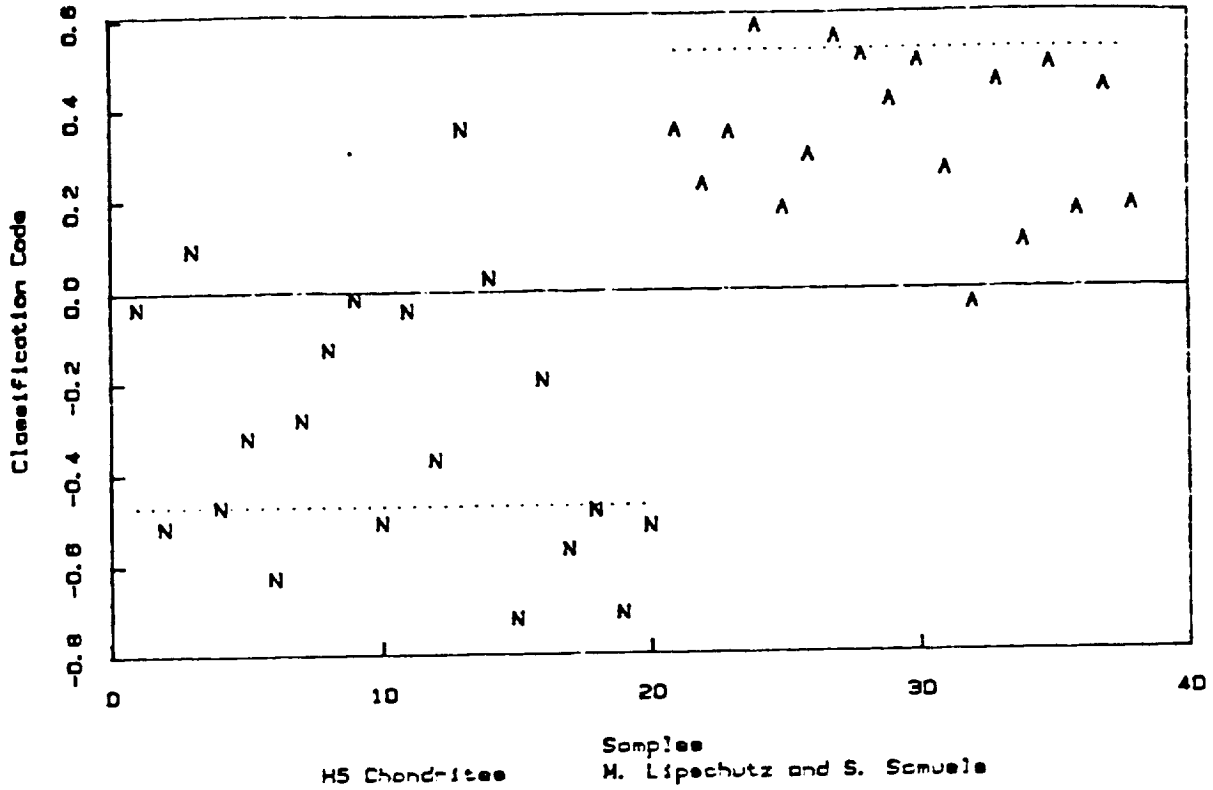
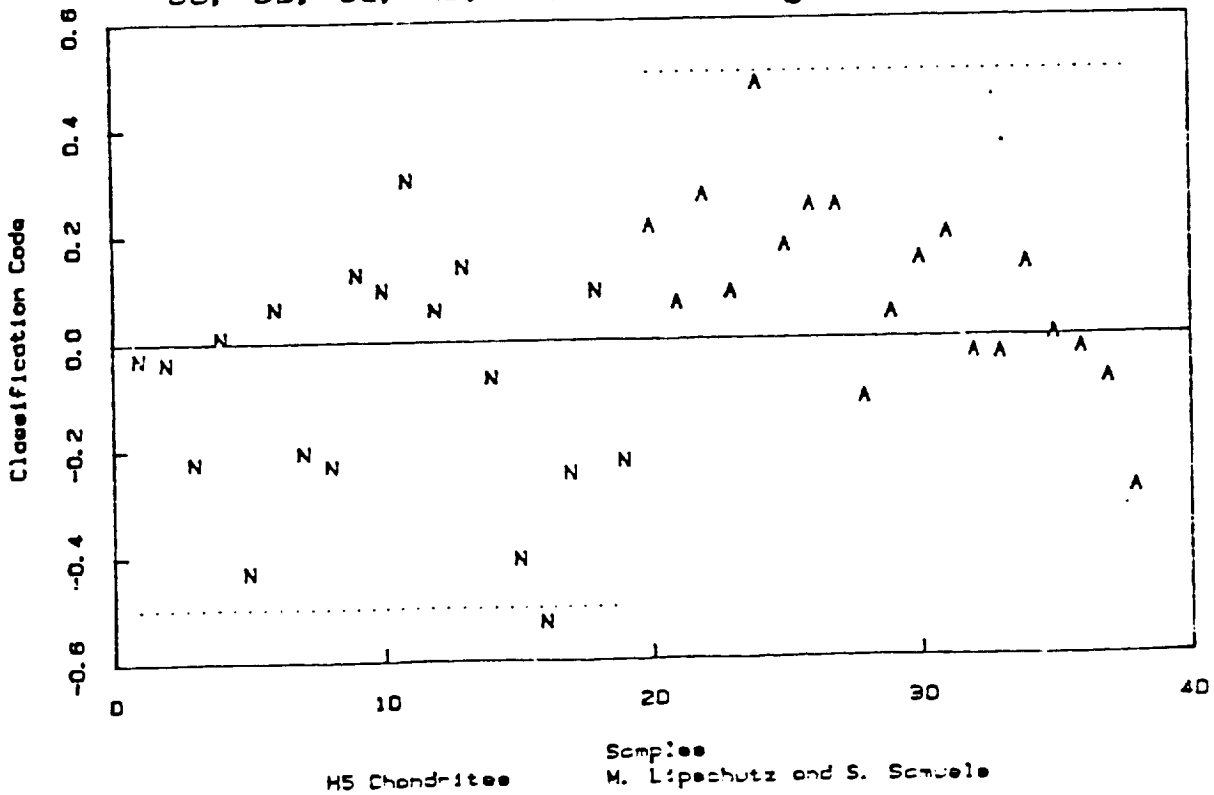


Figure 1

PSEUDO Discriminant Analysis Using 12 Trace Elements
Co, Sb, Se, Rb, Cs, Te, Bi, Ag, In, Tl, Zn, Cd



Logistic Regression [1], actually produces, for each sample, a “probability that it belongs” to a specified group, say Antarctic. This “probability” arises, by extensive computer calculation, from a model which assumes that if samples were selected randomly from the “Antarctic and non-Antarctic populations,” then the log of the *posterior odds*, $p/(1 - p)$ —where p is the probability of a sample having come from the Antarctic population, given its measured trace element composition—is a *linear* function of those, say, 13, values. (This model is known to be valid for various kinds of populations, including multivariate normal ones, for which the linear function is precisely the Linear Discriminant Function.)

In logistic regression, the two groups are completely distinguished if the *posterior* probabilities are, say, greater than 0.5 for all Antarctic samples, and less than 0.5 for all non-Antarctic samples. For example, logistic regression (using SAS PROC LOGIST) on the two groups of strongly shocked L4-6 chondrites cited above assigned probabilities 0.995 or greater to each of the 11 Antarctic samples, and 0.0002 or less to each of the 18 non-Antarctic samples. See the “All” column of the Table.

The relative merits and applicabilities of Linear Discriminant Analysis and Logistic Regression are discussed in [7] and [8]. In general, the former is more effective at distinguishing different multivariate normal populations, while the latter is relatively insensitive to normality assumptions.

Validation Runs are necessary, in both Discriminant Analysis and Logistic Regression, to avoid giving too rosy a picture. In such runs, part of the data (the training cases) are used to generate a discriminant function or a logistic regression function, which is then applied to the rest of the data (the validation cases). A high rate of correct classifications of these validation cases reinforces the argument for a real statistical difference between Antarctic and non-Antarctic meteorites.

For the strongly shocked L4-6 chondrites cited above, repeated runs with 20% (randomly selected) validation cases resulted in 81% correct classification by discriminant analysis and 81% by logistic regression. (The logistic regression, however, correctly classified all of the training cases, while the discriminant analysis did not.) Results for the Logistic Regression validation runs are given in the Table, with validation cases shown in **boldface** and misclassifications boxed. Also, both the Discriminant Analysis and the Logistic Regression results for one of the seven validation runs are displayed in Figure 2.

Another kind of validation run was performed on 26 Antarctic and 32 non-Antarctic H4-6 Chondrites in [9] and [10], respectively. Here the validation cases, rather than being chosen at random, were deliberately taken to be all of a particular group of Antarctic meteorites. In Figure 3a, the validation set consists of the five YAM12's (samples 54-58) which are from Yamato mountain where samples have terrestrial ages *atypical* of other Antarctic samples. Excluding them from the training set evidently results in perfect classification of the training set, but with a model which badly misclassifies three of the five YAM12's. On the other hand, if the validation set is chosen to consist of the six *typical* RKP12's (samples 48-53), Figure 3b shows that classification of the training set is not as good (there are seven misclassifications, of which three are YAM12's), but the model inspired by the training set does better at classifying the validation set: only two of the six RKP12's are slightly misclassified.

Table: Logistic Regression Validation Run Results

No.	Name	All	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
1	ALH A77254,11	1.0000	0.9917	0.9999	0.9999	1.0000	1.0000	0.9999	0.9998
2	ALH A81017,7	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	ALH A77231,25	0.9995	0.4782	0.9991	0.5918	0.9997	0.9997	0.9996	0.9994
4	ALH A77270,18	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5	ALH A77282,24	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999
6	ALH A77284,12	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
7	ALH A77296/7	0.9999	0.9997	0.9952	0.9998	0.9999	1.0000	1.0000	1.0000
8	EET A79010,6	1.0000	1.0000	0.0028	0.9999	0.1821	1.0000	1.0000	1.0000
9	MET A78002,19	1.0000	1.0000	1.0000	1.0000	1.0000	0.9997	1.0000	1.0000
10	MET A78028,73	1.0000	0.9999	0.9999	0.9997	1.0000	1.0000	0.9997	0.9999
11	RKP A79001,16	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
12	KNYAHINYA	0.0000	0.0001	0.0001	0.0001	0.0000	0.0035	0.0000	0.0000
13	TADJERA	0.0001	0.0001	0.0002	0.0001	0.0001	1.0000	0.0001	0.0002
14	FARMINGTON	0.0002	0.0002	0.0004	0.0003	0.0001	0.0003	0.0003	0.0004
15	MALAKAL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
16	BRUDERHEIM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000
17	RAMSDORF	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
18	ARAPAHOE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
19	LUBBOCK	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000
20	WICKENBURG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.1832	0.0000
21	ERGHEO	0.0000	0.0001	0.0001	0.9999	0.0001	0.0000	0.0000	0.0000
22	WITTEKRANTZ	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0001	0.0000
23	COLBY (WIS)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
24	ZAVID	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
25	ZOMBA	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	1.0000	0.0001
26	WETHERSFIELD	0.0000	0.0002	0.0000	0.0002	0.0000	0.0001	0.0001	0.0608
27	ZEMAITKIEMIS	0.0001	0.0000	0.0001	0.0000	0.0000	0.0002	0.0001	0.0002
28	CHATEAU RENARD	0.0002	0.0001	0.0003	0.0001	0.0002	0.9788	0.0001	0.9876
29	LOUISVILLE	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Validation cases are shown in **boldface** and misclassifications are **boxed**.

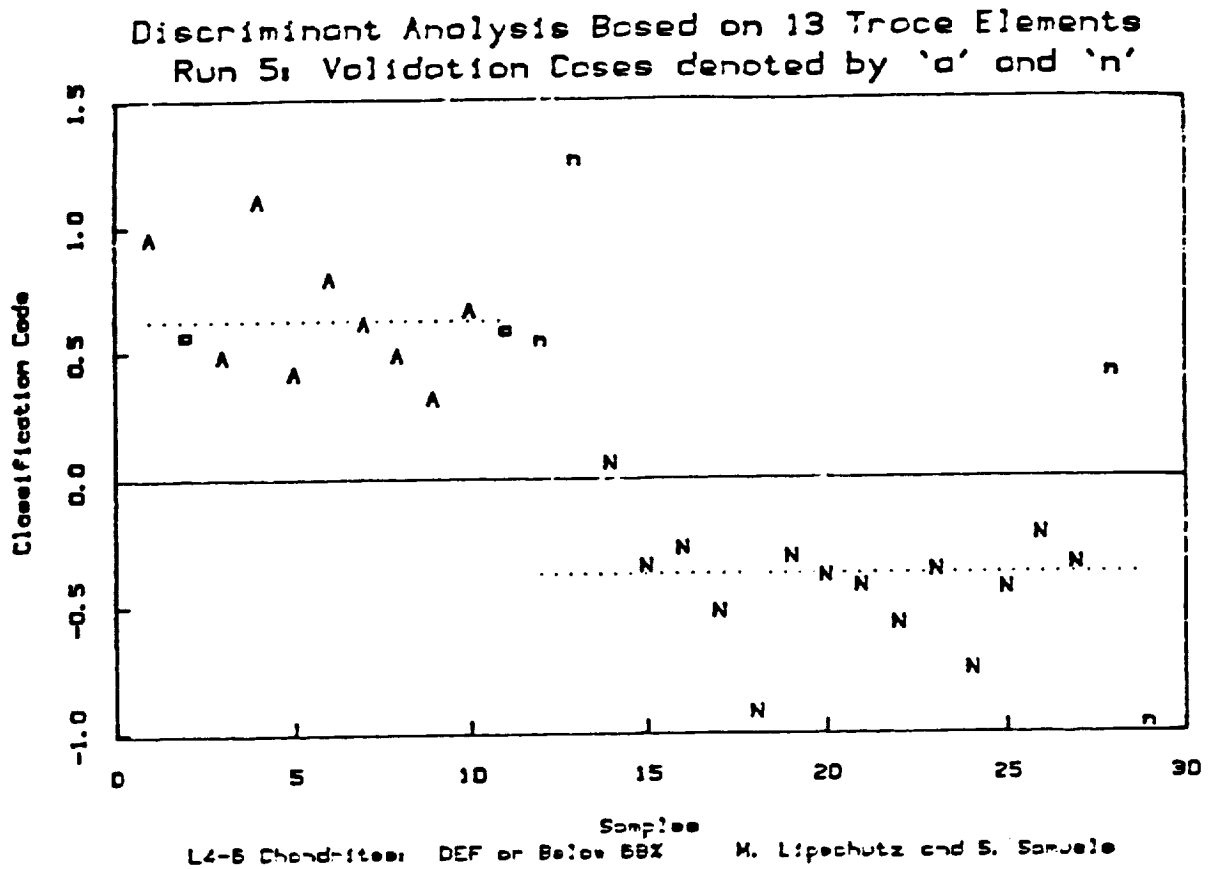
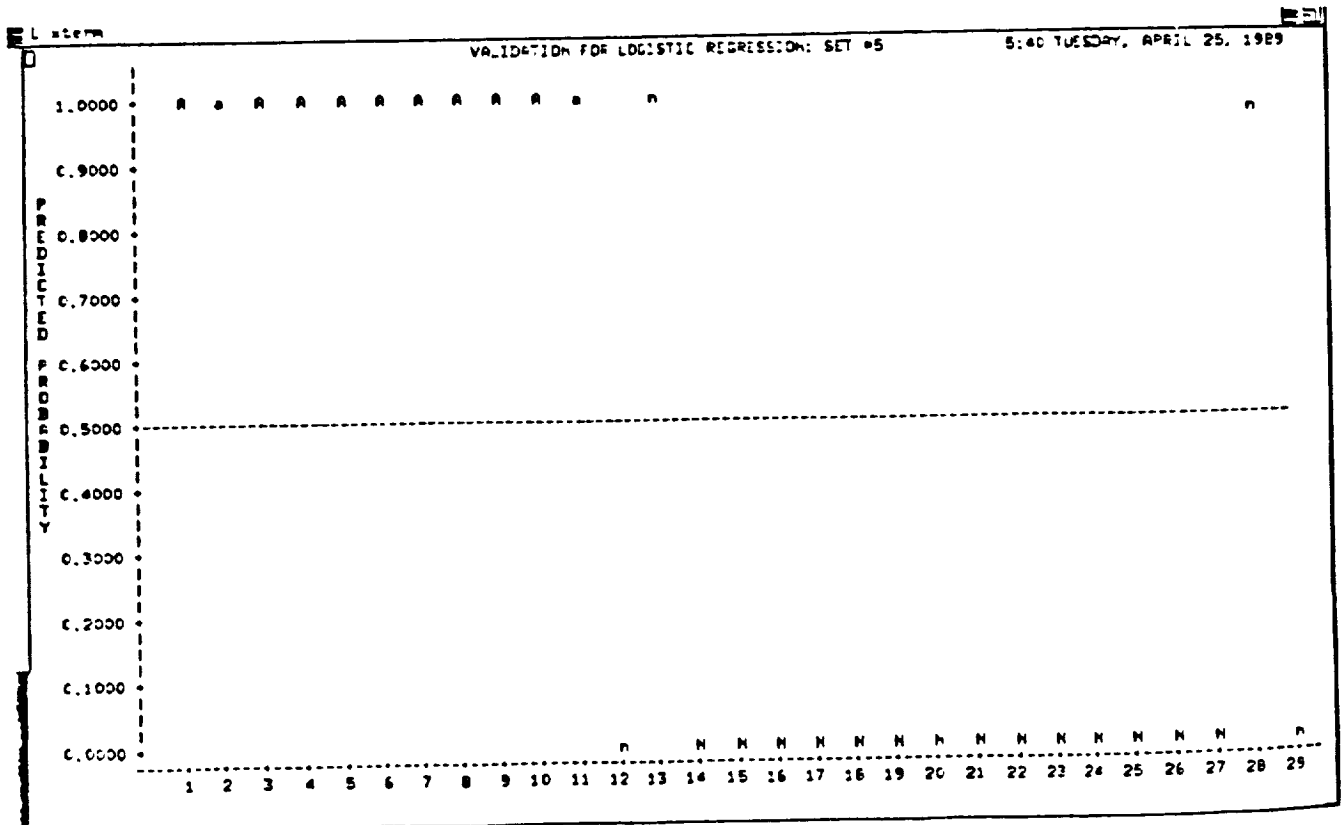


Figure 2.



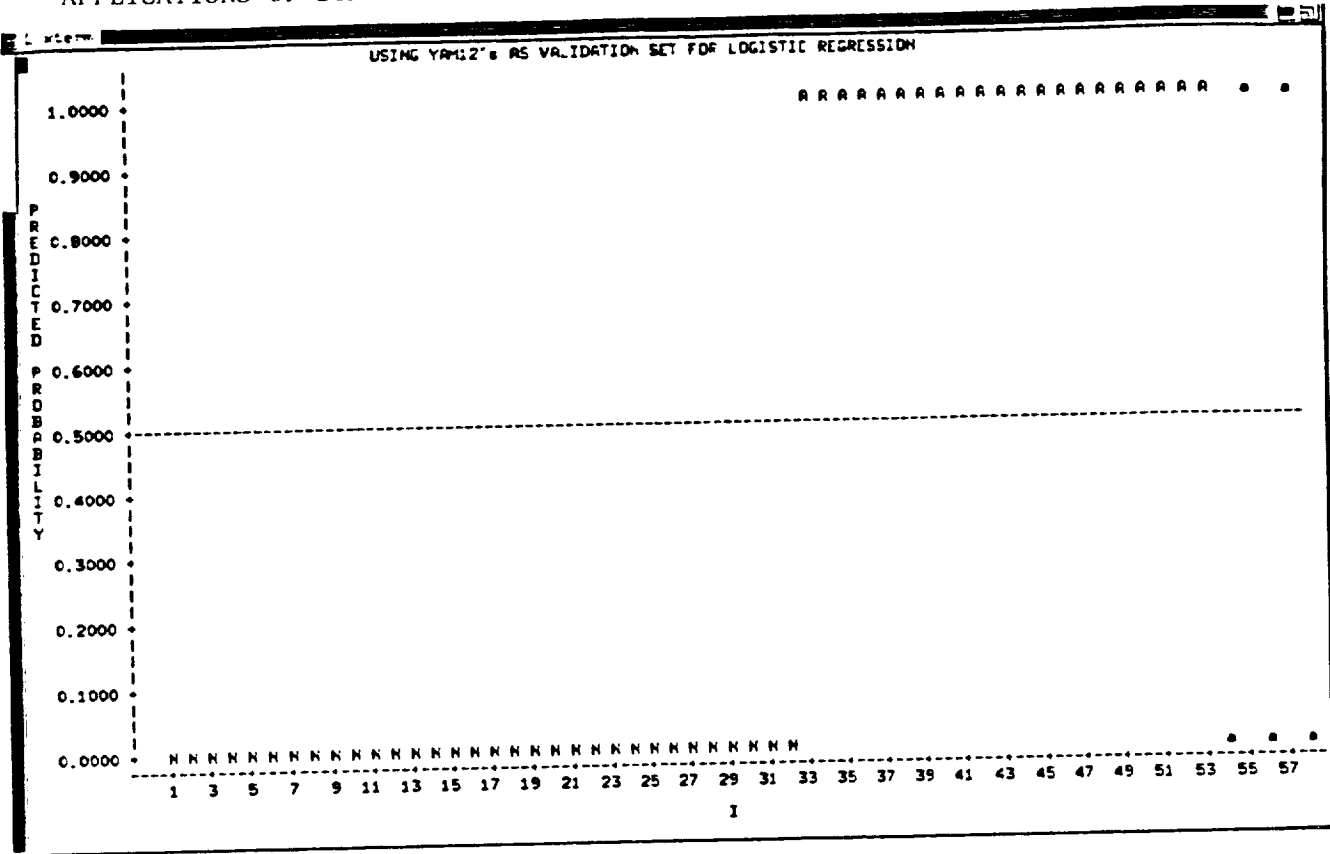


Figure 3a

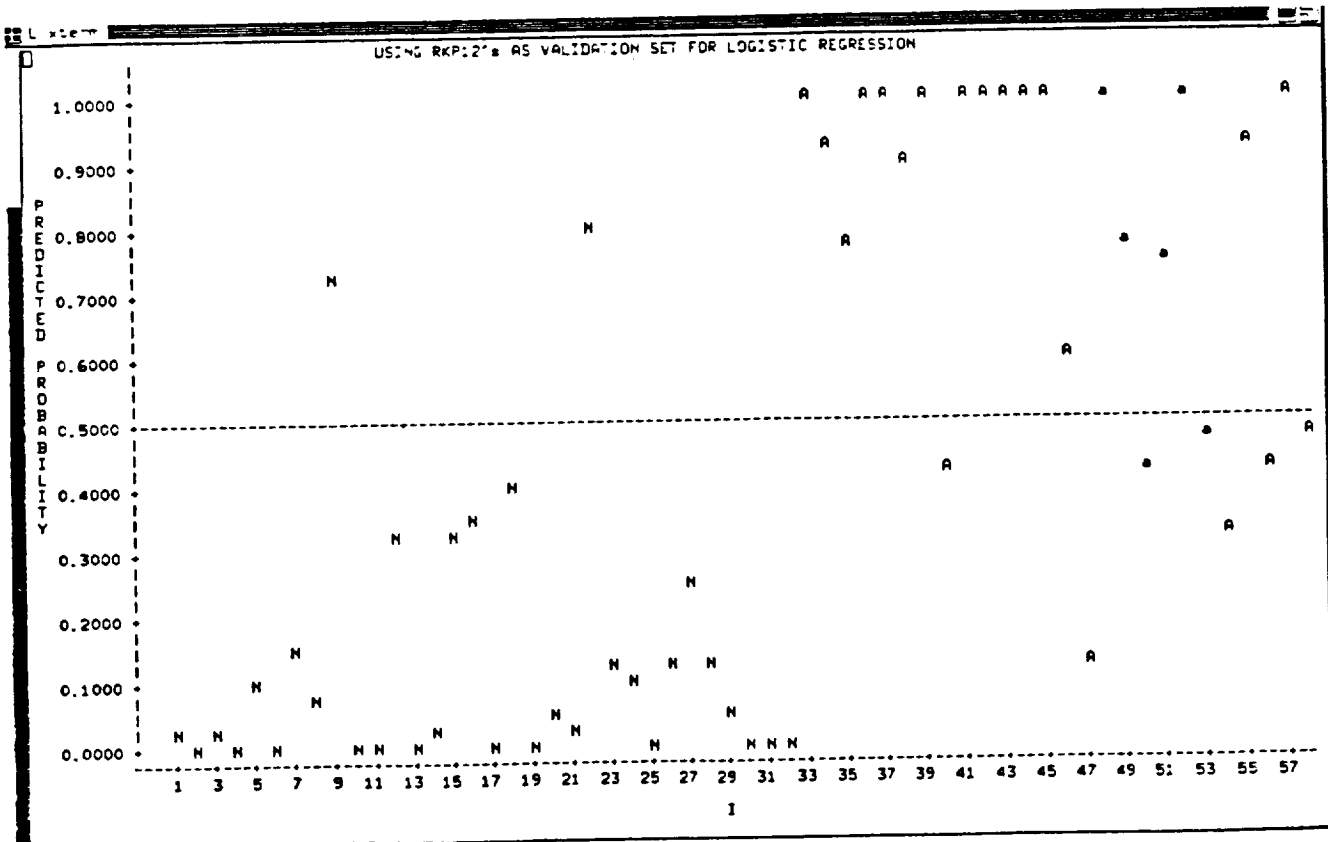


Figure 3b

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EXPOSURE AGES OF ANTARCTIC AND NON-ANTARCTIC H-CHONDRITES
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Introduction

On the basis of differences in the concentration of a number of trace elements, Dennison et al. [1] have suggested that H-chondrites recovered in Antarctica may represent an extraterrestrial meteorite population which is different from that falling in non-Antarctic areas. Because the terrestrial ages of Antarctic meteorites are generally higher than those of other finds, a temporal variation of the kind of meteoritical matter falling on Earth is implied. If indeed the differences between Antarctic and non-Antarctic meteorites can be attributed to preterrestrial sources it is conceivable that non-Antarctic meteorites represent too short an accumulation time to be a representative sample of the total meteorite population. Antarctic meteorites, however, collected over a much longer time, might stand for a better approximation to the true meteorite population in interplanetary space [2].

About 41% of all non-Antarctic H-chondrites have exposure ages between 4 and 8 Million years. This prominent exposure age peak is interpreted as caused by a major single collisional event which produced these meteorites as debris of their parent body. Such an exposure age distribution is not observed for L- or LL-chondrites. Hence, if Antarctic H-chondrites represent a population different from non-Antarctic H-chondrites one might expect that they are not produced in the same event but either at another time from a different part of the same parent body or possibly from a different parent body altogether.

This paper reviews exposure ages of Antarctic and non-Antarctic H-chondrites and is mainly based on new measurements of 31 Allan Hills stones [3] and a compilation of noble gases in meteorites [4].

Exposure ages.

Exposure ages are calculated from cosmogenic ^{21}Ne using production rate and shielding correction procedures as described by Eugster [5]. It should be noted that even with shielding corrections there remain considerable uncertainties in the production rate of about 20% which, for extreme shielding ($1.08 > ^{22}\text{Ne}/^{21}\text{Ne} > 1.20$), might be even higher.

Fig. 1 gives the exposure ages of 262 non-Antarctic H-chondrites and of 42 Antarctic H-chondrites from the Allan Hills.

Discussion.

The age distribution would be biased if many of the meteorites investigated were samples from one or a few meteorite showers. The samples discussed here have been chosen to avoid paired samples using field information and ancillary data.

EXPOSURE AGES: L. Schultz

Especially noble gas analyses provide criteria for the detection of paired samples. The presence of solar trapped gas, similar exposure ages and gas retention ages, as well as shielding trends can be used to recognize meteorite pairs.

The brecciated structure of solar-gas containing Antarctic meteorites is often masked by brown limonitic staining and is not obvious from hand specimen. So it was a surprise to find that 7 out of the 31 meteorites investigated showed at least small concentrations of solar gas without having the typical light-dark structure recognizable. Among these meteorites are three which are very similar in solar gas content and exposure age and which almost certainly belong to the same fall. The same is true for three other stones where noble gas data were taken from the literature [4]. Members of this group have exposure ages between 4 and 5 Ma.

Between 4 and 8 Ma 108 (= 41%) meteorites make up the prominent peak in the exposure age distribution of non-Antarctic H-chondrites. Such a peak is also observed for the Antarctic meteorites: 16 (= 39%) have exposure ages between 4 and 8 Ma. Note, however, that in the case of Antarctic meteorites the sharp peak between 4 and 6 Ma is less pronounced. The mean age of the specimens in the exposure age range 4 to 10 Ma is indistinguishable at 6 Ma for non-Antarctic and 6.3 Ma for Antarctic H-chondrites. Any effect of the larger terrestrial age of Antarctic meteorites would, of course, have the opposite effect, e.i. shift the suite of Antarctic samples to younger exposure ages.

With the present data the exposure age distribution does not corroborate the contention of an origin from different parent bodies of Antarctic Allan Hills and non-Antarctic H-chondrites, although the number of Antarctic H-chondrites which have been analyzed for their exposure ages is still small. The possibility of two major impact events at about the same time cannot be excluded but in this case one would have to explain why only H-chondrite parent bodies should have been affected and why it does not show up for L- or LL-chondrites.

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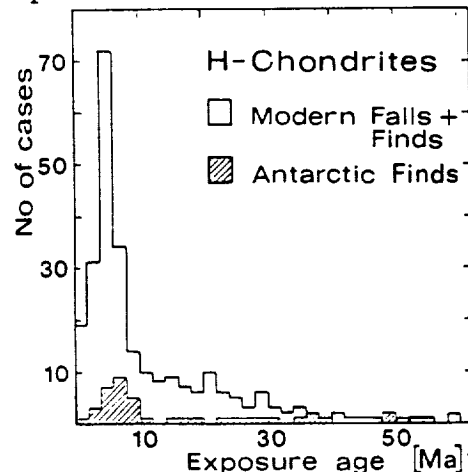


Fig.1: Exposure age distribution of non-Antarctic and Antarctic (Allan Hills) H-chondrites.

A COMPARISON OF THE INDUCED THERMOLUMINESCENCE PROPERTIES OF ANTARCTIC AND NON-ANTARCTIC H CHONDRITES. Derek W.G. Sears, Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701.

Introduction. Haq et al. (1) recently published induced thermoluminescence data for 74 H chondrites of which 33 were found in the Antarctic. They found differences between the Antarctic and non-Antarctic H chondrites in the TL sensitivity, and in TL peak temperature-peak width relationships. (These three parameters, and induced TL studies of meteorites in general, were recently reviewed in ref. 2). Here we summarize and discuss these data. Differences between Antarctic and non-Antarctic L chondrites may also exist, but the data are meager and the differences less marked.

TL sensitivity data (Fig. 1). The TL sensitivity of both Antarctic and non-Antarctic H chondrites range over a factor of around 30, but the Antarctic chondrites are skewed to lower values by a factor of around 3 (Fig. 1). Among the Antarctic samples, there is little or no correlation between TL sensitivity and weathering category A-C. With two exceptions, the Antarctic samples are all type 5 and 6 and, as in previous studies, show no relationship between TL sensitivity and type. Shock classifications are not available for the Antarctic H chondrites, although the two containing maskelynite have among the lowest TL sensitivities observed among this group. The non-Antarctic samples are observed falls, and presumably little weathered, and also show no obvious differences in TL sensitivity between types 5 and 6; the 10 type 4 chondrites do tend towards lower TL sensitivities, though. Most of the samples are of shock classification a-c; the two class d samples have among the lowest TL sensitivities observed in these data.

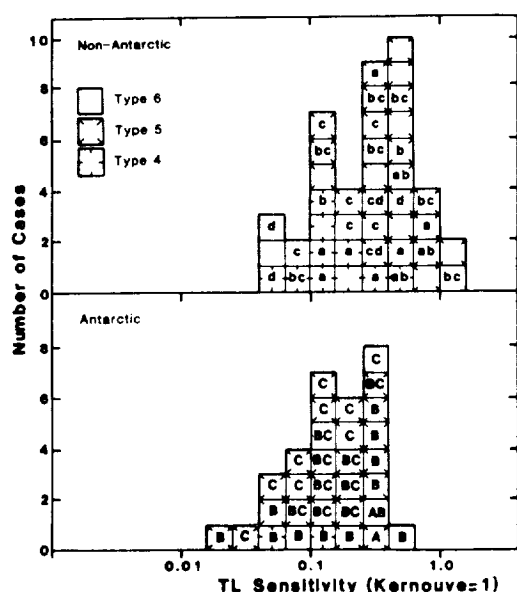


Fig. 1. Histograms of the TL sensitivity of H chondrites. The letters a-f represent shock classifications (least shocked = a) and A-C represent weathering classes based on the appearance of the hand-specimen (least weathered = A). While both Antarctic and non-Antarctic H chondrites show considerable spread in TL sensitivity, the Antarctic H chondrites tend to be skewed to lower values by a factor of about 3.

TL peak temperature and width data (Fig. 2). The non-Antarctic H chondrites plot on a statistically significant trend of increasing peak-temperature with increasing peak-width ($r = 0.90$, $n = 30$, significance 99.9%), with the majority of the data plotting at the lower end of the line. There is no obvious relationship between petrologic type, shock history and position on this line. Antarctic H chondrites do not display such a correlation. In-

Derek W.G. Sears
Induced TL of H Chondrites

stead, they show a narrower range of peak-width, and do not extend to such low values of peak temperature as the non-Antarctic H chondrites. (According to the t-test, the peak temperatures are different at the 99% level.) There is, therefore, very limited overlap between the non-Antarctic and Antarctic H chondrites in their peak temperature and peak width data.

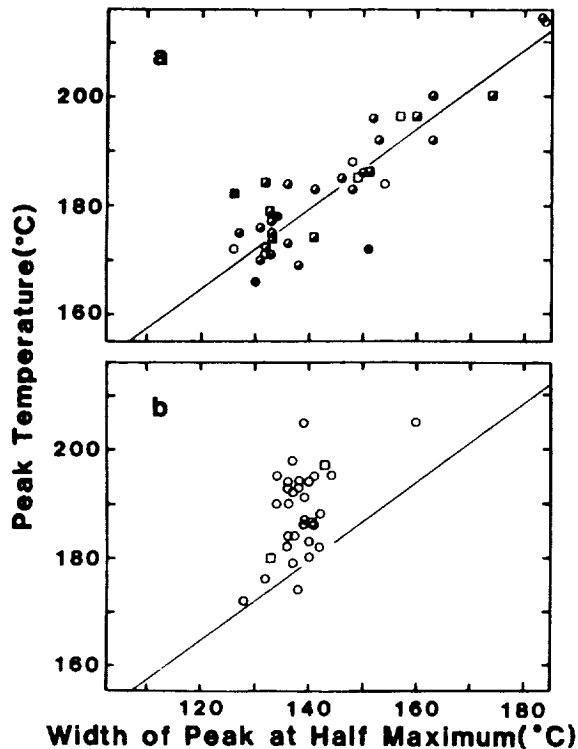


Fig. 2. Plots of the TL peak temperature against peak width for H chondrites. (a) Samples observed to fall world-wide; (b) samples found in the Antarctic. Squares refer to type 4, circles to types 5 and 6, filled symbols represent heavily shocked samples (classes d-f), half-filled symbols represent less heavily shocked samples (a-c), open symbols represent samples for which shock class is unavailable. The diagonal is a regression line through the data for non-Antarctic H chondrites. On this plot, H chondrites from the Antarctic behave differently to those from the rest of the world, and location on the plot does not appear to be related to shock classification.

Discussion. By a series of acid-washing experiments, Sears et al. showed that a factor of 3 decrease in the TL sensitivity of Antarctic meteorites is caused by weathering, the mechanism involving a reduction of albedo (3). Thus the weathering of Antarctic meteorites provides a reasonable explanation for the difference in TL sensitivities between Antarctic and non-Antarctic H chondrites observed here. Against this conclusion is the lack of a correlation between TL sensitivity and weathering category, but it could be that the degree of weathering required to affect TL sensitivity is less than that required to affect the macroscopic appearance of the sample; this is an untested but probably reasonable assumption.

There are no reasonable grounds for attributing the different temperature-width plots for Antarctic and non-Antarctic H chondrites to weathering. Observations on type 3 ordinary chondrites (4,5), data for samples of meteorite heated in the laboratory (4,5), and studies on natural and heat-treated terrestrial feldspars (6,7) show that there are two forms of feldspar producing TL, (these are somehow associated with ordered and disordered structures, but the details are unclear) and that the observed peak shape is determined by the relative proportions of the two forms. Haq et al. also reported data for heating experiments on an H5 chondrite, Kernouve (Fig. 3). As the samples were heated for 10 h at temperatures from 500 to 900 C the TL curves increased in peak temperature and width in a way that paralleled the trend shown by non-Antarctic H chondrites. In

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another series of experiments in which samples were heated at 1000 C for 1, 2, 10, 20 and 100 h the data moved from the trend line to higher peak temperatures without systematic change in peak width. These changes can also be interpreted in terms of disordering of the feldspar or some process associated with it, but whatever the details the data demonstrate that differences in thermal history are responsible for the distributions of the peak temperature and width data shown by the Antarctic and non-Antarctic H chondrites. Identifying the nature of these thermal histories is more speculative, but shock heating and metamorphism are obvious possibilities. Since there is no relationship between position on the trend line in Fig. 2 and shock classification, one might suspect that the cause of the trend shown by the non-Antarctic H chondrites, and the different behavior of the Antarctic H chondrites, are the result of differences in metamorphic histories, i.e. differences in peak metamorphic temperatures and post-metamorphic cooling rates.

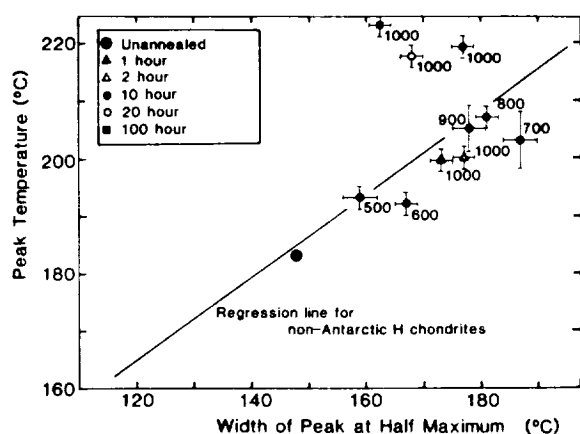


Fig. 3. Plot of TL peak temperature against peak width for samples of the Kernouve H5 chondrite heated in an inert atmosphere at the times and temperatures (C) indicated. Heating at 500-900 C for 100 h causes the data to move along a path close to the regression line in Fig. 2b, while heating at 1000 C for 1-100 h causes the data to move off the line to larger peak temperatures.

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COMPARISONS OF ANTARCTIC AND NON-ANTARCTIC ACHONDRITES AND A POSSIBLE ORIGIN OF THE DIFFERENCE. Hiroshi Takeda, Mineralogical Institute, Faculty of Science, University of Tokyo, Hongo, Tokyo 113, Japan.

Introduction.

Even in the beginning of our Antarctic meteorite researches, we recognized that textures and mineral assemblages of the Antarctic achondrites are different from those of the non-Antarctic ones. For example the first Antarctic diogenite Y6902 showed a glanoblastic texture (1); the first eucrite Y74159 was a polymict eucrite (2); and the first ureilite Y74659 was a magnesian ureilite (1). Numbers of such unusual achondrites increased with increasing total number of the collection (3). It is natural to have high chances of finding rare, unique or unknown types, as the total number of specimens becomes large, especially of smaller sized ones, which can be recognized easily on the Antarctic base ice fields. However, the true numbers of their falls will be smaller, because some of them may be paired. The numbers of unique Antarctic specimens within a known class appeared to be greater than what we expected from statistics of the non-Antarctic collections. Two groups of many unusual Yamato diogenites were found to represent two falls (1). Polymict eucrites have been identified as paired specimens and several groups of falls have been recognized and were compared with the non-Antarctic ones by Takeda et al. (4,5), Delaney et al. (6) and Takeda (1).

At the second Antarctic Meteorite Workshop at Mainz, we proposed the following possibility (7). Among several answers to the question of why polymict eucrites or other unique meteorites are common in Antarctica, there is an evidence to support an idea that the meteorites on a specific ice field may represent falls in the local area during a certain period in the past and that the distribution of achondrite meteorites reaching the earth might have changed with time and the Antarctic collection represents an average over a much longer time interval or during a certain period in the distant past. Old terrestrial ages of the Antarctic meteorites and differences between the Yamato and Victoria Land collections (5) are in favor of such hypothesis. Also, the larger number of smaller specimens which can be recognized easily on the Antarctic base ice field, give higher chances of finding unique meteorites. Dennison et al. (8) reported that even in more common meteorites, Antarctic and non-Antarctic meteorite may differ. They interpret these differences as reflecting derivation of Antarctic meteorites predominantly from parent sources or regions different than those from which contemporary falls derive. Wasson (9) discussed the differences among irons. First, we survey the differences between Antarctic and non-Antarctic achondrites with new data.

Results.

(1) Ureilites. Augite or orthopyroxene bearing ureilites found in Antarctica fall outside the definition of ureilite (10, 11). Discoveries of Antarctic ureilites have almost tripled the numbers of meteorite samples in the ureilite group although their sizes are small. Many of them showed some characteristic features in their chemistry or mineralogy. They are believed to be all different falls except for ALH82106/130 with some unique features (11). This situation is in real contrast with the Antarctic HED achondrites, in which many of them are pieces of the same fall. The range of chemical compositions of olivines and pyroxenes from the Antarctic

ureilites extended both towards the Mg-rich, Fe-rich and Ca-rich sides. The Fa contents of the core olivines expanded from 14 - 22 atomic % to 8 - 24 atomic %. It is to be noted that the large oxygen isotope anomaly was found only in Antarctic ureilites of magnesian subgroup of Clayton and Mayeda (12).

The wider range of the Fe/(Mg+Fe) ratios in pyroxene and correlation with the oxygen isotope subgroups of Clayton and Mayeda (12) enabled us to classify systematic variations of pyroxene chemistries. Three subgroups were identified, but the magnesian group was found only in Antarctica and showed the largest oxygen isotope anomaly.

(2) HED Achondrites. Discoveries of large number of polymict eucrites in both Yamato and Victoria Land raised a problem why such class of meteorites is abundant in Antarctica (5). Mineralogy, exposure ages, terrestrial ages (13, 14) indicated that many of them are paired (Table 1). The polymict

Table 1. Pairings of Antarctic HED Achondrites

Samples	Texture class	Nd/Sm	Mineral				REE	Exp. age Ma	Terr. age Ma
Y-74159	pE	A	BD				(A) I	72	-0.041
Y-74450	pE	A	BD	PC	OV	Na	(A) A	73.0 (A)	-0.032
Y-75011	pE	A	BD	PC	OV	Na	(A) A		
Y-75015	pE	A	BD	PC	OV	Na	(A) A		
Y-790007	pE		BD	PC			(A) H	73.3 (A)	-0.029
Y-790020	pE			PC			(A) H		
Y-790122	pE						I	24.4 (?)	0.110
Y-790260	pE			SM	OV		(B) B	21.6 (B)	0.140
Y-790266	pE			SM		Na	(B) B	21.9 (B)	0.150
Y-791960	pE		DI				(C)	6.81	0.27
Y-791962	pE		DI				(C)		
Y-792769	pE						(D)	3.73	0.35
Y-791186	mE		MC			Na	(E) E	13.33	0.24
Y-792510	mE		MC			Na	(E)	11.65	0.23
Y-7308	pH						F		
Y-790727	pH						G	12.7	0.150
Y-791208	pH						G		
Y-791492	pH						G		

p: polymict breccia, m: monomict, E: eucrite, H: howardite BD: Binda-type Inverted Pigeonite present. DI: diogenite, Y-75032 type, MC: Moore Co, PC: Y-75011,84, OV: fayalite veinlets, SM: shock melt, Na: Na-rich, A-H: meteorite shower, Isotope ratio after Wooden et al.(1983), Terr. age, Exp. age after Schultz (1986) and Nagao and Ogata (1989), REE: Fukuoka(1984).

euclrites are fragmental breccias of eucritic compositions produced by impacts, which destructed, mixed and excavated only eucritic terrains. They do not contain solar wind gases as in regolith breccias and howardites. Thus, the number of distinct falls of polymict euclrites has increased from that in 1986 (7). Judging from data of these studies, we identify the following pairing (1). A: Y74159, Y74450, Y75011, Y75015, Y790007; B: Y790260, Y790266, Y790122(?); C: Y791960, Y791962; and D: Y792769. Some of them were recovered from the different bare ice fields. In 1983, Y7308 was the only howardite, but the number of howardite increased by discovery of Y790727, Y791208, Y791492 and many others, which are distinct from Y7308 (3).

Our recent study of Antarctic monomict euclrites, Y791186, Y792510 and Y790266, Y791195, Y791438 indicates that their mineralogy are similar to the non-Antarctic ordinary euclrites, but they differ texturally and chemically. Most non-Antarctic monomict euclrites are products of thermal annealing at or near the crater floor or wall by impacts. The Y791186 and Y792510 pyroxenes were almost completely homogenized and parts of pigeonites are inverted to orthopyroxene by much slower cooling. The exposure ages by Nagao and Ogata (14) suggest that they are paired. Y791195 is a crystalline euclrite with chemistry similar to ordinary euclrites, but the coarse exsolution texture suggests the location within the eucritic crust may be different from the non-Antarctic one. Y791438 has chemistry similar to Mg-rich cumulate euclrites, but it shows texture similar to ordinary euclrites. The observation suggests Antarctic HED's came from regions different from source regions of non-Antarctic ones.

About 29 diogenites with granoblastic textures represented by Y74013 were found to be pieces of the same fall by Takeda et al. (15). Another group represented by Y75032 shows unique shock textures and chemistries. The Y75032 group fills the compositional gap between diogenites and the cumulate euclrites, and shows intermediate mineralogical characteristics in a trend of the fractional crystallization (16). Y791439 contains rare Fe-rich ordinary euclrite clasts. Y791073, Y791200, Y791201 and Y791439 contain more Fe-rich cumulate euclrite components. The facts suggested that the Y75032 group specimens are paired and came from a restricted region of the HED body. All Yamato diogenites are different from the non-Antarctic ones.

(3) Lunar Meteorites. Among six lunar meteorites, Y82192, Y82193, and Y86032 have been proposed to be paired from the noble gas abundances by Eugster (17) and mineralogy by Takeda et al. (18). The lunar meteorites are good examples, where meteorites from different bare ice areas represents meteorites from different region of the parent body, Moon.

Among the chondrite classes, the Antarctic LL chondrites show some unique textures acquired on their parent body (7). Lipschutz's group (8) studied difference in trace element chemistries of Antarctic chondrites. Wasson (9) pointed out unique features of the Antarctic irons. Tomeoka et al. (19) studied unique Antarctic carbonaceous chondrites.

Discussion.

It is to be noted that the differences between Antarctic and non-Antarctic achondrites are results of mixtures of several different factors. Larger number of smaller sized specimen may account for higher abundances of polymict euclrites, ureilites and primitive achondrites. The presence of only two distinct diogenite showers among the Yamato collection suggest that they represent falls on a specific ice field at certain distant past. Because it is expected that impacts or collisions of their parent bodies may produce

fragments from different parts to have different orbits, the Antarctic meteorites may sample some portions of their parent body unknown from the contemporary non-Antarctic meteorites. If so, this characteristics of the Antarctic meteorites will greatly help us to reconstruct the parent bodies or masses for genetically related meteorites. To obtain a better understanding of the parent sources and their relation to asteroids, we have been reinvestigating several Antarctic achondrites recovered recently and unique chondrites with electron microprobe and single-crystal X-ray diffraction and performed synthesis of their parent body for three classes of meteorites on the basis of pairing of the specimens. We summarize current states of some characteristics of the Antarctic achondrites (Table 1).

The discovery of the Vesta-like surface materials on Near-Earth asteroids, 1915 Quetzalcoatl (15), 1980PA, 1985DO2 and 3551 (1983RD) (20) suggests that fragments from different portions of them were delivered to Earth in different time sequence, if their orbits were disturbed by Jupiter and others, because their masses are very small. The polymict eucrites do not always show old terrestrial ages.

In summary, there are differences to suggest that the Antarctic meteorites represent meteorite falls from specific areas at a distant past in Antarctica and have been derived from different regions than those of the contemporary falls on the parent body, but no definite evidence to confirm this attractive idea of long term orbital changes of their parental masses has been found up to date. If so, they provide us with useful information on their parent bodies or masses. The unusual Antarctic achondrite falls in the past suggests that fragments from different portions of the parental mass may be delivered to Earth in different time sequence. However, we have to be careful about pairings of specimens and the differences may be an artifact produced by inadequate sampling. The discoveries of many smaller sized specimens on the Antarctic bare ice fields or sampling on specific ice fields may also account for some of the differences.

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YAMATO-82162 AND -86720: NEW KINDS OF CARBONACEOUS CHONDRITES; MINERALOGICAL AND PETROGRAPHIC COMPARISON

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INTRODUCTION

Yamato-82162 and -86720 (Y-82162 and -86720) are unusual carbonaceous chondrites found in Antarctica and now the subjects of a consortium study organized by Prof. Y. Ikeda. A recent oxygen isotopic study showed that they fall on the CI area in the three oxygen isotope plot [1]. However, they show many mineralogical and petrographic features different from the non-Antarctic CI chondrites [2-5]. Their trace element chemistries are also different [6]. These meteorites propose new aspects of carbonaceous chondrite mineralogy, petrology, and chemistry and potentially provide invariable information regarding the nature of the CI and CM parent bodies. We here present a review of the mineralogy and petrography of these meteorites and compare them with other CI and CM chondrites, especially non-Antarctic ones.

MINERALOGICAL AND PETROGRAPHIC COMPARISON

Y-82162: This meteorite consists largely of fine-grained, dark matrix; no chondrules and aggregates of anhydrous silicates are present. It contains a major amount of Ni-bearing pyrrhotite and minor amounts of framboidal, platy, and spheroidal magnetite, Mg-Fe carbonates, and Ca-phosphate. Isolated clusters of coarse phyllosilicates are also present. The texture and the presence of these minerals support the idea that Y-82162 is a CI chondrite.

However, this meteorite has a much higher abundance of coarse phyllosilicates than non-Antarctic CI chondrites, and has no veins of sulfates that are common in the non-Antarctic CI chondrites. In Orgueil, there is evidence that the coarse phyllosilicates were altered to matrix during the aqueous alteration that produced sulfate veins [7]. The sulfate-vein formation appears to have occurred in a very late stage of aqueous alteration [8-10]. The abundance of coarse phyllosilicates and the absence of sulfates suggest that Y-82162 did not experience the late aqueous alteration stage.

The Y-82162 phyllosilicates have compositions close to smectite or mica and are unusually enriched in Na (1.4 to 4.5 wt% Na₂O). Na is a highly water soluble element and is strongly depleted in the non-Antarctic CI chondrite matrices [9]. The enrichment of Na in the Y-82162 phyllosilicates appears to be consistent with the hypothesis that this meteorite experienced a lesser degree of aqueous alteration than non-Antarctic CI chondrites.

Y-86720: In a thin section, this meteorite consists in major part of dark, fine-grained materials, and thus it was initially described as a CI chondrite [11]. However, our observations reveal that it has chondrules and aggregates that are completely replaced by brownish, translucent material. The modal proportion of real matrix is approximately 80 %. The replacement products contain major Si, Mg, Fe, and variable Al; they are probably phyllosilicates, although they seem to have been considerably dehydrated as dis-

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cussed below. Thus, based on petrographic texture, this meteorite can be classified as a CM chondrite that has experienced extensive aqueous alteration; the degree of alteration is the highest of the known CM chondrites. However, Y-86720 shows several mineralogical features distinct from ordinary CM chondrites.

A striking difference is seen in the phyllosilicate mineralogy. Chondrules and aggregates in most CM chondrites were altered by phyllosilicates to various extents. The phyllosilicates are predominantly Fe-Mg serpentines. In contrast, the phyllosilicates in the Y-86720 chondrules and aggregates have approximate compositions falling intermediate between serpentine and smectite. Na is also relatively enriched (up to 2.8 wt% Na₂O). Thus, they resemble the phyllosilicates in Y-82162 and also in other CI chondrites [7]. These features of the phyllosilicate mineralogy suggest that the aqueous alteration in Y-82162 and Y-86720 occurred in similar physical-chemical conditions, but in distinct conditions from ordinary CM chondrites.

THERMAL METAMORPHISM

Both meteorites contain a high abundance of submicron-size grains of olivine in their matrices, which poses a remarkable contrast with ordinary CI and CM chondrites. Our transmission electron microscope (TEM) observations provide evidence that the olivine was formed from phyllosilicates probably by heating [2,3]. Recent analyses of trace elements [6] are consistent with our view. Such thermal transformation was also reported from other Antarctic carbonaceous chondrites, B-7904 and Y-793321 [12]; of particular interest is that B-7904 also plots in the CI area in the oxygen isotope diagram [1].

Heating experiments of the Murchison CM chondrite show that transformation of serpentine to olivine commences in the range between 500 and 600°C in air [12]. Thus, the minimum metamorphic temperature experienced by Y-82162 and -86720 was probably in that range. Our TEM observations indicate that the degree of metamorphism is higher in Y-86720 than in Y-82162. Our estimates of temperature and relative degree of metamorphism are consistent with those derived from analyses of trace elements [6].

These meteorites contain significantly larger amounts of Fe-sulfides--pyrrhotite in Y-82162 and troilite in Y-86720-- than other CI and CM chondrites. They mostly occur in small grains (<10 μm) that are dispersed throughout the meteorites. On the other hand, our microprobe analyses show that their matrices are strongly depleted in Fe and S relative to those of ordinary CI and CM chondrites. The small grains of sulfides may have resulted from thermal transformation of thermally labile S-bearing phases such as tochilinite and/or ferrihydrite, thus resulting in the depletion of Fe and S in the matrices.

Although most CI and CM chondrites experienced various degrees of low-temperature, aqueous alteration, no evidence of significant thermal metamorphism has been reported from non-Antarctic CI and CM chondrites. Thus, Y-82162 and Y-86720 pose a new dimension of variation, i.e. thermal metamorphism, that occurred in the CI and CM parent bodies.

CONCLUSIONS

We hypothesize that Y-82162, Y-86720, and probably B-7904 are genetically related to each other and they came from a common parent body that is different

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from the parent body (or bodies) from which ordinary CM chondrites were derived. The mineralogical and chemical differences between Y-82162 and Y-86720 may reflect the heterogeneities within their parent body.

Considering the new aspects proposed by these meteorites, it is necessary to establish a new classification for carbonaceous chondrites. We suggest to divide the carbonaceous chondrites into separate groups such as CI and CM in terms of oxygen isotopic signature, which should reflect different precursor materials or parent bodies. Then, each group can be subdivided in terms of mineralogy, petrography, and chemistry (e.g., CI1, CI2, CM1). According to such a scheme, Y-82162 and Y-86720 can be classified as CI1 and CI2. We may need a further subdivision to indicate the degrees of aqueous alteration and thermal metamorphism.

We believe that it is significant that the four Antarctic carbonaceous chondrites, Y-82162, Y-86720, B-7904, and Y-793321 show similar thermal effects that have not been known from non-Antarctic CI and CM chondrites. The differences in thermal history probably reflect distinct meteorite sources. Further quest of thermally metamorphosed CI and CM chondrites is urgent to understand the range of chemical and mineralogical variations of the parent bodies of these meteorites.

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**TERRESTRIAL WEATHERING OF ANTARCTIC STONY METEORITES -
DEVELOPMENTS 1985-1989; Michael A. Velbel¹ and James L. Gooding²**
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Introduction. Terrestrial weathering interferes with the use of meteorite mineralogy and chemistry as windows into the pre-terrestrial history of the meteorites, their parent bodies, and the early solar system, because weathering transforms original minerals to alteration products and redistributes chemical elements. Nowhere is this phenomenon of greater concern to meteorite scientists than in Antarctica. More than 7000 samples, representing several thousand meteorites, have been collected in Antarctica in the past two decades [1]. However, none of these are fresh falls. Although weathering is thought to proceed only slowly in the cold, dry Antarctic environment, Antarctic meteorites have been exposed to terrestrial conditions for tens of thousands to hundreds of thousands of years [2,3]. Thus, ample opportunity exists for small increments of weathering to accumulate into measurable effects. Characterization of terrestrial weathering effects is therefore crucial to studies of Antarctic meteorites [4,5] to prevent terrestrial alterations from being misinterpreted as primary compositional attributes of the meteorites.

The purpose of this paper is to summarize recent (since 1985) studies of elemental redistribution and mineral alteration in Antarctic stony meteorites. Progress in understanding Antarctic weathering of iron meteorites has been reported by Buchwald and Clarke [31]; as these authors [31] and Buchwald (this workshop) point out, new developments in the study of corrosion of meteoritic metal apply not only to iron meteorites, but to the metal in stony meteorites as well.

Hydrocryogenic weathering and the role of liquid water. The importance of liquid water as an agent of Antarctic meteorite weathering is now being recognized. Gooding [4,5] described circumstances under which liquid water can exist under Antarctic conditions, and introduced the term "hydrocryogenic" to describe these conditions. Liquid water can occur either as capillary water, or as undercooled films of water on mineral surfaces. Persistence of liquid water by undercooling occurs because of crystallographic misfit between ice and the structure exposed at the mineral surface; this misfit inhibits heterogenous nucleation and epitaxial growth of ice at the mineral surface. Such "unfrozen" water would form thin films. Schultz [6] experimentally determined that temperatures in the interior (2 cm depth) of a sample of the Allende (CV3) meteorite exposed to Antarctic conditions reached 5°C on wind-free days during austral summer, despite the fact that the air temperature never exceeded -11°C over the study period. Thus, insolation heating of meteorites in Antarctica is sufficient to raise the temperature of meteorite interiors above the freezing point of pure water, to depths of several centimeters. Examining thermodynamic relations among some common meteoritic silicate minerals and a previously observed Antarctic weathering product [nesquehonite, {Mg(HCO₃)(OH)·2H₂O}; 11,17], Velbel [7] found that the hydrolysis reaction forsterite + water + carbon dioxide = = > nesquehonite + silica at Antarctic temperatures and pCO₂ is thermodynamically spontaneous for all water activities greater than 0.3, compatible with the presence of liquid water as thin films or brines. Thus, small amounts of liquid water in the weathering microenvironments of Antarctic meteorites probably play a role similar to the role water plays in other terrestrial weathering environments.

The common occurrence of alteration products as veins in weathered Antarctic meteorites, and the internal petrographic textures of these veins, support an important role for liquid water in the weathering process, and indicate that the fluids entered the weathering microenvironments *via* fractures [4,5,8,31]. The importance of fractures as a poorly understood but important component of meteorite weathering processes was emphasized by Mittlefehldt and Lindstrom [this workshop]. Previous studies found no relationship between fracturing and weathering, but this probably reflects the complexity of the weathering process, not the relative importance of fractures as locii of fluid transport.

Mineral weathering & mineralogy of weathering products. *Hydrous Fe-oxides, clay mineraloids & other silicates.* "Rust" is the most widely recognized weathering product of Antarctic meteorites - in fact, until recently, the weathering classification of Antarctic meteorites was based exclusively on the amount of "rust" visible to the unaided eye. Gooding [5] described both "metallic" (Fe-Ni-S) rust, which forms by weathering of primary Fe-Ni metal and troilite, and "sialic" (Fe-Si-Al) rust, which forms by weathering of mafic silicate minerals. The precise mineralogical nature of the rust is not well known, although goethite {alpha-FeOOH} [8,9], lepidocrocite {gamma-FeOOH} [10], akaganeite {(beta-FeO(OH,Cl))} [31] and jarosite

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{ $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$ } [8,32] have been tentatively identified by powder X-ray diffraction (XRD). Clay mineraloids were identified compositionally by Gooding [5], but are not present in sufficient abundance (or are not sufficiently crystalline) for mineralogical characterization by conventional XRD [9]. The occurrence of zeolites (especially stilbite { $\text{NaCa}_2\text{Al}_5\text{Si}_{13}\text{O}_{36}\cdot 14\text{H}_2\text{O}$ }) as weathering products of Antarctic meteorites has been postulated on both compositional grounds [5,8] and on the basis of preliminary XRD data [9].

Evaporite minerals. The most obvious and widely noted "non-rusty" alterations are white powders or efflorescences on the surfaces of meteorites [11]. Although relatively rare, occurring on less than 5% of the specimens, the white deposits are nevertheless the second most widely recognized form of terrestrial alteration, after the formation of rust. Several descriptive mineralogical studies have been published (summarized in [11], Table 1; also, [8,12-17]), which demonstrated that the deposits consist of various evaporitic carbonates and sulfates, predominantly of Mg and Ca. Specific minerals include nesquehonite { $\text{Mg}(\text{HCO}_3)(\text{OH})\cdot 2\text{H}_2\text{O}$ }, hydromagnesite { $\text{Mg}_5(\text{CO}_3)_4(\text{OH})_2\cdot 4\text{H}_2\text{O}$ }, starkeyite { $\text{MgSO}_4\cdot 4\text{H}_2\text{O}$ }, epsomite { $\text{MgSO}_4\cdot 7\text{H}_2\text{O}$ }, and gypsum { $\text{CaSO}_4\cdot 2\text{H}_2\text{O}$ }. Mineralogical work provisionally suggests that Mg-carbonates occur primarily on achondrites and equilibrated ordinary chondrites, whereas identifiable sulfates occur primarily on carbonaceous chondrites and unequilibrated ordinary chondrites. Because of the small number of evaporite deposits whose mineralogy has been well-determined to date ($n=8$), these patterns are only tentative.

The formation of hydrous minerals (hydrous carbonates and sulfates, Fe-oxhydroxides, clay mineraloids, zeolites, etc.) is also indicated by elevated H_2O contents of Antarctic ordinary chondrites relative to falls [Jarosewich, this workshop], and absorption features indicative of OH bonds in infrared spectra of Antarctic ordinary chondrite and achondrite powders [19].

"Glacial" vs "periglacial" weathering. Gooding [4] postulated that Antarctic meteorites are most likely to be exposed to liquid water when the meteorite resides on the ice surface, either shortly after fall, or after emergence of the meteorite from the glacier at the zone of ablation and accumulation ("periglacial" weathering). Some alteration may also take place while the meteorite is encased in the glacial ice ("glacial" weathering); ALH 82102 (H5) was found still partially encased in ice, yet even its submerged side was already significantly rusted [4,18].

New light has been shed on the rate and timing of Antarctic meteorite weathering by the work of Jull and others [17]. XRD and scanning electron microscopy of the white efflorescences on LEW 85320 (H5) revealed the efflorescences to consist predominantly of nesquehonite { $\text{Mg}(\text{HCO}_3)(\text{OH})\cdot 2\text{H}_2\text{O}$ }, a hydrous Mg-carbonate. Carbon-14 analysis showed that the nesquehonite formed during the last 40 years, indicating that formation of weathering products under Antarctic conditions can occur *very* quickly - quite likely under "periglacial" conditions.

"Weatherometers" & weathering classification. The Antarctic meteorite community still awaits a reliable index of weathering for any meteorite group [18]. The present procedure for classifying the weathering of Antarctic meteorites is based on the amount of rust visible to the unaided eye; weathering categories "A", "B", and "C" indicate, respectively, "minor", "moderate", and "severe" rustiness (e.g., [18]). The principal shortcomings of the present classification are 1) that it is subjective and qualitative, and 2) that it "measures" only one form of weathering - oxidation. Recent attempts to reduce subjectivity and impose rigor on the "oxidation" classification include reflectance spectrophotometry, to quantitatively measure "redness" associated with rust [8,18]. Another measure of "rusting" during weathering measures "loss-on-ignition" for equilibrated ordinary chondrites [20]. Fresh equilibrated ordinary chondrites should experience weight gain upon ignition, due to oxidation of (predominantly metallic) iron. Prior oxidation (e.g., by weathering) means that less iron will be oxidized upon ignition; therefore, weight gains less than that typical of fresh chondrites reflect prior oxidation, and the magnitude of the shortfall between measured and "ideal" weight gains is a measure of the degree of oxidation by weathering.

Numerous weathering processes besides oxidation are known to operate in the terrestrial weathering environment. These include hydration, hydrolysis, solution, and carbonation [4]. Much progress has been made in recognizing that other weathering processes *besides* oxidation affect Antarctic meteorites, and that the effects of these other processes are not correlated with the "rust" index. The most obvious and widely noted "non-rusty" alteration is the appearance of white powders or efflorescences on the surfaces of meteorites. Velbel [11] found that the distribution of white evaporitic deposits differs among different meteorite compositional groups and weathering categories of Antarctic meteorites. Evaporites occur with

unusual frequency on carbonaceous chondrites, and are especially common in carbonaceous chondrites of weathering categories A and B. Among achondrites, weathering categories A and A/B show the most examples of evaporite weathering. Unlike carbonaceous chondrites and achondrites, most evaporite-bearing ordinary (H and L) chondrites are from rustier meteorites of weathering categories B and, to a lesser degree, B/C and C. LL chondrites are conspicuous by their complete lack of any evaporitic weathering product.

Almost two-thirds of all evaporite-bearing meteorites belong to weathering categories A, A/B, and B. Where chemical data are available, surficial evaporite deposits are associated with elemental anomalies in meteorite interiors ([11]; see below). Velbel [11] suggested that a lower-case "e" should be added to the weathering classification of evaporite-bearing Antarctic meteorites, to inform meteorite scientists of the presence of evaporite deposits and their associated compositional effects. This modification is now part of the Antarctic meteorite weathering classification [21].

The recognition of important non-oxidative weathering processes affecting Antarctic meteorites has implications for the development of more reliable "weatherometers". The discernable effects of various processes are not always correlated with one another, so no one effect measures all "weathering". For example, recent studies of infrared spectroscopy have attempted to quantify the extent of hydrous mineral formation [19], and have shown that neither halogen content [33] nor infrared measures of hydration correlate with the "rust" index [Ebihara and others, this workshop]. Weathering of Antarctic meteorites affects thermoluminescence sensitivity, yet the magnitude of this effect is not correlated with the A-B-C "rust" index [Sears, this workshop]. The occurrence of surficial evaporite deposits (the formation of which involves hydrolysis, solution, hydration, and carbonation [17]) is also not correlated with the A-B-C rust index [11].

Furthermore, different processes will affect different compositional groups of meteorites in different ways, restricting the applicability of the potential weatherometer [4,18]. For example, chemical [Jarosewich, this workshop] or infrared [19] measures of hydration may be useful only in meteorites which are originally essentially anhydrous (equilibrated ordinary chondrites, non-SNC achondrites), whereas modest hydration would be harder to discern in many carbonaceous chondrites, and possibly some unequilibrated ordinary chondrites. Carbonation may be detectable by chemical and spectroscopic techniques on achondrites and ordinary chondrites [19; Miyamoto, this workshop], but is less likely to be detected on carbonaceous chondrites, where possible sources of any surficial carbonate include redistribution from the meteorite itself. Even improving the characterization of oxidation of metal (on which the present "weathering" classification is based) is of limited utility, because metal is not present in all types of meteorites [4,19]. Therefore, improved characterization of weathering effects on Antarctic meteorites requires concurrent study of multiple processes which operate simultaneously but are not coupled to one another; there is no single "weatherometer" which encompasses all possible alterations on all classes of meteorites.

Cosmochemical interferences. Numerous workers have reported apparent element redistribution associated with Antarctic meteorite weathering. Many previous studies [22-24] reported minor leaching of certain elements, and surficial enrichment of certain elements. They concluded that leaching effects are minor, and do not affect meteorite interiors or "rust-free" (ostensibly unweathered) Antarctic meteorites. However, as noted above, oxidation and formation of visible rust are not the only forms of weathering, and the absence of visible rust cannot be taken to imply a complete absence of weathering. Velbel [11] compiled a catalog of evaporite-bearing meteorites, then retrieved compositional data on evaporite-bearing meteorites from the literature. Velbel [11] found that interiors of evaporite-bearing meteorites have lower Rb, I, and Ca concentrations than interiors of evaporite-free meteorites. This suggests two things: 1) previous workers [24] were correct in suggesting that leaching is the principal mode of trace- (and major-?) element mobilization during Antarctic meteorite weathering. *However*, 2) contrary to the conclusions of some previous workers [24,25], meteorites of weathering categories A and B also exhibit compositional anomalies - they are in fact "compositionally compromised" [11]. This may be a leaching effect, although mass balance calculations using presently available evidence are inconsistent with this hypothesis [10,11].

High surficial contents of elements like Rb, I, and Cs have been attributed to external contamination [22,33]. However, extensive element fractionation would be required for the evaporite deposits to be of external (terrestrial) origin, whereas less fractionation would be required to derive the

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minor elements from the meteorite [10,34]. Furthermore, if the source of the evaporite material is external, it becomes very difficult to explain why evaporite deposits are preferentially associated with meteorites anomalously low in interior Rb, Co, I, and Ca [11]. Transfer of these elements from meteorite interiors to meteorite surfaces by leaching and evaporation leading to evaporite formation is a more satisfactory hypothesis for the association of surficial evaporites with interior depletions and surficial enrichments of mobile elements. Mass transfer of this kind is a problem for cosmochemistry even if the phenomenon is isochemical overall (i.e., even if elements accumulate on meteorite surfaces without being lost to the Antarctic environment), because removal of elements from interiors to surfaces would leave internal samples depleted in the elements of interest. The magnitude of this effect, however, is not sufficiently known [11].

A third possibility is that evaporites and compositional anomalies are associated because both are consequences of some process, as yet unidentified. Additional work is required to explain this association. Nevertheless, regardless of the *reason* for the association, evaporite deposits *are* associated with compositional anomalies, even in meteorites with minimal rusting. Evaporite efflorescences serve as a warning that the sample in question is compositionally compromised [11].

Little is known about terrestrial weathering of terrestrial rocks at high latitudes, or about elemental mobility during such weathering. The only significant trend reported by Kelly and Zumberge [26] in their study of weathering of a quartz diorite at McMurdo Sound, Antarctica, was oxidation of iron. The more extensively weathered samples were also slightly enriched in Na, Cl, and sulfate relative to fresher samples, indicating contamination by sea spray in this coastal weathering environment. Kelly and Zumberge [26] suggest the presence of ferric sulfates, based on parallel behavior of Fe_2O_3 and SO_3 . Evans and Chesworth [27] report losses of Ca, Mg, Mn, and total Fe, due to weathering of olivine and augite, during basalt weathering on Baffin Island, Canada. Claridge and Campbell [28] suggest that the initial stages of high-latitude weathering are similar to the early stages of weathering in warmer climates. If so, trace- and rare-earth element data from other terrestrial weathering environments might provide first-order guidelines for the anticipated behavior of elements of cosmochemical interest during Antarctic meteorite weathering. Studies of elemental mobility during non-Antarctic weathering of terrestrial rocks [29,30] suggest that major elements (Na, Mg, K, Ca, S), and minor and trace elements (Cr, Co, Ni, Cu, Zn, Rb, Sr, Ba, Nd), are quite likely to be mobilized, redistributed, and possibly leached, during weathering. Other elements (including La, Ce, Eu, Sm, and most other light rare earth elements) may also be affected (leached), albeit to lesser degrees; La/Ce fractionations may be among the more notable effects. The apparent leaching (depletion) behavior implied for Sb and Cs [24] has no non-Antarctic weathering counterpart; these elements are usually unaffected or enriched in weathered residues [30].

As noted in the section on mineral weathering, the evaporite minerals of equilibrated ordinary chondrites and achondrites are hydrous carbonates [11,17]. Infrared spectroscopy suggests that hydrated Mg-carbonates may be ubiquitous on Antarctic ordinary chondrites [Miyamoto, this workshop]. Isotopic analyses of the most abundant example known to date indicate that the C and O in the hydrous carbonates are of terrestrial origin [17,35]. Taken together, these results suggest that evaporite formation on equilibrated ordinary chondrites and achondrites may contribute to modification of their stable C-isotope content [e.g., Grady and others, this workshop].

Summary. Recent research has revealed much about the effects of weathering processes on Antarctic meteorites. The presence and possible properties of small amounts of liquid water are now recognized. Mineralogical studies have elucidated the nature of the widely recognized "rust" (goethite, lepidocrocite, akaganeite, and possibly jarosite), suggested the existence of hydrous silicates (clay mineraloids and zeolites), and identified and better characterized a host of evaporite minerals which occur as weathering products (nesquehonite, hydromagnesite, starkeyite, epsomite and gypsum). Characterization of these minerals has been important in recognizing that the weathering of Antarctic meteorites involves multiple processes, not only oxidation of metal, but also hydrolysis of silicates and glass, hydration, solution, and carbonation. Isotope and compositional studies of evaporites reveal rapid formation of observable quantities of weathering products, and prove that the weathering products themselves are *not* simply external (terrestrial) contaminants - rather, they contain *both* terrestrial contamination *and* redistributed elements of meteoritic provenance, with potentially significant implications for at least some elements of cosmochemical interest. Improved characterization of weathering effects on Antarctic meteorites requires

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concurrent study of multiple processes which operate simultaneously but are not coupled to one another; there is no single "weatherometer" which encompasses all possible alterations on all classes of meteorites.

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COSMIC SPHERULES FROM ANTARCTIC ICE CORES AS PROXY INDICATORS OF EXTRATERRESTRIAL MATTER INFLUX DURING THE LAST ~ 150 000 YEARS

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Spherules of extraterrestrial origin have been found in deep sea sediments by Brownlee (1) and on Greenland ice by Maurette and Hammer (2). A cometary origin of a large fraction of these objects has been suggested by Raisbeck et al (3,4). As pointed out by Yiou and Raisbeck (5), Antarctic ice cores offer two important advantages compared to deep sea and Greenland reservoirs for the study of extraterrestrial matter: (i) an absolute flux can be estimated quite quantitatively; (ii) possible time variations in this flux over at least the last 10^5 years can be looked for. The disadvantage is, in counterpart, that the concentration of these extraterrestrial particles in such ice cores, is expected to be very low. We were encouraged nevertheless in this quest by the discovery of 5 "cosmic spherules" from an ice core drilled at Dome C in Antarctica (5). In parallel with our measurements of ^{10}Be concentration profiles in Antarctic ice cores as described, for example, in Raisbeck et al (6), we have then started a systematic study of the abundance of extraterrestrial matter in relatively well defined ice cores levels. For this, each sample studied for ^{10}Be (~1kg melted) is filtered through a $30\mu\text{m}$ mesh size filter. Each filter is examined under a stereomicroscope and magnetic spherules of diameter $>50\mu\text{m}$ are isolated, their diameter is measured, they are kept for further analysis by electron microprobe. The filters themselves are preserved for further extraction of eventual non melted fragments and a global analysis in Iridium.

During the past year we have studied in this way several Antarctic ice cores, in particular one drilled at Vostok (7) which extends over a time period of ~ 150 000 years and covers a whole climatic cycle. From samples spaced roughly uniformly over this latter core, more than 50 spherules of $>50\mu$ in diameter have been isolated. A complete analysis is not yet performed at the time of this writing, but we hope to be able for this meeting, to give a repartition in size and composition of these "Antarctic Cosmic spherules",

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as well as a rough estimate of the global flux of extraterrestrial matter in the form of spherules during the past ~ 150 000 years, and indicate variations if any, of this flux during that period.

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