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INTERNATIONAL WORKSHOP ON

ANTARCTIC METEORITES

WORKSHOP ON ANTARCTIC METEORITES

Mainz '85

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INTERNATIONAL WORKSHOP ON

ANTARCTIC METEORITES

J. O. Annexstad
L. Schultz
H. Wänke

Sponsored by

International Association of Geochemistry and Cosmochemistry
Lunar and Planetary Institute
Max-Planck-Society

Hosted by

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Preface

A first workshop on Antarctic glaciology and meteorites was held April 19–21, 1982 at the Lunar and Planetary Institute in Houston, Texas. The results of this meeting were summarized by Colin Bull and Michael E. Lipschutz and published as LPI Technical Report 82-03. Of the 36 participants in the workshop, only two came from countries outside the United States of America.

The idea of a second workshop with a decidedly international flavor was conceived during an 8-day storm in Antarctica at the Allan Hills camp. In spite of discouraging remarks by a tent mate (P. Pellas), the reasons, listed below, became more pronounced as the storm continued.

- Search for and research on Antarctic meteorites has become more internationalized during recent years. Nations that have traditionally been doing meteorite research also became involved in Antarctic research. If these nations could agree on similar procedures for collecting, curating, distribution, etc., many difficulties could be avoided. An international workshop on Antarctic meteorites for the exchange of ideas about current theories of meteorite concentration mechanisms as well as discussions on the development of some general rules for meteorite handling, curation, and distribution would be useful and timely.
- The 48th Annual Meeting of the Meteoritical Society was scheduled for July, 1985 in Bordeaux, France. This conference is generally attended by a large international group of meteorite researchers. If a workshop could be held just prior to this conference, non-European participants could attend the workshop without much additional travel cost.
- It is becoming more and more obvious that Antarctic meteorites are not only space probes which result in valuable information about the solar system, but they are also closely related to Antarctic processes. Antarctic meteorites are important tools in the study of Antarctic ice.

In discussions with the Chairman of the "Working Group of Extraterrestrial Geochemistry" of the International Association of Geochemistry and Cosmochemistry (H. Wänke) it became

evident that the topic of Antarctic meteorites would fit very well within the aim of this working group. Also the Meteorite Working Group of the Lunar and Planetary Institute (Houston) showed interest in a workshop on Antarctic meteorites. In this way the workshop became jointly sponsored by IAGC and the LPI. Once it was decided to hold the workshop at the Max-Planck-Institut für Chemie in Mainz on July 10–12, 1985, we also obtained support from the Max-Planck-Society. This made it possible to support a number of speakers and to bring together meteorite researchers, the "users" of Antarctic meteorites, glaciologists and those scientists who combine field observations with laboratory experiments to understand the phenomenon of Antarctic meteorites.

Ten invited speakers delivered 30–40 minute summary talks and 13 speakers contributed 15-minute talks on specific subjects. The 78 participants in the workshop represented 12 different countries. Most speakers have submitted abstracts of their talks, and some have been extended into short papers.

Many of the papers raised lively discussions. At the end of the workshop, a general discussion was held to assess current activities of individual nations, future work in the field, and in the laboratory. From the discussions a general consensus was obtained on recommendations for future programs and projects.

Introduction

History of Meteorites in Antarctica

Every continent on the Earth has contributed to the scientific store of meteorites through observed falls and the finds of specimens. The Antarctic is no exception to this rule except for the facts that no meteorites have been observed to fall there and, until 1969, only four specimens had been found. As a target of great size (14×10^6 km^2) with a preserving environment, meteorites should be in abundance in Antarctica if they are not obscured by snow. However, this was not realized by the early explorers and scientists who visited that remote continent.

Strictly by chance, a party of Japanese glaciologists discovered nine specimens on a blue ice surface in 1969. The story as reported by Yoshida et al., 1971 is well known and has been publicized by many authors since that time. The significance of that find has prompted numerous searches for meteorites in Antarctica with the result that 7083 fragments have been collected for analysis up to March, 1985. Table 1 lists the number of meteorite fragments, find localities and the year of find.

Table 1. Antarctic meteorites.

Year	Name(s)	Number
1912	Adelie Land	1
1961	Lazarev	2
	Thiel Mts.	2
1964	Neptune Mts.	1
1969/70	Yamato	9
1973/74	Yamato	12
1974/75	Yamato	663
1975/76	Yamato	308
1976/77	Allan Hills	9
	Mt. Baldr	2
1977/78	Allan Hills	310
	Purgatory Peak	1
1978/79	Allan Hills	262
	Bates Nunatak	6
	Derrick Peak	15
	Meteorite Hills	28
	Reckling Peak	4
1979/80	Allan Hills	53
	Belgica	5
	Reckling Peak	11
	Elephant Moraine	10
	Yamato	3676
1980/81	Allan Hills	32
	Outpost Nunatak	1
	Reckling Peak	67
	Yamato	13
1981/82	Allan Hills	378
	Yamato	133
1982/83	Allan Hills	45
	Elephant Moraine	17
	Pecora Escarpment	32
	Thiel Mts.	18
	Taylor Glacier	1
	Yamato	211

Table 1. Antarctic meteorites.

Year	Name(s)	Number
1983/84	Allan Hills	161
	Elephant Moraine	207
	Inland Forts	1
	Yamato	43
1984/85	Allan Hills	265
	Frontier Mts.	42
⟩	Yamato	58
	Elephant Moraine	9
1985/86*	Allan HIlls	159
	Beardmore Glacier area	210

*Precise count and locations not available at time of distribution of this report.

The Antarctic to date has hardly been picked clean of meteorites and this bodes well for the possibility of finding more of the very rare and possibly unique specimens. A good example is the Yamato ice field, at 4000 km² the largest known, which has been visited many times by Japanese parties but is still largely unsearched.

Meteorite Curation and Distribution

When it was realized that meteorites could be found in abundance in Antarctica, it became necessary to develop methods of handling and distribution. In the United States an agreement among the National Science Foundation (NSF), the Smithsonian Institution (SI), and the National Aeronautics and Space Administration (NASA) provided the vehicle for this effort. The agreement established an overall management team composed of agency representatives (Meteorite Steering Group), who guide this part of the program. Organizational responsibilities were assigned to NSF for funding the searches, NASA/Johnson Space Center for curation and distribution of the specimens, and the Smithsonian for iron meteorite curation and final repository facilities. Funding for the laboratory curation and distribution efforts is provided by the Smithsonian and NASA to their respective organizations. Funding for the analysis of the specimens and related studies is provided by the NASA Planetary Materials Office and the NSF Division of Polar Programs through proposal grants for scientific research. To assist in the distribution of specimens for research and general program direction, the NSF awarded a contract to the Lunar and Planetary Institute of Houston for the establishment of an advisory board composed of university and government scientists called the Meteorite Working Group (MWG). The first formal distribution of samples from the U.S. collection began in 1978, with twice-yearly allocation (MWG) meetings since that time. Through 1984 over 2700 samples were issued to 142 investigators laboratories in 17 countries.

The United States' curation effort benefited greatly from the Apollo experience and the facilities of the Johnson Space Center (Annexstad and Cassidy, 1980). The Japanese, on the other hand, were faced with a much more difficult problem because they had returned hundreds of specimens to Tokyo, where no curation facilities existed. To their great credit, they developed these capabilities quickly and began systematically to distribute samples. From 1975 on, the Japanese have received 410 research proposals from laboratories in 15 countries. To date they have issued over 2100 samples to qualified scientists.

Scientists interested in receiving information from U.S. and Japanese collections, respectively, should direct their inquiries to:

Secretary, Meteorite Working Group
Planetary Materials Branch, SN2
NASA/Johnson Space Center
Houston, Texas 77058 U.S.A.

and

Curator of Antarctic Meteorites
National Institute of Polar Research
9-10, Kaga 1-chome, Itabashi-ku
Tokyo, 173, Japan

Information about new Antarctic meteorites recovered by U.S. expeditions since 1976 is given in the *Antarctic Meteorite Newsletter* (issued by the Meteorite Working Group). Since 1982 the National Polar Institute (Tokyo) distributes *Meteorites News*, which contains the basic characteristics and preliminary descriptions of the Japanese Antarctic meteorites. Many original papers about Antarctic meteorites are collected in the *Annual Proceedings of Symposia on Antarctic Meteorites* (NIPR, Tokyo) and in some *Smithsonian Contributions to the Earth Sciences* (Smithsonian Institution, Washington, DC).

Nomenclature and Abbreviations

The Nomenclature Committee of the Meteoritical Society has been the forum for approving the official names for meteorites found throughout the world. Their accepted procedure is to select a name (usually proposed by the finder) for a meteorite that places the find or fall near the closest post office, but is not a duplication of the name of another specimen. This information is published periodically in the Meteoritical Bulletin. This technique worked remarkably well until the Antarctic finds proliferated and the convention of one meteorite per area had to be violated.

The large number of finds in Antarctica changed the rules and so the Nomenclature Committee met on August 15, 1978 at Sudbury, Ontario to reach order out of chaos. Their procedure, utilizing an alpha numeric system, was published in *Meteoritical Bulletin 57,* in *Meteoritics* **15**, 93–94, March 1980.

Although this was a good method for naming the Antarctic specimens, a number of scientists found fault with the system. The most notable problems arose from the use of an expedition letter preceding the numbers and the lack of a provision for numbering more than 999 finds in a single season. The committee met yearly from 1980 to 1984 to resolve these and other disagreements. At a meeting on July 31, 1984 in Albuquerque, New Mexico, the Nomenclature Committee adopted the following revised version of the procedures for naming Antarctic Meteorites:

Revised Wording of the Procedures for Naming Antarctic Meteorites

1. Numerous meteorites have been collected from restricted areas of the Antarctic continent, and large numbers of new recoveries can be anticipated in the future. Since few locality names are available, and since the numbers involved exceed the letters in the alphabet, the normal procedure cannot be applied. The Committee on Meteorite Nomenclature has adopted the following procedure.

2. The name of an Antarctic meteorite shall consist of:
    (a) a geographical locality term;
    (b) a two-digit number specifying the Austral summer season of collection, i.e., the December year of the expedition;

(c) a number of two or more digits specific to the individual specimen. This number will continue to refer to the specimen regardless of subsequent pairings or possible pairings. Before publication, these numbers shall be approved by the Meteorite Nomenclature Committee.

Parts (b) and (c) of the name shall not be separated by spaces or punctuation marks, but a space should be left after part (a).

3. Where pairings have been established, and where it is required for statistical or other purposes to quote names for Antarctic meteorites as distinct from individual specimens, the lowest specimen number, the most widely studied mass-number or the largest mass number may be used for the collective meteorite name. Once approved and accepted by the Committee, this set name shall not be changed.

4. Names previously applied to existing expedition collections shall not be modified to conform exactly to the above procedure.

5. The name of an Antarctic meteorite consists of the complete geographical name together with the numerical code, e.g., Allan Hills 82505 or Yamato 75031.

A careful reading of these procedures will show that the proper designation for an Antarctic meteorite is the full name of the geographical locality. This, of course, becomes cumbersome when referring to a specimen many times in a published paper or on lengthy computer listings. The accepted procedure and one that is suggested to editors of journals is to publish the full name at the beginning of the article and use an abbreviation throughout the text.

The use of abbreviations was not addressed by the Nomenclature Committee but has evolved by convention. Following the initial acceptance of procedures in 1978, the Curator's Office of the Johnson Space Center initiated a three-letter abbreviation for computer compatability. This three-letter abbreviation was not considered official, but, by convention, was adopted for use by meteorite researchers. The usage has continued, with the Japanese and the Meteorite Working Group assigning their respective abbreviations. Table 2 is a list of Antarctic Meteorite find geographical localities and the abbreviations commonly in use today. Figure 1 shows the Antarctic continent with the locations of meteorite finds to date and the location name abbreviation. From this figure, it can be seen that the majority of finds are centered near coastal mountain regions like the Transantarctic Mountains.

Table 2. Abbreviations and Coordinates of Antarctic Meteorite Find Localities

Abbreviation	Locality	Coordinates	
ALH	Allan Hills	76°43'S	159°40'E
B	Belgica	72°35'S	31°15'E
BTN	Bates Nunatak	80°15'S	153°30'E
DRP	Derrick Peak	80°04'S	156°23'E
EET	Elephant Moraine	76°15'S	156°30'E
FRO	Frontier Mountain	72°59'S	160°20'E
ILD	Inland Forts	77°38'S	161°00'E
MBR	Mount Baldr	77°35'S	160°34'E
MET	Meteorite Hills	79°41'S	155°45'E
OTT	Outpost Nunatak	75°50'S	158°12'E
PCA	Pecora Escarpment	85°38'S	68°42'W
PGP	Purgatory Peak	77°20'S	162°18'E
RKP	Reckling Peak	76°16'S	159°15'E
TYR	Taylor Glacier	77°44'S	162°10'E
TIL	Thiel Mountains	85°15'S	91°00'W
Y	Yamato	71°30'S	35°40'E

The earlier individual finds Adelie Land (1912), Lazarev (1961), Neptune Mountains (1964) and Thiel Mountains (1961) are not abbreviated.
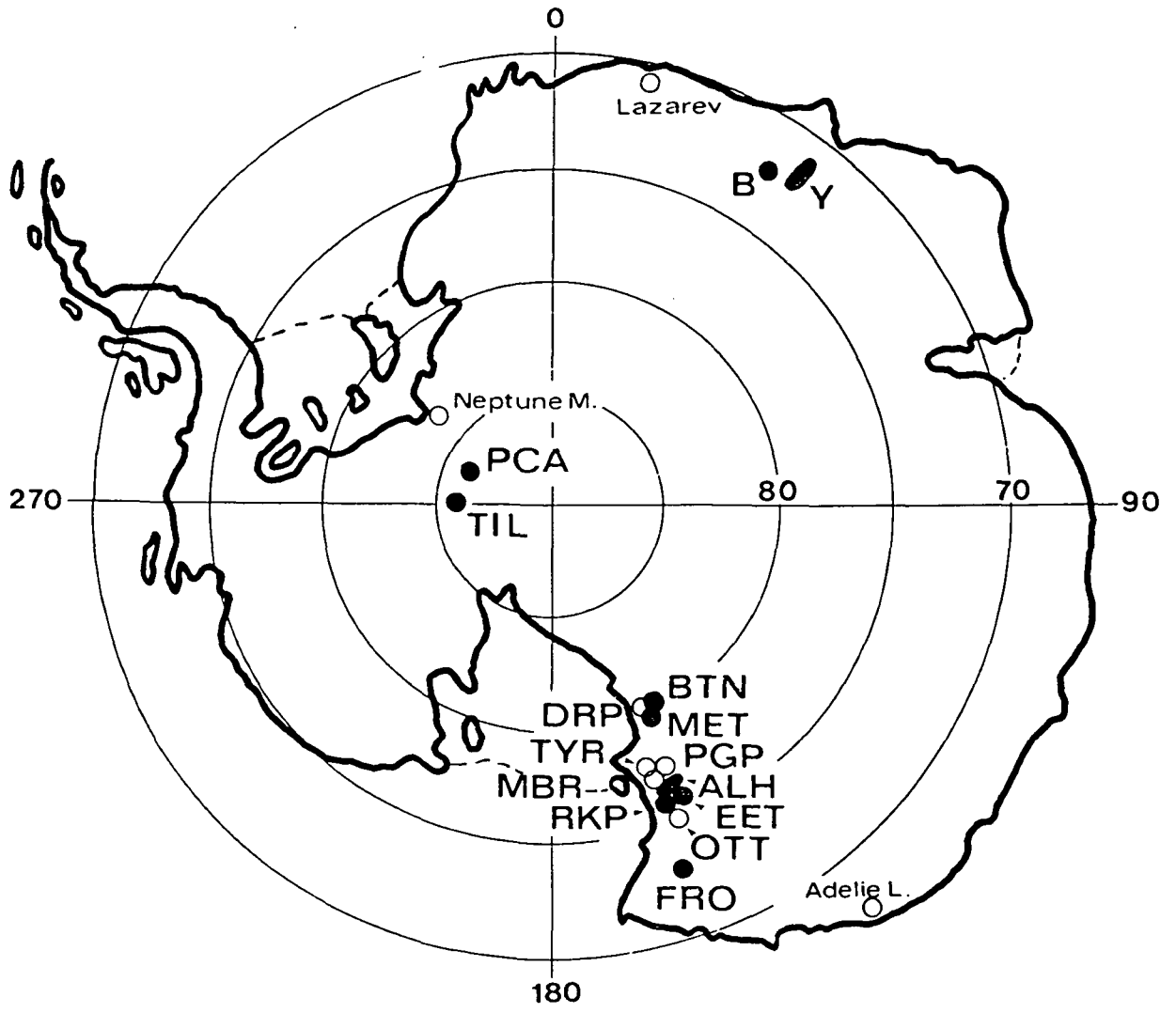
Fig. 1: Find localities of Antarctic meteorites. Filled symbols indicate concentrations with many specimens.

Program

Wednesday, July 10, 1985
2:00–6:00 p.m.

W. A. Cassidy   (Pittsburgh)
Meteorites and the Antarctic ice sheet   (invited talk).

K. Yanai and H. Kojima   (Tokyo)
Over 5600 Japanese collection of Antarctic meteorites: Recoveries, curation and distribution   (invited talk).

G. Delisle et al.   (Hannover/Mainz)
Discovery of meteorites on a blue-ice field near Frontier Mountain, North Victoria Land, Antarctica.

D. J. Drewry   (Cambridge)
Entrainment, transport and concentration of meteorites in polar ice sheets   (invited talk).

H. Oeschger   (Bern)
Modern experimental methods in glaciology   (invited talk).

Thursday, July 11, 1985
9:00 a.m.–5:30 p.m.

H. Palme   (Mainz)
Rare and unique meteorites from Antarctica   (invited talk).

U. Krähenbühl et al.   (Berne)
Distribution of elements and noble gas isotope measurements on grain size fractions of ALHA lunar meteorite 81005.

H. Takeda   (Tokyo)
Parent sources of Antarctic meteorites as inferred from pairing of the specimens.

R. S. Clarke, Jr.   (Washington, D.C.)
Antarctic iron meteorites: An unexpectedly high proportion of falls of unusual interest   (invited talk).

F. A. Hasan and D. W. G. Sears   (Fayetteville)
The natural thermoluminescence of Antarctic meteorites: Some comparisons with non-Antarctic meteorites.

S. R. Sutton and R. M. Walker   (St. Louis)
Thermoluminescence of Antarctic meteorites: A rapid screening technique for terrestrial age determination, pairing studies, and identification of specimens with unusual prefall histories.

B. Lang et al.   (Warsaw)
Thermoanalytical characterization of several Antarctic meteorites.

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J. L. Gooding   (Houston)
Weathering of stony meteorites in Antarctica   (invited talk).

M. E. Lipschutz   (W. Lafayette)
Trace elements in Antarctic meteorites: Weathering and genetic information   (invited talk).

G. Dreibus et al.   (Mainz)
Mysterious iodine-overabundance in Antarctic meteorites.

J. T. Padia and M. N. Rao   (Ahmedabad)
Weathering effects and solar components in two Allan Hills chondrites.

P. P. Sipiera and C. A. Landis   (Dunedin)
A preliminary report on a possible stromatolite find from Elephant Moraine: Possible directional indicator for ice movement.

K. Thiel et al.   (Köln/Orsay)
Meteoritic ablation and fusion spherules in Antarctic ice.

Friday, July 12, 1985
9:00–11:40 a.m.

K. Nishiizumi   (La Jolla)
Terrestrial and exposure histories of Antarctic meteorites   (invited talk).

K. Kigoshi and E. Matsuda   (Tokyo)
Radiocarbon datings of Yamato meteorites.

L. Schultz   (Mainz)
Terrestrial ages of Antarctic meteorites: Implications for concentration mechanisms.

S. Vogt et al.   (Köln/Zürich)
Cosmic ray records in Antarctic meteorites.

J. O. Annexstad   (Houston)
Meteorite concentration mechanisms in Antarctica (invited talk).

General Discussion: Future plans, coordination of effort, workshop report, etc.

Workshop Summary

Field Work and Observations

The workshop sessions began with descriptions of the search and recovery programs of meteorites by W. A. Cassidy and K. Yanai. Cassidy discussed the United States effort, which began in 1976 following the initial Japanese discovery in 1969. Yanai noted that the Yamato Mountains Meteorite Icefield, at over 4000 km^2, is the largest known "blue ice" field in Antarctica and has yielded over 5100 meteorite fragments. The Japanese search effort has achieved notable success by returning over 5600 meteorite fragments since 1969.

Cassidy estimates that, at the Allan Hills site alone, over 100,000 fragments should appear. He assumes a fall rate of 2–4 meteorites per km^2 per 10^6 years, with each fall producing 10 fragments over the period of 14 $\times$ 10^6 years (the length of time the Antarctic ice sheet is estimated to have existed). This number is far from the real case since, to date, only about 1000 fragments have been found by the Allan Hills search parties. To explain such a disparity, Cassidy suggests that the meteorite accumulation areas are transitory regions that are alternately flushed clean and that accumulate specimens by the action of a thinning and thickening ice sheet. These so-called stranding surfaces exist for relatively short periods of time and have varying degrees of maturity when compared with one another.

About 100 km from the Allan Hills ice field is another meteorite concentration area known as Elephant Moraine, which is located well away from any obvious flow-blocking mountain. If meteorites found in the Elephant Moraine region have younger terrestrial ages than those from the Allan Hills, then Cassidy would rate it as a younger stranding surface. The oldest type stranding surface would be known as a fossil unit, which would be produced by the flushing action of the expanded ice sheet and would appear somewhere downstream from present day sites. Although examples of stranding surfaces of varying maturity have been found, a fossil surface has yet to be discovered.

A more mature stranding surface should be one that has a large enough concentration of specimens to reflect the true abundances of meteorite classes. According to Cassidy, this cannot be done in Antarctica by comparing numbers of specimens to the world's collection because the Antarctic collections are all finds that inaccurately reflect the true numbers of meteorites. Therefore, he compares the weight percent of meteorite type found in Antarctica by U.S. parties to percent weight by type of world falls, and finds reasonable agreement. By this method he reasons that the stranding surfaces searched near the McMurdo area are relatively mature surfaces, i.e., they have existed for at least 10^5 years

The Yamato Meteorite Icefield, as described by Yanai, with its large surface area has yielded an enormous number of fragments in a few short years of searches. The entire region has not been completely searched, so it is expected to produce specimens for many years to come. This constant supply of meteorites is related to a mechanism of concentration suggested by Nagata (1978) which shows that specimens carried by the ice sheet tend to emerge and collect upstream of flow-blocking mountains and nunataks. This picture adequately describes, in a general sense, the concentration mechanism that appears to be operative in the Yamato and Allan Hills regions.

An alternative view to the accumulation picture presented by Yanai was shown by G. Delisle, who reported a find of 42 fragments near Frontier Mountain in North Victoria Land. These meteorites were discovered by the West-German Ganovex IV expedition of the Federal Institute for Geosciences and Natural Resources, Hannover, in the Austral summer 1984/85. The meteorites were found on a blue ice field located downstream of the mountain, and glaciologists suggest that the ice field is fairly young (200,000 years). The main ice flow today is around the flanks of the mountain so the find area exists as a small backwater. Delisle noted that ablation due to wind is very high in the area and the location of prominent dust bands indicates compressive surface flow. Radio echo soundings are interpreted to show that the

meteorites resided on an ice pool that has formed by the flow-blocking action of a subglacial rock fragment barrier. The meteorites found are H- and L-type chondrites of varying petrologic grade, which rules out the possibility of a common fall.

The suggestion by Cassidy that downstream stranding sites should exist is strengthened by the West German discovery in North Victoria Land. The location of such sites needs to be plotted and it is useful to know, if at present, there are downstream locations where the ice sheet is generally retreating. During the discussion period, Cassidy remarked that his team visited Pecora Escarpment in 1982/83 and they also found meteorites in a downstream ice field.

P. P. Sipiera reported analyses of black calcite clasts from Elephant Moraine. An attempt to detect their source locality from comparisons with Antarctic stromatolites did not yield any answers, but the author suggested that these interesting specimens may provide clues to an understanding of regional ice movement.

Meteorites and Ice

The glaciological picture was presented by D. Drewry, who referred to ice sheets as global storage facilities and slow moving conveyor belts for material. He noted that ice sheets deposit material into the Antarctic seas via huge drainage systems such as the Amery, Byrd and David glaciers. Looking closely at these systems, it can be seen that the known meteorite collection areas are located on their periphery. Drewry referred to the collection areas as stagnant interbasin regions of sluggish dynamics.

The ice streams and large basins that drain the ice sheet respond sensitively to the change in thickness of the ice sheet. As sensitive responders or regulators these basin regions may possibly buffer the small interbasin meteorite collection areas from all but the most extreme fluctuations. Hence, the slow operating concentration mechanism is preserved for long periods of time and the interbasin areas retain their character as insensitive responders to the climate fluctuations of the glacial and interglacial periods.

Drewry suggested an alternative to the Cassidy model of accumulation and flushing-out of specimens by a changing ice sheet. The Transantarctic Mountains have experienced uplift of significant proportions and this may be a partial cause of the existence of meteorite concentration areas. The normal seaward flow of ice would be disrupted by uplift and an inland migration of the ice would result in an accumulation of specimens of a limited terrestrial age. Paleo-stranding sites would also be left behind by the retreating ice sheet.

The importance of the terrestrial age of meteorites can hardly be emphasized enough because they can be used as proxy tracers of the ice sheet. Drewry suggested that if specimens of terrestrial ages greater than 125,000 years were found in central West Antarctica they would provide proof of the long-term stability of that region. Along with those data, it would also be useful to obtain determinations of meteorite fall (terrestrial source) regions, flow paths, and ice measurements of total gas and isotopic composition. A coordinated picture of the meteorites and their relationship to glaciological processes is certainly needed.

In conjunction with meteorite terrestrial ages, it is imperative to locate the origins of the ice and to determine the age of the ice in the meteorite concentration zones. H. Oeschger addressed these questions and suggested that the information from the concentration zone would provide answers on the ice flow pattern in a compressed form that could possibly be compared to a deep core from the interior of the ice sheet. As Oeschger pointed out, however, a sample of the ice from the ablation area would suffer severe distortions but this might be overcome by comparing information to known drill cores.

To adequately sample the ice relating to meteorite concentrations would require a multiphase field and laboratory investigation. A start would be to sample ice below the 2-meter depth within the main meteorite collection areas. These near surface samples would be measured for the stable isotopes

oxygen and hydrogen, total gas composition and concentration, chemical composition and cosmic-ray-produced isotopes like ^{14}C, ^{10}Be, ^{36}Cl, and ^{81}Kr. The next phase of the investigation would be to obtain an intermediate core from, an estimated, 100–400 meters depth a few kilometers inland of the ablation zone. The ice depth in these areas is presently unknown but the core should be drilled to bedrock so the main flow lines to the ablation area are intercepted. Laboratory analytical studies would be similar to those performed on the near surface samples.

As discussed by Oeschger, the near surface information may reflect the deeper bore hole profile and will help to establish the location of the flow lines into the ablation area. The present situation in the ablation area is complicated by the fact that the upwelling ice is probably overturned and folded during the emergent process. If a solid comparison is to be made, the next operational phase would be to sample, by surface methods, from the ablation area back into the accumulation zone. The analytical data from that analysis could be compared to data obtained by the French traverse and additional comparisons would be made to the information obtained from the deep cores at Dome C and Vostok. The use of O and H isotopic variations with depth, radioisotope determinations for age, reference horizons for climate levels and total gas for altitude studies would be useful comparisons.

Concentration Mechanisms

In a summary about blue ice fields and concentrations mechanisms, J. O. Annexstad pointed out the present state of knowledge of the program. Little quantitative data are available but many qualitative descriptions of blue ice and its relationship to the concentration of meteorites have been attempted. Therefore, some pictorial representations of the mechanism have been shown and popularized, but these may not show the true picture. A general mechanism may not reflect what occurs at all blue ice fields.

The physical descriptions of blue ice indicate that it occurs primarily inland, near mountains or nunataks, and is a long-term feature not subject to seasonal climate changes. Surface features of blue ice described by Annexstad are tensional cracks, rippled or whaleback-type forms and exposures of dust or tephra bands. Most of the blue ice found in Antarctica is upstream of the coastal mountains, although some can be found downstream as relict systems from previous glaciations.

In a discussion of the various models of meteorite concentration, Annexstad pointed out that they differ in estimates of the path length from meteorite fall to find. The longer path length models tend to fit the data presented from terrestrial ages of the meteorites, but the shorter models relate to implied subglacial obstructions and data.

As a conclusion, Annexstad noted that the present state of knowledge about the glaciological processes in Antarctic meteorites was sketchy at best. He suggested that additional work was needed to determine accumulation/ablation rates, surface flow parameters, flow lines within the ice sheet, subglacial features, isotopic ratios, and total gas content from ice cores.

Any quantitative model for the explanation of meteorite concentrations depends on the flux of infalling meteorites. This number is not well known although from measurements of cosmic dust particles extracted from Antarctic ice, K. Thiel has concluded that the infall rate of meteorites might be higher than previously adopted.

Weathering

J. L. Gooding introduced the audience to the phenomenon "weathering," which is very important for Antarctic meteorites because of their long residence time on Earth and their specific environment.

Weathering is a collection of processes that physically decompose rocks. It is connected with chemical alterations that result in addition or removal of mass. This process has many implications among which

the cosmochemical properties of meteorites as early solar system samples can be altered or even destroyed with many consequences for meteorite research. Such alterations can be seen in element fractionations and also in the disturbance of isotopic systems for dating purposes.

An example for element fractionation was given by G. Dreibus. She reported on halogen abundances in Antarctic meteorites. It was observed that iodine in some Antarctic eucrites is enriched by a factor of about 10^3 or more compared to eucrite falls. Also, an enrichment of chlorine, but not bromine, is observed. This overabundance of iodine, and to a lesser degree of chlorine, must be due to terrestrial contamination (= weathering) because neutron-produced ^{128}Xe is not observed in these eucrites. No correlation with the degree of weathering given in catalog descriptions is seen. Several possible sources for this contamination were discussed but, at the moment, it is unclear which process dominates the contamination.

M. E. Lipschutz also reported chemical alterations by weathering in ordinary chondrites. However, in most cases and for many elements, these effects are small and—with proper precautions—negligible. A careful study of weathering processes of Antarctic meteorites—which often yield secondary minerals—may give information about a contaminating medium, e.g., ice, and might be important for some glaciological problems in the Antarctic ice for a long time. This is a long-term experiment that cannot be duplicated but can be studied in the laboratory.

The difference in weathering of meteorites from more temperate latitudes and the Antarctic mainly involves liquid water. In Antarctic meteorites, water vapor condenses and causes leaching. Meteorites from other latitudes can be contaminated by liquid water solutions. Antarctic weathering processes seem not to be limited to the ice surface. Allan Hills 82102—just emerging from the ice—was already substantially rusted and contained gypsum crystals on the bottom surface.

The scale of weathering (as developed by JSC and also used by the Japanese Polar Institute) is based on the rustiness of the sample. This A-B-C classification is, however, only a very qualitative scale. A more quantitative base for the determination of the degree of weathering could be by spectrophotometric methods, or, as Lang pointed out, by thermoanalytical methods.

An observation that was interpreted as a weathering effect was reported by M. N. Rao. The Allan Hills meteorites 77215 and 77252 are "gas-rich." They are regolith breccias and contain—like lunar samples—large amounts of solar gases. The solar corpuscular radiation introduces noble gas ions into mineral surfaces. The solar wind particles are trapped in the outermost skin of the crystals, while solar flare particles, with their higher energies, penetrate deeper.

A comparison of neon isotopic ratios of these Allan Hills meteorites with mineral fractions of the gas-rich howardite fall, Kapoeta, that were etched in the laboratory yielded very similar results. This similarity was interpreted as the loss of surface material from mineral grains of Antarctic meteorites due to weathering. This "etching by weathering" removes the solar wind gases and leaves the solar flare particles that are trapped in deeper locations. Similar observations, however, are made on non-Antarctic meteorites.

Interesting weathering effects are also seen on iron meteorites. R. S. Clarke, Jr. reported on the special exteriors of some Antarctic iron meteorites. The Widmanstatten patterns of these meteorites are revealed by weathering because taenite erodes less than the softer kamacite.

Weathering is also used for the interpretation of terrestrial ages of Allan Hills meteorites. L. Schultz explained the exponential decrease of terrestrial ages of these meteorites by the decomposition of rocks sitting on the ice surface. This interpretation leads to a destruction half-life of about 1.6×10^5 years, which is about a factor of 40 longer than in more moderate climates.

Terrestrial Ages of Antarctic Meteorites and Ages of Ice

The length of time a meteorite spends on Earth is called its terrestrial age. In temperate latitudes the maximum terrestrial age can be short and depends on the weathering conditions and the kind of

meteorite. Under Antarctic conditions (most of the time no liquid water is available) weathering is retarded compared to more moderate climates and, therefore, terrestrial ages of Antarctic meteorites tend to be longer than those of non-Antarctic stones.

K. Nishiizumi summarized knowledge of terrestrial ages of meteorites and reported new results. Terrestrial ages were also discussed in the talks of K. Kigoshi, U. Krähenbühl, L. Schultz, and S. Vogt. These ages, calculated from various cosmic-ray-produced radionuclides, cover a certain time span: ^{14}C: 2×10^3 to 3×10^4 years; ^{81}Kr: 7×10^4 to 5×10^5 yrs; ^{36}Cl: 1×10^5 to 3×10^6 yrs; ^{26}Al: 3×10^5 to 5×10^6 yrs. In the future, ^{41}Ca may fill the gap between ^{14}C and ^{81}Kr.

For Antarctic meteorites a number of observations have been made, and can be summarized as follows:
- Terrestrial ages of Antarctic stone meteorites range up to about 7×10^5 yrs. and may be even longer.
- Distributions of terrestrial ages vary for different find localities (e.g., Yamato Mountains meteorites are younger than those from the Allan Hills).
- No correlation is observed between terrestrial age and the A-B-C-degree of weathering.
- Among stony meteorites, only L-group chondrites have ages greater than 4×10^4 yrs.
- Antarctic iron meteorites found on non-ice covered areas have high terrestrial ages (Lazarev: 3×10^6 yrs; Derrick Peak: 1×10^6 yrs.)
- For Allan Hills meteorites, Nishiizumi finds some correlation between find location and terrestrial age. He suggests that meteorites found close to the Allan Hills tend to have longer ages than those found farther away.
- The new finds from Frontier Mountain have long terrestrial ages.

Schultz interpreted the terrestrial age distribution of Allan Hills meteorites. This distribution can be explained by direct falls and transported meteorites. Weathering (decomposition) is the main sink for meteorites while they are exposed on the ice surface.

The transport time within the ice from fall to emergent zone is about 1.5×10^5 yrs and the ratio of direct falls to transported meteorites is about 1. The relatively young terrestrial ages of Yamato meteorites indicate a different collecting mechanism.

Nishiizumi reported very interesting measurements concerning the ages of ice and surface exposure ages of terrestrial rocks. The ages of ice are based on ^{36}Cl/^{10}Be ratios measured in young ice samples and in blue ice. For the Allan Hills, values of 3 to 6×10^5 yrs were obtained; Yamato ice has an age of about 3×10^5 yrs. This new method of determining absolute ages of ice may have applications for glaciological problems.

Another application is the dating of samples exposed to cosmic rays on the Earth's surface. A quartzite sample taken from the top of the Allan Hills indicates that this rock was exposed to about 1×10^6 yrs and the erosion rate was about $1 \text{ cm}/10^5$ yrs.

Unique or Rare Meteorite Types

It is assumed that the number of meteorite fragments from a single fall in the Antarctic is 4 ± 2. Thus, the 7000 specimens found to date represent about 1200–3500 individual falls. This number is similar to the number of non-Antarctic meteorites. Therefore, it can be expected that hitherto rare or even unknown meteorite types may be among the Antarctic meteorite collection. However, the true number of fragments per fall is not known, but D.W.G. Sears reported applications of thermoluminescence techniques to Antarctic meteorites which may also allow the detection of paired samples.

One of the great surprises was the discovery of lunar meteorites. These rocks were discussed by H. Palme, U. Krähenbühl, and K. Yanai. The known lunar meteorites are: Allan Hills 81005 (31.4 gms); Yamato 791197 (52.4 gms) and Yamato 82192 (36.7 gms). A comparison of observations and analyses of

these stones with those of lunar highland breccias show such a remarkable agreement that the general consensus is for a lunar origin.

ALH81005 and Y791197 were objects of intense scientific investigations in consortia mode. Both rocks show differences in irradiation parameters, chemical composition and petrographic observations; however, it cannot be excluded completely that both rocks were ejected from the Moon by the same impact event.

The KREEP component in these rocks is rather low and is indicative that both stones come from the lunar farside. Hence, these unique meteorites provide an opportunity to learn more about lunar geochemistry and to answer questions about the origin and history of the Moon.

Another exciting topic and recently widely discussed problem in cosmochemistry was prompted by the shergottite Elephant Moraine 79001. This rock and Allan Hills 77005 contain information that indicates an origin from the planet Mars. Together with other SNC meteorites (from Shergotty, Nakhla and Chassigny), these stones are the subjects of intense scientific investigations.

Members of another differentiated parent body are the eucrites, howardites, and diogenites. H. Takeda reported on this achondrite family and the reconstruction of their parent body. Figure 2 shows the Ca content as a function of the Mg concentration of this meteorite group. The Antarctic meteorites from Elephant Moraine and the Yamato Mountains provide links between these three groups. Yamato 75032 is transitional between the diogenites and the howardites and the Elephant Moraine polymict eucrites are compositionally intermediate between the eucrite and howardite fields.

Another rare group of meteorites are the ureilites. Prior to the Antarctic meteorite discoveries, there were only eight known members of this group; now the number is increased to 25. The origin of these
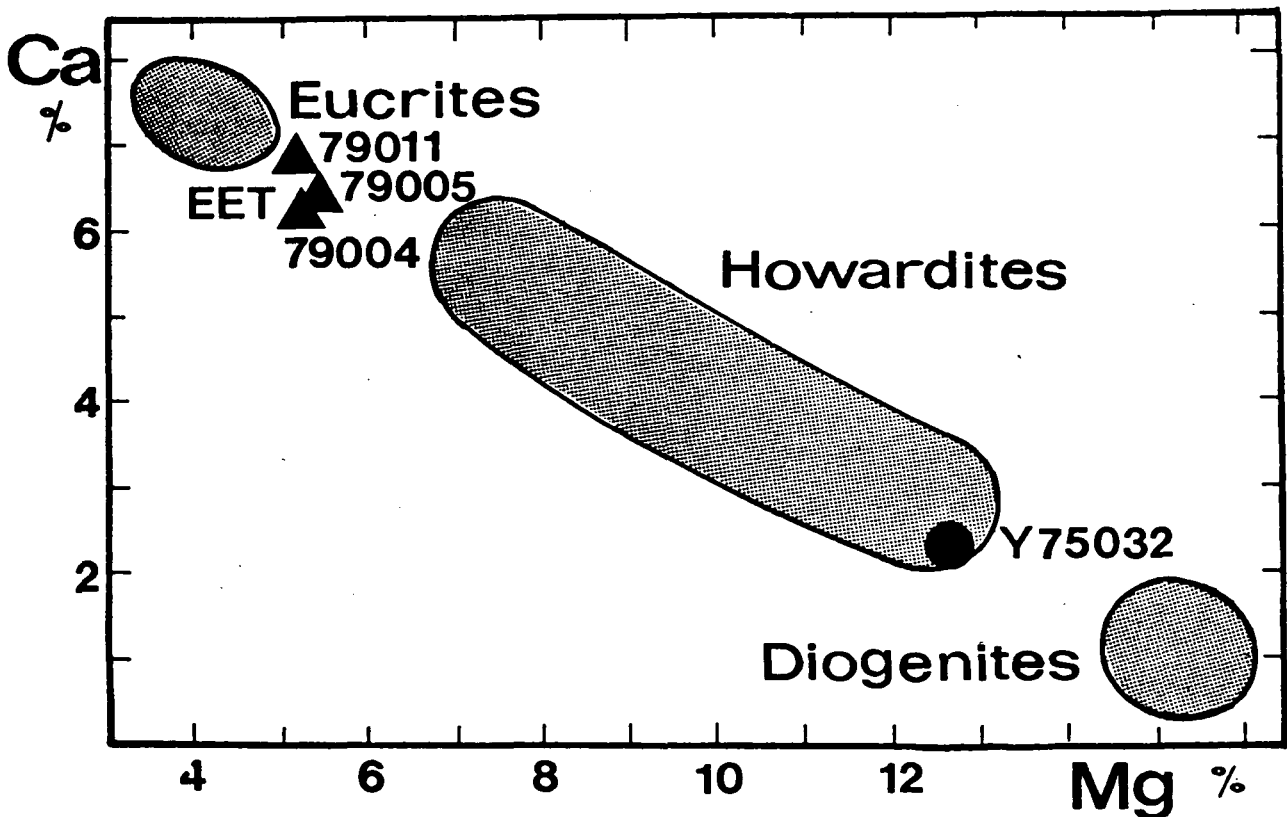

Fig. 2: Ca-Mg-plot for eucrites, howardites and diogenites. Antarctic meteorites provide links between the members of this family.

meteorites is an enigma among all meteorite groups. Further studies are needed to unravel their origin and details of their complex history. The new Antarctic ureilites—some compositionally different from others—are valuable specimens for this purpose.

The only known olivine-pyroxene-stony-iron meteorite, Lodran, is now accompanied by a similar 30-gram specimen from Yamato. The list of meteorites of great scientific interest can be extended. Because of the smaller masses of Antarctic meteorites (small specimens get lost in vegetation and among normal terrestrial stones in non-Antarctic regions) irradiation effects can be studied that involve the outermost part of meteorites, which is ablated in the atmosphere for larger ones.

Are Antarctic and non-Antarctic Meteorites Different Compositionally?

This important question was raised during the workshop several times, and discussed in detail by Lipschutz and Takeda. The large number of rare meteorite classes would suggest a difference; however, pairing of Antarctic meteorites is a serious problem that can be solved only with much more investigation. Nevertheless, the number of Antarctic meteorites with unusual textures within a given class appears to be larger than in non-Antarctic meteorites. For example, all Yamato diogenites are different from other diogenites.

As pointed out by Clarke, twenty-one different iron meteorites have been found in the Antarctic. For non-Antarctic meteorite falls, about 5% are irons. This percentage would yield a total of 410 Antarctic meteorite falls. This number is much lower than that calculated from the number of finds and an assumed number of 2–6 fragments per fall. Thus, iron meteorites seem to be underrepresented in the Antarctic collection. Also, different numbers are obtained for ordinary chondrites. The ratio of H-group chondrites to L-group chondrites is about 3, while a number of about 1 is observed in non-Antarctic stones of the same kind as pointed out by Lipschutz.

Lipschutz investigated the difference in trace element composition between Antarctic and non-Antarctic chondrites. Thirteen trace elements were measured in 23 Antarctic and 20 non-Antarctic L-5 chondrites. In both groups, the distribution of concentrations for 8 elements differs significantly, indicating that for L- and H-group chondrites, sample populations of each group differ in composition. This question was also discussed earlier by Cassidy.

Possible explanations for this effect were offered: Polar regions may sample meteorites that have more inclined orbits than those that fall in non-polar regions and furthermore, temporal variations of meteorite fluxes of individual classes could cause differences if the Antarctic contains older meteorites.

During the discussion questions concerning weathering, pairing and statistical arguments were discussed. Monte Carlo calculations of asteroid debris do not strongly select meteorites with different orbits and the terrestrial ages of Antarctic meteorites are still short compared to their exposure ages. It was also mentioned that the detection of smaller meteorites in the Antarctic may cause a selection effect if small samples come from different sources than large ones.

Summary of Discussion

At the end of the workshop a general discussion was held that concentrated on open questions and future work.

Many participants of the workshop are meteorite "users," i.e., scientists mainly interested in obtaining more objects for laboratory study. However, during the discussion it became obvious that the limited resources for Antarctic work should not only be used for meteorite searches. The interrelationship between meteorites and the Antarctic suggests that these samples can also be used to study the ice sheet, e.g., the dynamics of the ice can give information about climate changes during the last million years.

Intense study of Antarctic meteorites may lead to new techniques that have applications in other research areas. This is demonstrated by the new dating techniques of Antarctic ice.

To understand the phenomenon "Antarctic meteorites," a number of additional measurements are necessary. There is a need for the measurement and determination of accumulation and ablation rates, surface flow parameters, and sub-glacial topography of the ice sheet. Additional laboratory investigations of isotopic studies (oxygen, hydrogen) of ice samples are needed and the effects of weathering of meteorites under Antarctic climatic conditions should be studied. Furthermore, cosmogenic nuclide measurements leading to terrestrial ages or to the detection of pairings of meteorites are of importance.

The importance of wind transported meteorites for mass fractionation was discussed. Experiments with rocks of different mass on the ice field of the Allan Hills could give answers to this question in the future.

Part of the discussion was directed to the collection of cosmic dust and very small meteorites. Dust collectors are in operation and Antarctic ice also serves as a tracer for cosmic dust particles. Small meteorites may be found in melt scoops of large rocks sitting on the ice.

In the near future several countries plan to conduct meteorite search expeditions. The USA and Japan will continue to search for new areas of meteorite concentrations. India plans to look for meteorites around the Wohlthat range and West Germany around the Shackleton range. Also, South Africa, Norway, and Australia may, in connection with other Antarctic research, pay special attention to meteorites.

It was also mentioned that many polar scientists are not aware of Antarctic meteorites and their scientific significance to the planetary community. With the help of SCAR and the Meteoritical Society, a coordinated effort of search, recovery and distribution is recommended.

Recommendations

The Antarctic Meteorite Programs at this point have reached different degrees of development of maturity. The workshop consisted of scientists from different countries and different interests and a good picture was received of the actual needs for future work. The convener of this workshop therefore, decided to summarize possible activities that should be carried out during the next years.

Meteorite Search and Recovery

The great success of this portion of the program is best shown in Figure 1 and Table 1 where the locations and numbers of these finds are illustrated. These meteorites form a solid base for meteorite research and all its implications for better understanding of the early solar system and its history. It has also been shown that some "key meteorites" like the lunar meteorites and those possibly originating from Mars, initiate new and exciting ideas. It is, therefore, recommended that the search for meteorites in Antarctica must continue and include the recovery of very small meteorites and cosmic dust.

Recent reports from other nations suggest that, in future years, others will join Japan and the U.S.A. in conducting searches for meteorites in Antarctica. It would be very valuable if these expeditions could be coordinated. The Meteoritical Society and/or SCAR should be notified about all activities in this direction and interested parties should be able to obtain information from these bodies.

Meteorite Curation and Distribution

The scientific value of Antarctic meteorites is greatly enhanced if these rocks are made available for scientific investigation soon after collection. This is the case for meteorites from Japanese and U.S. expeditions and it is recommended that other nations develop similar procedures for their Antarctic meteorite finds. This includes also a preliminary description of meteorites and the possibility that these samples are made available to specialized laboratories.

Meteorites and Antarctica

The facet of the entire program that received the least attention is the so-called "cosmic connection" between meteorites and Antarctic processes. Since Antarctica is a dynamic system that appears to collect, preserve, transport, and concentrate specimens, it plays an important role in the process. Some preliminary measurements of ice movement have been made and a few theories of concentration mechanisms presented. To date these efforts have been largely subjective and so the processes involved are poorly understood. Attempts have been made to expand this work in a concerted form, but the efforts have been largely unsuccessful.

It is recommended that the following lines of research should be objects of special attention:

1. The relationship to current models of meteorite concentration of a combination of ice movement and ablation, and terrestrial ages of meteorites.

2. Weathering processes of Antarctic meteorites and their influences on destruction and degradation of meteorites.

3. Detailed studies of ice fields with high meteorite concentrations including the determination of bedrock topography, ice coring and the investigation of selected isotopes and total gas content of ice by modern laboratory techniques.

4. Methods for dating old ice should be developed further. The possibility of absolute dating of ice opens many new applications for Antarctic glaciology. This also includes the dating of surface exposure of Antarctic rocks.

Communications

Meteorite research is an interdisciplinary science that is integrated through the journals and activities of the Meteoritical Society. Unfortunately, many Antarctic geologists and glaciologists are poorly informed about the field of meteoritics and its possibilities for integrative studies with polar processes. It is also true that a complete understanding of the meteorite concentration mechanism is impossible without an extensive knowledge of ice sheet parameters. It is recommended that communications between these two groups be improved by holding regular workshops and meetings of interested scientists for the purpose of exchanging ideas and presenting new information. Increased contact between meteoriticists and polar scientists can only enhance the possible use of meteorites as tracers of motion within ice sheets and as sensitive markers of time.

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ABSTRACTS

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METEORITE CONCENTRATION MECHANISMS IN ANTARCTICA
by John O. Annexstad
NASA/Johnson Space Center
Houston, Texas 77058

Introduction   The location of most Antarctic meteorite finds has been on stagnant, highly ablative surfaces known as "blue ice." A few fragments, mainly irons, have been discovered on mountain sides and within moraine fields but these finds are exceptions to the rule. The role of "blue ice" is that of transporter, concentrator and preserver of specimens from the time of fall until find. The actual processes involved in this role are imperfectly understood at present but a basic theory of the mechanism of concentration can be proposed from the ideas suggested by various researchers.

Blue Ice   Blue ice is formed by the compression of$_3$sucessive layers of snow accumulation when the density reaches 830 kg/m^3 (60 to 100 m depth in Antarctica) and the air spaces between the grains are closed off. This high density ice reaches the surface when sub-glacial peaks or mountains and nunataks force the moving ice sheet upward. In general, surface blue ice is found near coastal mountains, moves very slowly if at all and is presumed to be quite old.

Physical descriptions of blue ice fields have been reported [1], [2], [3], [4]. All authors reported that the blue ice fields were regions of high ablation, of little or no surface melting and of high and rather constant wind velocities. Other features characteristic of surface blue ice fields are:

Surface cracks – small crack systems 1 to 5 mm wide interlace the surface ice and are oriented along and perpendicular to the direction of surface motion. The cracks are presumed to be tension features which contract and expand with changing air temperature. Whaleback forms – the ice surface is rippled or cupped in areas exposed constantly to the prevailing winds. This feature is elongated in the direction of wind motion, protrudes 5 to 10 cms above the surface and is separated from an adjacent cup by about 20 cms. Flow line streaks – surface bands of tephra or dust extend in a parabolic curve across blue ice fields. The bands are easily seen from the air. Moraines – medial and terminal moraines such as boulder fields and/or elongated strips of detritus related to nearby outcrops are commonly seen near the regions of highest ablation. Step features – these are ice cliffs produced by a sub-glacial obstruction (monocline) or the retarded motion of the ice sheet (compressive) that tend to be located upstream from the stagnant portions of the ice field. These features are quite often synonymous with large concentrations of meteorite specimens.

Concentration of Meteorities by Blue Ice – Hypotheses
Yanai-Nagata Model   They [5], [6] discussed the concentration of meteorites found near the Yamato Mountains and concluded in their papers that transport by ice flow was the most plausible mechanism. Their model predicts that meteorites which fall in an accumulation area become an integral part of the ice sheet and are eventually transported along flow lines to the coastal regions of Antarctica. As the flowing ice reaches a mountain barrier which impedes forward progress the ice tends to flow upward (upwells) in a region where ablation removes the emerging ice. Meteorites entrapped within the ice are eventually exposed by ablation and remain uncovered on the ice surface.

This model assumes a steady state condition in the concentration area where the emerging ice is continuously scraped away by the ablation process at an equal rate. One author [6] suggested a rather long path length from the accumulation zone to the ablation zone and predicted that most meteorites fell at least 10^4 -10^5 years ago.

Nishio et al. Model The ice taken from a borehole (8 meter) near the geographical center of the Allan Hills Icefield was examined petrographically [7]. The age of the ice was estimated at 20,000 yrs by using accumulation and uplift rates and the growth rate of grains in the samples. This model suggests that meteorites fell in an area within 25-40 km upstream of the concentration zone between 20 and 100×10^3 years B.P. The specimens were then transported slowly in submerged ice to a stagnant blue ice area which was produced by the barrier effect of the Allan Hills.

To explain the existence of large numbers of meteorites and the old terrestrial ages, the authors proposed that: 1 - during the last ice age the catchment (accumulation) area was expanded greatly and meteorites which fell during this time are still emerging in the concentration zone, 2 - the maximum terrestrial age of the meteorites could be an indicator of the time when the ice sheet covering the Allan Hills began to recede.

This model is based upon an estimated depth of the depositional ice between 500 and 1000 meters. The path length of meteorite travel within the ice is very short, but it does agree with their estimated age of the ice.

Whillans-Cassidy Model This model [8] employs standard glaciological considerations in the hypothesis and predicts that the exposed ice in the concentration zone must be very old.

Meteorites that fall onto the ice sheet are incorporated into the ice and normally carried to the sea without being concentrated. In special places, the ice is prevented from reaching the sea, ablates away at the surface, thereby exposing the contained meteorites. A characteristic of such ablation zones is compressive ice flow which helps to concentrate the specimens.

The rate of surface concentration of meteorites (M) is represented by

$$\frac{dM}{dt} = \gamma A_b + f - \dot{\epsilon}_s M$$

where γ = rate of reappearance of meteorites which fell in the accumulattion area at the ablation zone

A_b = rate of ice loss in the ablation zone, f = direct meteorite falls in the ablation zone, $\dot{\epsilon}_s$ = sum of the two horizontal strain rates (a negative quantity). This model assumes a steady state condition between the meteorite infall rate and snow accumulation and that meteorites are concentrated by steady ice sheet flow and that ice mass is lost through evaporative sublimation in the ablation zone. The authors predict that the ice in the ablation zone can be as old as 600×10^3 years, that the older meteorites (terrestrial age) are found nearer the snout of the glacier and the flowline is hundreds of kilometers long. The combination of catchment area size and meteorite infall calculations predicts accurately the number of specimens found in the Allan Hills Icefield.

Annexstad-Schultz Model In this model [9] meteorites which fall upon the Antarctic ice sheet are incorporated into the ice and transported along flow lines toward coastal areas. In a region like the Allan Hills Icefield where the seaward motion of the ice sheet is blocked from further movement, the encased meteorites are brought to the surface with the emerging ice and

uncovered by the ablation process. Meteorites do not emerge only in the concentration zone, but anywhere between the snout of the glacier and the equilibrium line. The emergence zone can be many kilometers long and is produced by ice flowing over a subglacial obstruction, which causes uplift, and the flow blocking action of a mountain or nunatak. The emerging meteorites are transported by horizontal compressive movement toward the concentration zone where they are joined by direct falls on the ice surface. The time it takes for the meteorite to move from its emergent location to the concentration area is short in comparison to its terrestrial age.

State of Knowledge The hypotheses presented all agree on a basic theory of "blue ice" as a transport and concentration mechanism but they differ on the path length between accumulation and ablation zones. The path length will have a definite bearing on the terrestrial residence age of a specimen which falls in the accumulation area. Weathering as the main destructive force of a meteorite proceeds at a much faster rate if the specimen is exposed on the surface than if the specimen is encased within the ice.

The Annexstad-Schultz model uses quantitative data based upon surface ice movement and ablation measurements from the Allan Hills triangulation network [10]. The other hypotheses are generally based upon qualitative assumptions derived from general ice flow considerations and visual observations. Before a complete picture of the concentration of meteorites by the moving ice sheet can be derived the following data must be obtained:

Accumulation/ablation rates from the source region and the find area.

Surface flow parameters including accurate strain rates and vertical emergence/submergence data.

Sub-glacial topographic features from the source region to the find area.

Oxygen/hydrogen isotopic ratios from ice cores along the path length.

Weathering rates of meteorites showing the ice encased time and the surface exposure time.

Terrestrial residence ages of all found specimens as a function of find location.

From the data presented to date the hypotheses can be condensed to the statement: Meteorites that fall upon the Antarctic ice sheet are transported within the sheet along flow lines to emergent zones of high ablation. The uncovered specimens are transported by horizontal surface movement of the ice sheet to stranding zones produced by the retardation effect of a mountain or nunatak.

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METEORITES AND THE ANTARCTIC ICE SHEET; W. A. Cassidy, Department
of Geology and Planetary Science, University of Pittsburgh, PA 15260.

The United States Antarctic Meteorite Program was begun in 1976, in
collaboration with the Japan National Institute of Polar Research. It began
as a direct outgrowth of the original Japanese discovery of nine meteorites
on a small part of a large ice field near the Queen Fabiola (Yamato)
Mountains (1,2). The first two specimens during that first field season
were found by Keizo Yanai, on a small patch of ice between Mts. Baldr and
Fleming, during our first 25 minutes in the field. For the next six weeks
we worked steadily northward along the margin of the East Antarctica ice
plateau, finding nothing until we reached a patch of exposed ice on the
plateau side of the Allan Hills, where we found forty-three specimens during
two brief helicopter-assisted searches (3). Over the succeeding eight field
seasons the Allan Hills site has supplied the majority of specimens recover-
ed in the U.S. program. Other major concentrations have been located,
however, namely at Elephant Moraine and in the Thiel Mountains - Pecora
Escarpment region (4).

Our ideas on the types of surface where meteorites occur have under-
gone a degree of evolution since 1976. Beginning with the idea that
meteorites only can be stranded on ice surfaces that are completely stagnant
due to the impoundment of ice behind an impassible barrier we later included
ice surfaces located at sites where ice flow is not completely halted, but
only slowed down. In addition, important concentrations of meteorites have
been found in some moraines located downstream of rocky barriers; the
significance of the morainal occurrences has not yet been evaluated.

The abstract of the original research proposal for the first year of
the U.S. program read in part as follows: "Identification of areas where
meteorites have been concentrated in Antarctica can provide new meteoritic
material for study, may lead to collection of rarer meteorite types that
are better preserved under Antarctic conditions, may permit better esti-
mates of average meteorite composition, may lead to information on relative
ages of Antarctic ice masses, and may result in discovery of previously
unknown types of meteorites. They could also be areas where lunar ejecta
have been concentrated." During the period of the U.S. program and the
concurrent Japanese program it has been demonstrated that all the expected
results involving the recovery of rare or previously unknown types of meteo-
rites, and even recovery of lunar ejecta, have been realized. The relation
between these remarkable concentrations of meteorites and the Antarctic ice
sheet itself has been documented less well: ice flow vector studies have
been made (5-11) and concentration models have been proposed (12-14),
however in many cases we still do not understand why meteorites are found at
one site and not at another. There is some evidence (15) suggesting that
meteorites are held at concentration sites only for relatively short periods
of time, of the order of the periods involved in climate changes, but this
is somewhat speculative.

A useful term to describe a surface on which we find a concentration
of meteorites is stranding surface. It is useful also to think of strand-
ing surfaces in terms of their degrees of maturity because this may be
quantifiable and, if so, would allow us to compare stranding surfaces in
order to decide, for an individual surface, how representative of the
meteorite flux in space will be the suite of specimens collected there. A
mature concentration of meteorites is defined as a concentration whose

numbers are large enough to reflect the true abundances of meteorites in space, as modified by atmospheric entry processes.

Earlier estimates of the abundances of meteorite types have been based on numbers of falls in the world's collections, with each fall being counted as one regardless of its relative mass. Although fundamentally flawed, this method has been useful because it does not require that the total fall, which may be an extensive shower, be recovered and weighed. In dealing with the problem of determining the relative abundances of different types of meteorites on a stranding surface it is more useful to think in terms of relative masses of the various types than in terms of relative numbers of individual specimens; this is because there are serious problems with pairing individuals at a given site. Reliance on total recovered masses of all meteorite types may in fact give a more reliable estimate of the meteorite flux in space because the Antarctic accumulations have been integrated over longer periods of time (16); more complete collections of shower individuals probably are possible in Antarctica because of the absence of surface clutter; and the fact that the smallest individuals, which are most likely to be overlooked even in Antarctica, contribute the least mass. Thus, data have been accumulating, and will accumulate during future field seasons, that will allow more reliable estimates of the source region of most meteorites.

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ANTARCTIC IRON METEORITES: AN UNEXPECTEDLY HIGH PROPORTION OF
FALLS OF UNUSUAL INTEREST: Roy S. Clarke, Jr., Division of Meteorites,
Smithsonian Institution, Washington, D.C. 20560, U.S.A.

The inhabited and explored areas of Earth have contributed 725 iron
meteorites to our collections, accounting for 28% of the 2611 authenticated
meteorites known of all types. This percentage is known to be weighted in
favor of iron meteorites over other types if frequency of fall is
considered. Their greater resistance to weathering and the higher proba-
bility of recognition of irons after long residence times on the ground is
responsible. Observed fall statistics give a much different view of relative
abundance. The 42 historic iron meteorite falls spanning 230 years suggests
a frequency of one fall per 5.6 years and represents only 4.9% of the total
853 known falls. For statistical purposes, 42 is a small number when
compared either to the total number of falls or to the 14 recognized iron
meteorite classification groups. Estimates, therefore, of either the
relative abundance of iron meteorite falls or of the relative frequencies of
falls of various iron meteorite types must be considered as unsatisfactory
approximations. The numbers used herein for non-Antarctic meteorites were
taken from the recent summary of such data in the "Catalogue of Meteorites"
by A.L. Graham, A.W.R. Bevan and R. Hutchison (1985).
Antarctic iron meteorite recoveries offer promise of providing a new
perspective on these aspects of the influx problem. Neither ease of
recognition nor resistance to weathering seem to have the same importance
for Antarctic recoveries as they do for other environments that have produced
meteorites. Small meteorites are recognized on the ice almost as readily as
large ones. The weathering of Antarctic irons seems to be restricted mainly
to exterior surfaces and to penetration along major grain boundaries.
Although these meteorites may have had long terrestrial residence times
compared to non-Antarctic irons, no really severely internally weathered
irons have yet been recovered. The pairing problem is, of course, severe in
Antarctica, but it may prove to be less severe for irons than for stones.
At least 42 iron meteorite specimens have been found during the last 25
years by various field teams working in Antarctica. Most of these specimens
have not been described in detail, but the available data indicates that 21
separate falls are represented, 50% of the number of recovered specimens.
Twelve of these falls have been both structurally classified and placed into
chemical groups. On the basis of incomplete data, 8 of them appear to be
anomalous, not to fit into one of the defined chemical classification groups.
This leads to an interesting comparison with non-Antarctic recoveries.
Meteorites of the three most common iron meteorite types (IAB, IIIAB and IVA)
comprise 50% of finds, 40% of falls, and 33% of Antarctic irons. Anomalous
meteorites comprise 11% of finds, 12% of falls, and 38% of Antarctic irons.
This may be an indication that the Antarctic recovery area produces a more
representative proportion of small and compositionally unusual iron meteor-
ites. The 21 separate iron meteorite falls may also be extrapolated using
available fall statistics to suggest that a total of 430 meteorite falls have
occurred in areas that have provided meteorites to the collecting sites.
This is a crude figure that seems to be consistent with what is known of
stony and stony iron meteorite recoveries and pairing.
Twelve of the 21 falls have been both structurally classified and placed
into chemical groups. They are listed in order of increasing structural
complexity and/or Ni content. The hexahedrites (IIA) are represented by

ANTARCTIC IRON METEORITES

Roy S. Clarke, Jr.

Yamato-75105, Allan Hills A78100, and ALHA81013; coarsest octahedrites (IIB) Derrick Peak A78001* and Elephant Moraine 83245; coarse octahedrites (IA) by Neptune Mountains (1964), ALHA76002*, ALHA77283, Purgatory Peak A77006; medium octahedrites (IIIA) by Y-790724 and Reckling Peak A80226; and the fine octahedrite (IVA) by ALHA78252.

Anomalous and/or ungrouped meteorites are: the medium octahedrite Lazarev (1961); the fine octahedrite ALHA81014; the plessitic octahedrites Y-75031* and ALHA80104; the axatites ALHA77255 (12% Ni), EET83230 ($\sim$15% Ni), Inland Forts 83500 ($\sim$20% Ni), and Y-791694 ($\sim$36% Ni). The meteorite Y-790517 is severely reheated.

*Indicates paired meteorites: DRPA78001 is paired with DRPA78002 through DRPA78016; ALHA76002 is paired with ALHA77250, ALHA77263, ALHA77389 and ALHA77290; Y-75105 is tentatively paired with Y-791076.

Discovery of Meteorites on a Blue-Ice Field near the Frontier
Mountains, North Victoria Land, Antarctica

G. Delisle, H.-C. Höfle, R. Thierbach, Federal Institute for
Geosciences and Natural Resources, 3000 Hannover, FRG
L. Schultz, Max Planck Institute for Chemistry, 6500 Mainz, FRG

Members of the West German GANOVEX IV expedition 1984/85 (German
Antarctic North Victoria Land Expedition) discovered a high con-
centration of meteorites on a blue-ice field northeast of the
Frontier Mountains. As a result of a systematic search, a total
of 42 meteorites were discovered.

The Frontier Mountains pierce the polar ice sheet over a length
of approximately 8 km with a NW-SE trend. Glacial flow from the
polar regions approaches from WSW, flowing around the mountain
range at both ends (Figure 1). Due to the barrier function of
the range, the ice surface to the southwest is higher than in
the northeast by an estimated 200 m. Large areas of crevasses
caused by the stepwise descent of the ice sheet occur at both
ends of the Frontier Mountains. A blue-ice field has formed on
the lee side of the range, characterized by high rates of subli-
mation and abrasion due to frequent strong catabatic and foehn
winds, as well as compressive ice flow, as evident from the oc-
currence of numerous dust bands.

The crevasse pattern outside the valley is obviously controlled
by the flow pattern of the ice masses around the Frontier Mts.
Meter-wide crevasses run parallel to the trend of the Frontier
Mts. in zones in which the elevation rapidly decreases. Past
the range to the E, the crevasse orientation swings gradually
from NW-SE to SW-NE, while crevasse widths decrease to a few cm.
Noteworthy are the surprisingly deep depressions in the blue
ice, reflecting changes in elevation by more than 100 m (esti-
mated).

The current glacial situation has evolved through various stages.
By the orientation of grooves and striae on bedrock at various
levels of elevation, at least three different stages of glacia-
tion characterized by different ice-flow directions can be di-
stinguished:

- Grooves only at the highest points of the range were formed by
  an SSE-NNW trending ice-flow (long arrows in Fig. 1). In ana-

logy to glaciological observations in the Dry Valleys, we assume an Upper Miocene age for this episode.
- A lowering of the ice surface of the polar ice sheet (Pliocene?) resulted in a change of the flow direction toward SW-NE (medium size arrows in Fig. 1).
- A further reduction of surface elevation of the polar ice sheet exposed the Frontier Mountains to a large extent. Now, glacial flow controlled by topography prevails (short arrows in Fig. 1).

Today, the following situation has evolved:

The greatest depression in the blue-ice field to the E of the range occurs in a valley an the southeastern end of the Frontier Mountains. The valley serves as a preferred channel for catabatic and foehn winds that are the cause of the locally high degree of sublimation and abrasion. The mass losses are counteracted by blue-ice moving into the valley from the east (nearly opposite of the regional flow direction).

The thickness of the blue ice was measured with a radio echo sounding instrument (RES) along the profile A-B (see Fig. 1) parallel to the long axis of the valley. From the 0 to 300 m mark, a complicated reflection pattern was observed for depths of more than 150 m indicative of an irregular subsurface pattern at the interface ice-bedrock. Reflections from this interface are indicated in Figure 2a as bars. Dots represent reflections from a non-horizontal surface.

The interpretation of the available RES-data is depicted in Figure 2b. A local glacier entering the western end of the valley apparently sustains at its bottom a ground moraine judging from the extensive reflection pattern for depths below the first major reflection. The side reflections (dots in Fig 2a) are apparently caused by a buried lateral moraine at the glacier front. No evidence, however, is seen at the ice surface. The pressure on the lateral moraine is balanced by the inflowing blue-ice from the E. RES-measurements on the blue-ice in general yield a less complicated reflection pattern past the first major reflection indicative of a smoother ice-bedrock interface.

An obvious connection of the reflectors with steeply dipping dust bands, trending almost perpendicularly to the long axis of the

valley, was not detected. The lateral separation of these dust bands, slightly parabolic, ranged from a few dm to about 30 m.

The highest concentration of meteorites were found within an area of 300 m by 1 500 m within the valley. With reference to profile A-B, most meteorites were found between the 600 m to 900 m marks (see Fig. 2).

The largest meteorite, about 14 cm long, was discovered about 3 km ESE of the entrance to the valley. The blue ice there is very sparcely covered by wind-blown rock fragments of local origin.

The main discovery site, is covered by an almost unbroken veneer of rock fragments. Trending from W to E, the size of the rock fragments increases steadily from pebble size to boulders with diameters in excess of 3 m. The latter are on top of an ice ridge at the E-entrance to the valley (identical with point B of Fig. 2), surrounded by a rock veneer several cm thick.

The total weight of the recovered meteorites is 1.2 kg, however, only 7 specimens have masses larger than 10 g. The specimens from the main discovery site are moderately weathered; cuts through the specimens show brown limonitic staining throughout, but most of the metal has been preserved. Preliminary mineralogical investigations of the larger specimens show that these meteorites belong to different petrological and chemical types of H- and L-group chondrites. Noble gas and ^{10}Be analyses of 7 meteorites yield different records of irridation which exclude pairing of these investigated samples. Two H-group chondrites - FRO 8405 (H3) and FRO 8409 (H4) - contain large amounts of solar trapped gases (^{4}He: 1.8×10^{-3} ccSTP/g). A brecciation, however, is not visible in hand specimens because the brown staining obscures any primary structure.

^{26}Al has been measured in 4 of these meteorites. FRO 8403, an H6 chondrite with a ^{21}Ne-exposure age of about 5 million years, has a ^{26}Al-activity of 29.2 dpm/kg. This number corresponds to a terrestrial age of about 6.6×10^5 years and is one of the longest terrestrial ages for Antarctic meteorites observed so far.

Figure 1: Ice flow-directions around Frontier Mountains. The
orientation of grooves and striae on bedrock, caused
by three differnt stages of glaciation, are shown:

long arrows: Upper Miocene glaciation
medium size arrows: Pliocene (?) glaciation
short arrows: third recognized stage of glaciation

The meteorite field is shown as hatched area. Most meteo-
rites were found along the eastern margin of the field.
RES-measurements were carried out along line A - B.

Figure 2a: Results of RES-measurements along A-B. Bars mark first
major reflections indicative of the ice-bedrock interfa-
ce. Dots mark reflections from inclined surfaces.

Figure 2b: Interpretation: The ice masses on the left end of the
profile are part of a local glacier approaching from the
west. At its base we suspect a ground moraine of un-
known thickness. The glacier is apparently bounded at
its front by an ice-buried lateral moraine. From the
east, blue-ice enters the valley. The internal structure
of the blue-ice, as shown, is inferred from the occur-
rence of dust bands at the blue-ice surface.

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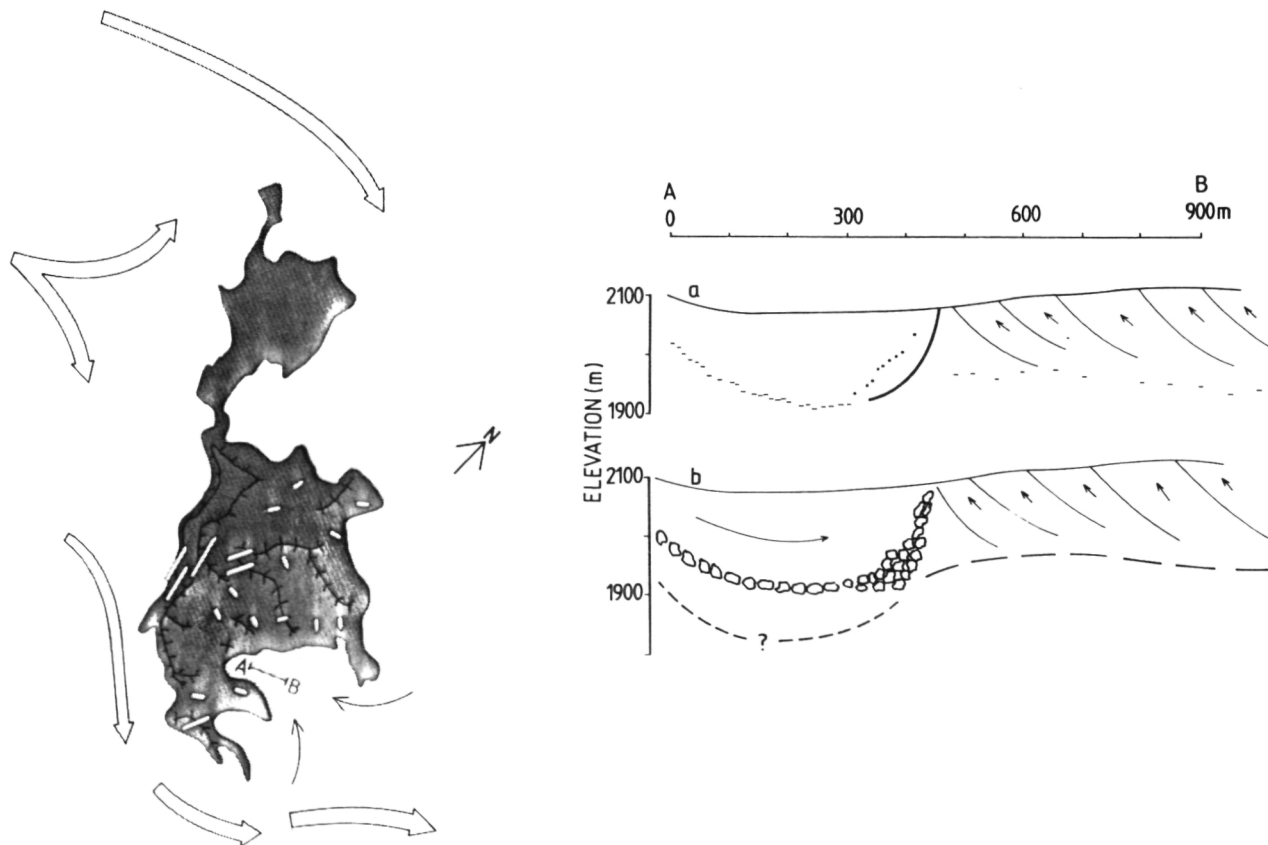
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MYSTERIOUS IODINE-OVERABUNDANCE IN ANTARCTIC METEORITES.

G. Dreibus, H. Wänke and L. Schultz, Max-Planck-Institut für Chemie, 65 Mainz, F.R. Germany.

Halogen as well as other trace element concentrations in meteorite finds can be influenced by alteration processes on the Earth's surface. The discovery of Antarctic meteorites offers the opportunity to study meteorites which have been kept in one of the most sterile environment of the Earth. However, many of the Antarctic stony meteorites are badly weathered and can be classified with respect to their degree of weathering and fracturing. Of meteorites found in Antarctica we have analysed 9 eucrites, 1 howardite, 1 diogenites, 2 shergottites, 1 carbonaceous chondrite (C2) and 1 H-chondrite (H3). These meteorites were collected in the following areas: Allan Hills (ALH), Elephant Moraine (EET), Pecora Escarpment (PCA), Thiel Mountains (TIL) and the Yamato Mountains (Y).

Table 1 gives the data of our halogen determination in Antarctic meteorites compared with non-Antarctic samples. The important result of this study is the iodine-overabundance in most of the Antarctic meteorites compared to the respective values in non-Antarctic meteorites. We find no correlation between iodine concentration and weathering index, or terrestrial age. However, it might by possible that the overabundance of I is restricted to small meteorites only because stones with masses larger than 1 kg show no excess. The polymict eucrites from Elephant Moraine have the highest iodine excess (11-15 ppm), whereas the Shergottite EET 79001 found in the same area has only in one of its two lithologies an I-overabundance. Also mysterious are the different I-concentrations (6 and 0.23 ppm) in the two eucrites ALH 78132 and ALH 79017 which belong to the same meteorite shower but were collected 1978 and 1979.

Even in eucrites PCA 82503 and TIL 82403 collected about 450 km from the South Pole an I-overabundance is found. Among Cl, Br and I the observed relative excess is largest in the case of iodine but also noticeable for Cl in some cases.

Bromine however, seems not enriched in all meteorites studied. Thus the Cl/Br ratios and the I/Br ratios can be used to estimate the overabundance of Cl and I, respectively (Table 2). Relative to C 1-chondrites the I/Br ratio is up to a factor of 1600 higher, the Cl/Br ratio up to a factor of 9.

Beside the I and Cl-enrichment in the Elephant Moraine eucrites (Table 1), we find for these meteorites a drastical depletion of carbon compared to non-Antarctic eucrites whereas the sulfur content is untouched. If the high C-content in the non-Antarctic eucrites is indigeneous and not changed due to terrestrial contamination the observed carbon depletion in the Antarctic eucrites may be related to the weathering process in a cold environment (1).

Chemical alteration effects on Antarctic meteorites due to weathering have been observed previously for various other trace elements (2). Our halogen measurements on Antarctic meteorites indicate a contaminating phase rich in iodine and partly containing also chlorine. The ice beneath meteorites collected in the Elephant Moranie locality is very low in halogenes (Cl=0.31 ppm, Br=0.015 ppm,I= <0.2 ppb). However, iodate-rich nitrate deposits have been found in Victoria Land Mountains (3).

An other source for I-contamination could be expected from aerosols. Several investigators (5, 6) have observed that the I/Cl ratio in marine aerosols as well as in marine atmospheric particulates ranges from 100 to 1000 times the value of seawater (Table 2), whereas the Cl/Br ratio is much closer to the seawater value. A further enrichment of I relative to Cl was observed in Antarctic atmospheric particulates as to be expected on the basis of their size

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Table 1:	F	Cl	Br -ppm-	I	C	S	W*I	terr. Ages [4] (10^5yr)	Weight (kg)
Eucrites									
ALH 78132	49	51	0.038	6.3			A	1.2	0.656
ALH 79017	39	7	0.063	0.23			A	1.2	0.310
EET 79004	60	49	0.119	11.2	2	2610	B	2.5	0.39
EET 79005	51	105	0.043	15.5	9	1140	A	1.8	0.45
EET 79006	178	463	0.185	11.0			B	1.9	0.72
EET 79011	153	151	0.081	15.2	39	5173	B		0.086
PCA 82502	40	36	0.018	1.1				3.1	0.89
TIL 82403	69	31	0.029	1.1				<0.3	0.050
Y 74450	-	153	0.047	1.176				<0.5	0.24
Sioux Country	21	12	0.11	0.030	783	1023			4.1
Stannern	25	298	0.70	0.20	687	2789			52
Cachari	-	93	0.96	0.48					23.5
Pasamonte	52	26	0.149	0.056					3.5
Béréba	53	16	0.102	0.134					1.8
Jonzac	12	6	0.093	0.010					2.5
Howardites									
Y 7308	6	7.55	0.074	6.6					0.48
Molteno	11	125	0.24	0.28					0.14
Kapoeta	-	147	0.17	0.30					11
Frankfurt T	-	16	0.10	0.05					0.65
Diogenites									
Y 74013	1.5	2.6	0.017	0.010					2.0
Johnstown	2.0	5.5	0.051	0.020					40
Shergottites									
ALH 77005	22	14	0.085	1.72			A	1.9	0.48
EET 79001-A	39	26	0.189	0.10			A		0.79
EET 79001-B	31	48	0.289	0.96			A		
Shergotty	41	108	0.891	0.036					5
Carbonaceous, 2									
Y 74662	42	340	2.67	4.5					0.15
Murchison	38	180	0.61	0.19					100
H-Chondrite									
ALH 78084 (H3)	8	140	0.39	0.129			B/C	<1.4	14.3
Mt. Baldr (H5-H6)				0.171					17.8
(Heumann, pers. communication)									
Kesen (H4)	8	90	0.36	0.06					135

*W.I. Weathering Index: A is unweathered, C is highly weathered.

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Table 2:	I/Cl	$\frac{I/Cl}{(I/Cl)_{Cl}}$	I/Br	$\frac{I/Br}{(I/Br)_{Cl}}$	Cl/Br	$\frac{Cl/Br}{(Cl/Br)_{Cl}}$
Eucrites						
ALH 78132	0.13	160	160	730	1330	5
ALH 79017	0.033	40	3.7	20	110	0.4
EET 79004	0.23	280	94	430	410	1.5
EET 79005	0.15	180	360	1640	2450	9
EET 79006	0.024	30	60	270	2520	9
EET 79011	0.10	120	188	850	1880	7
PCA 82502	0.031	40	61	280	2000	7
TIL 82403	0.036	40	38	170	1070	4
non-Antarctic	3.9×10^{-3}	5	0.50	2	180	0.7
Howardites						
Y 7308	0.91	1100	89	400	100	0.4
non-Antarctic	2.4×10^{-3}	3	1.0	5	500	2
Shergottites						
ALH 77005	0.12	150	20	90	165	0.6
EET 79001-A	0.0040	5	0.53	2	140	0.5
EET 79001-B	0.020	20	3.3	15	170	0.6
non-Antarctic	3.3×10^{-4}	4	0.040	0.2	120	0.4
H-chondrites						
ALH 78084	9.1×10^{-4}	1	0.33	2	360	1
non-Antarctic	6.7×10^{-4}	1	0.17	1	255	1
Carbonaceous, 2						
Y 74-662	1.3×10^{-2}	20	1.69	8	130	0.5
non-Antarctic	1.1×10^{-3}	1	0.31	1	295	1
C 1	8.3×10^{-4}	1	0.22	1	270	1
Seawater	2.6×10^{-6}	3×10^{-3}	8×10^{-4}	4×10^{-3}	300	1
marine aerosol[3]	10^{-4}-10^{-3}	1	0.5	2	300	1
marine atmospheric particulates [4]	5.6×10^{-4}	1	0.29	1	520	2
Antarc. atmos. partic.[4]						
a) McMurdo	1.3×10^{-2}	15	1.0	5	73	0.27
b) South Pole	4.9×10^{-2}	59	1.0	5	23	0.09
Ice (Elephant Moraine)	6×10^{-4}	1	0.013	0.06	20	0.1

distribution. Contrary to Cl the major portion of I is found in particles with radii from 0.3 μm to 0.6 μm and these small particles have a significantly longer atmospheric residence time than larger particles. Thus, the iodine in the aerosol should not show larger variation with its distance from their source area (6).

So far we have not reached a definite conclusion about the I and Cl enrichment processes in achondrites during their storage in Antarctica. A H_2O-leach experiment of the eucrite EET 79006 has shown that from 463 ppm Cl almost all (428 ppm) is leachable, however, only 3.8 ppm of the 11 ppm total I; Br is not leachable. Our studies have shown that most of the meteorites from Antarctica suffered severe terrestrial contamination for iodine and to a lesser degree also for chlorine. This contamination is independent of the terrestrial age, the degree of weathering and the locality where the meteorites were collected.

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Entrainment, transport and concentration of meteorites in polar ice sheets

D. J. Drewry

Scott Polar Research Institute
University of Cambridge,
Cambridge, CB2 1ER, England

Glaciers and ice sheets act as slow-moving conveyancing systems for material added to both their upper and lower surfaces. Because the transit time for most materials is extremely long ($10^2 - 10^4$ a) the ice acts as a major global storage facility. Ice flow is not uniform, however, with considerable horizontal and vertical motions leading to concentration or dispersion in 3-dimensions. Externally induced changes to ice volume and and tectonic uplift of adjacent mountainous areas present complicating factors to meteorite accumulation.

Plainimetric concentration

The pattern of flow in the Antarctic ice sheet exhibits partitioning into distinctive drainage basins which may possess varying degrees of dynamic independence. Fig. 1 illustrates the principal ice drainage basins of the ice sheet as defined from the most recent geophysical studies (Drewry 1983).

It is quite clear that some of these basins are capable of concentrating, into quite small outlets, material accumulated over a very extensive inland catchment. The largest basins are the Amery-Lambert, the Byrd and Slessor Glaciers. They could be considered the ideal source areas for meteorite collection and plantimetric concentration. Meteorites discovered in Antarctica to date, however, show that in most cases their locations are peripheral to the

large ice drainage basins. In certain localities they have no present-day relationship with major basins. This establishes a paradox between the apparent need to concentrate ice from as large an area as possible and the actual occurrence of meteorites in regions which at present possess only limited potential for such focussing.

This problem introduces the notion of stagnant inter-basin regions where the considerably smaller size of the catchment is compensated by its very sluggish dynamics. Consider a drainage basin such as the Byrd Glacier (Fig. 2). It has an area of ~ 1 M km^2. Assuming a mean basin velocity of 50 m a $^{-1}$, a random infall of ~ 5.2 meteorites per 10^6 km^2 a^{-1} (Olsen 1983) a steady state meteorite density would be achieved in ~10 Ka with a steady-state population of 26000 meteorites. Consider a small adjacent basin near Darwin Glacier with an area of only 50000 km^2 and an average ice velocity of only 10 m a^{-1}. The steady-state population is 52000 – twice that of the more dynamic and considerably larger outlet. Although this is a simplistic result it nevertheless underscores the real situation that meteorite accumulation is favoured by areas of slow-moving ice which are found in zones between the major outlet glaciers. These regions are characterized by small ice thicknesses, and low driving stresses (Drewry 1982).

Horizontal/Vertical motions in the Ice Sheet

Meteorite collections require that material be brought to the local ice surface. The path traced out by a meteorite within an ice sheet can be separated into horizontal and vertical motion (Fig. 3).

The horizontal direction travelled by a meteorite will be determined by the maximum regional surface slope. The distance moved,

per unit time (δt):

$$\delta x = \bar{U} \, \delta t$$

where $\bar{U}$ = column balance velocity

$$= \frac{1}{\rho_i} h \int_0^x M \, \delta x$$

where ρ_i = ice-column averaged ice density

   h = ice thickness

   M = surface mass balance

The vertical path per unit time is a function of the surface accumulation:

$$\delta_z = U_z \, \delta t$$
$$= M \left[\frac{H - h_m}{H} \right] \delta t$$

where

   H = total ice depth

   h_m = depth to meteorite below the ice surface

   U_z = vertical ice velocity

In most parts of Antarctica M is usually positive (i.e. there is a net gain in mass) and meteorites are buried their depth increasing down the flowline. In certain peripheral regions M is negative (i.e. there is net ablation). In these areas there is upward ice motion which may eventually bring meteorites to the ice surface where they accumulate at a rate determined by U_z and the meteorite density in the ice.

Long-term ice sheet variations

A consequence of the model which suggests inter-drainage basin

regions as key locations for meteorite accumulation is the need for long term stability of the ice sheet to allow concentration to take place. Drewry (1980) showed that at Allan Hills any ice sheet thickening of the order of $\gtrsim$ 100 m would effectively "flush-out" meteorites into Mawson Glacier and hence there had been little change to the ice thickness during the period of accumulation which was estimated, conservatively, between 17 and 33 ka BP.

Significant fluctuations in the extent and thickness of the East Antarctic Ice Sheet are known and on scales of 10^4 - 10^5 years which span the range of meteorite ages found at places like Allan Hills. Detailed discussions of these variations have been given elsewhere (Stuvier et al 1981). It appears that in places the ice sheet has thickened considerably (by more than several hundreds of metres) particularly in its outer regions such as the Transantarctic Mountains. Such thickening during the Wisconsin maximum ($\sim$ 17-20 ka BP) would be more than sufficient to destroy meteorite accumulation sites.

It would appear, however, that in places such as the Transantarctic Mountains Ice Age-induced thickness changes have not everywhere been of the same magnitude. Referring to the model of drainage basins, the major ice streams discharging through the Transantarctic Mountains act as the principal and sensitive regulators of the ice sheet to changes in inland mass balance, and sea level. In this manner they tend to buffer the inter-basin areas from all but the most extreme ice fluctuations and therefore preserve their slowly operating concentration mechanism.

Vertical tectonics

Bull and Lipschutz (1982) draw attention to the role that uplift in the Transantarctic Mountains may have played in disrupting ice flow and providing at least a partial cause for the initiation of meteorite accumulation areas. There is considerable evidence for uplift but until recently rates have been difficult to determine with any consistency or precision. Smith and Drewry (1984) in presenting a new theory for the uplift mechanisms of the Transantarctic Mountains discussed a number of uplift rates which indicate a consistent pattern of elevation of the order of 90 m Ma^{-1} (Fig 4) and sustained over the last 45 Ma.

This rate would suggest that the continued vertical motion of the mountain range has been a contributing factor within the period of the oldest meteorite found at Allan Hills when uplift would have been in the order of 70 M. 500 m of uplift would have occurred during the last 5.6 Ma. Such values suggest that the accumulation of meteorites may pregressively migrate inland and, in their present-day location, may be only relatively recent. [Fig. 5].

Proxy tracers in the Ice sheet

The determination of the source areas of meteorites and their transport paths is a problem of central importance since it relates not only directly to concentration mechanisms but to wider issues in glaciology and meteoritics.

Elucidation of past flow conditions is fundamental to a number of glaciological studies and any assessment of ice sheet margin stability or instability will assist in reconstructing the configuration and dynamics of the Antarctic ice sheet in the past and the resolution of a number of

problems related to former ice sheet extent. If for instance meteorites with terrestrial ages in excess of 125 Ka BP were located in central west Antarctica (in the region of Mount Woollard or Mount Moore or the Whitmore Mountains) they would testify to the continued presence of the ice sheet in West Antarctica during the last interglacial and to long-term stability of that region. Such results are important in glaciology to evaluating the stability of West Antarctica particularly in predicting its response to CO_2 induced climate changes.

Accurately determined source areas and flow paths for meteorite accumulations, combined with good terrestrial dates on those recovered, will measurably assist in refining the meteorite infall rate to the Earth's surface, possibly elucidating variations due to latitude and certainly improving the various weighting factors devised for fragmentation and observational bias.

Meteorites per se do not allow their source areas within the ice to be pin-pointed. However the ice and snow into which a meteorite falls, and which moves with it to the concentration area, will encode information about the infall location. The principal environmental conditions being former elevation, temperature (also related to elevation) and age of the ice.

Elevation of the source area for instance, may be derived from the fact that pores within the snowpack or firn close-off at a given density and thereafter preserve a record of former ambient atmospheric pressure (Reynaud 1983, Jenssen 1983). Total gas content (V) (reduced to standard temperature and pressure) may be expressed in terms of pressure (P) and temperature (T) at pore close-off and a standard

pressure (P_O) and temperature (T_O):

$$V = V_C \frac{P}{T} \cdot \frac{T_O}{P_O}$$

where V_C = proportional gas volume at close-off. Various corrections and refinements are required to the technique as described by Reynaud (1983) but it is possible to obtain a proxy indicator of the elevation of the surface entrainment location by analysis of the total gas content.

Temperature and hence also elevation may be obtained by determination of the isotopic composition of the ice. Oxygen (^{16}O, ^{18}O) and hydrogen (D) isotopes are principally used and their ratios relate to the condensation temperature of water droplets which precipitate as snow onto the ice sheet surface. The technique has been extensively used in Antarctica in yielding valuable information of former ice sheet temperatures as well as elevations and flow properties (see Robin (1983).

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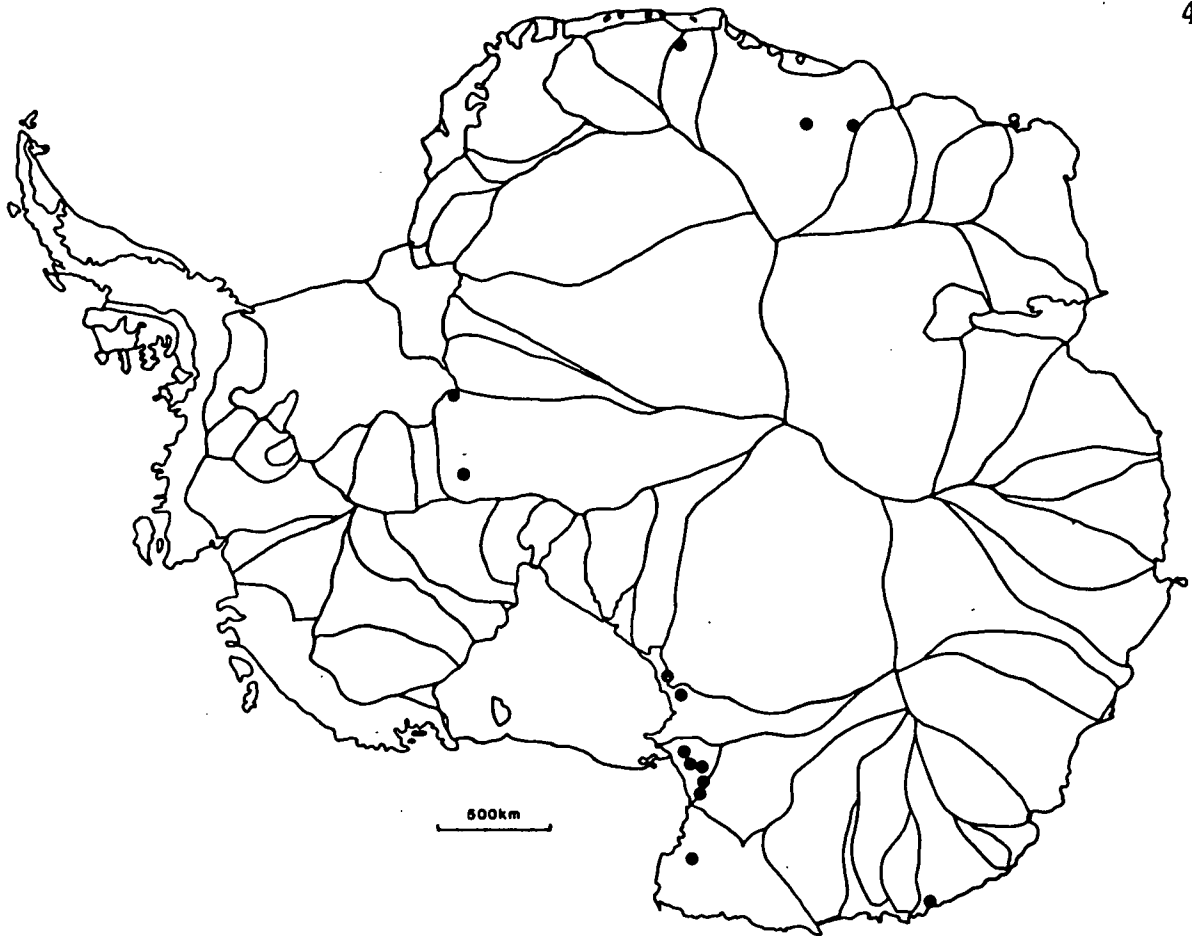
Figure 1   Principal ice drainage basin in Antarctica and location of meteorite accumulation areas.
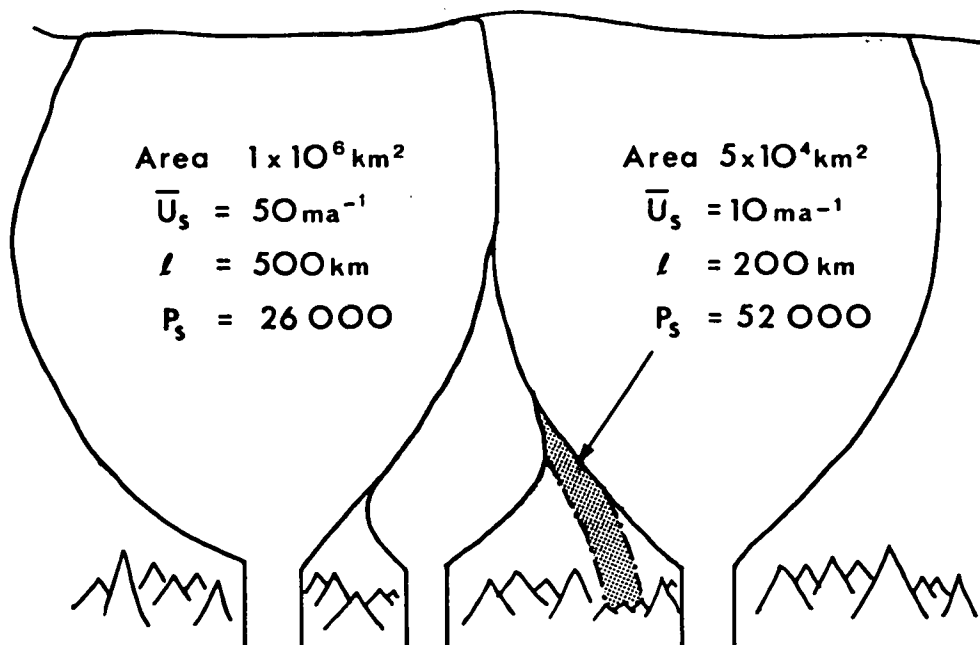

Figure 2   Comparison of steady-state meteorite populations (P_s) for a large ice sheet basin draining through an outlet glacier and a small inter-outlet basin. $\overline{U}_s$ = average ice velocity; l = flowline length.
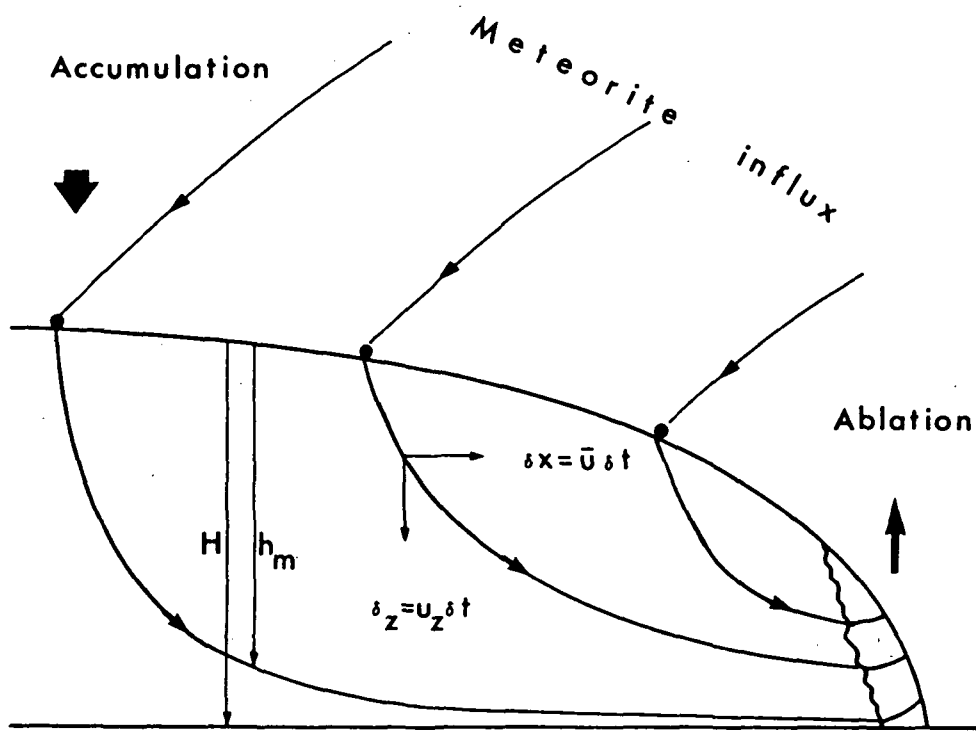
Figure 3   Vertical and horizontal motions in an cie sheet (see text).
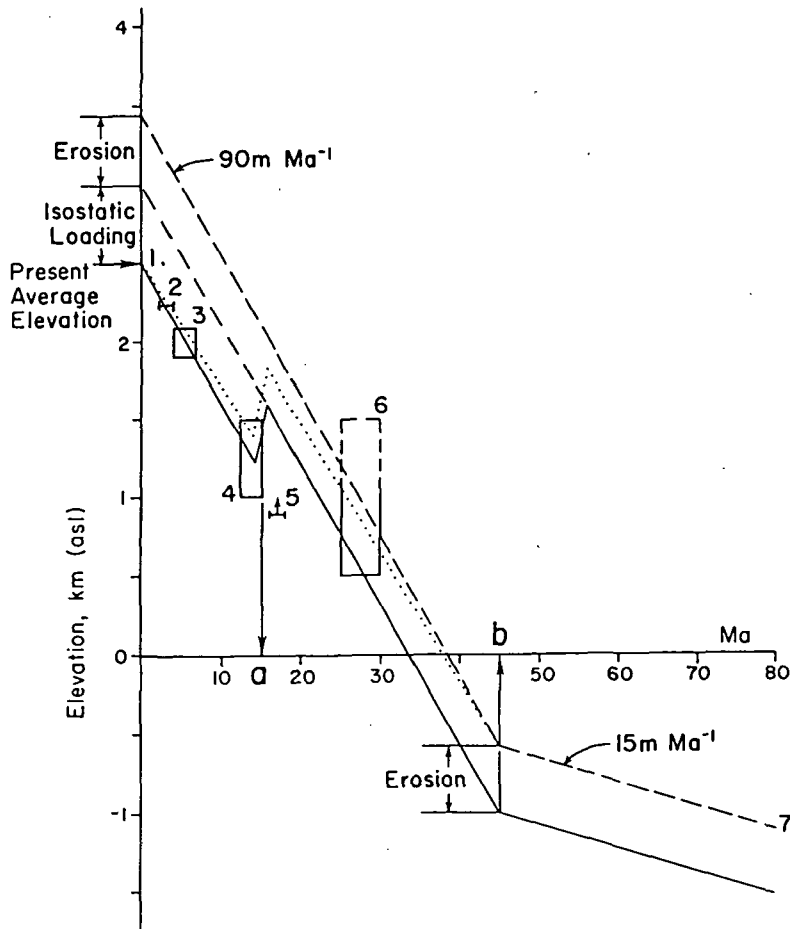

Figure 4   Uplift curve for the Transantarctic Mountains established from a variety of sources (from Smith and Drewry, 1984).
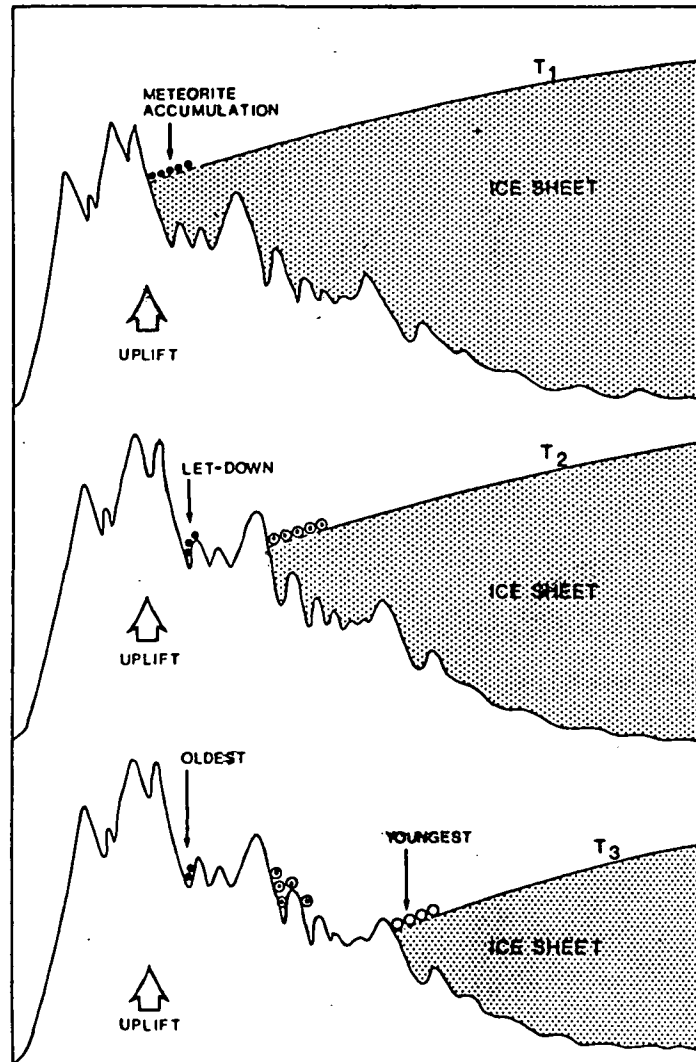
Figure 5   Cartoon depicting the effect of tectonic uplift on meteorite
accumulations on the inland flank of the Transantarctic Mountains.

WEATHERING OF STONY METEORITES IN ANTARCTICA.

J. L. Gooding, SN2/ Planetary Materials Branch, NASA/Johnson Space Center, Houston, TX 77058 USA.

Introduction. Weathering produces undesirable physical, chemical, and isotopic changes that might disturb the records of cosmochemical evolution that are sought in meteorites. As partial compensation, though, weathering of meteorites in an icy "regolith" offers, by analogy, insight into processes of rock alteration that have probably operated on icy planetary bodies such as comets, asteroids, satellites of the Jovian planets, and planet Mars. For Antarctic geoscience, weathering effects in meteorites might be "marker horizons" that contain information about histories of Antarctic ice sheets.

Meteorites are physically disintegrated by crack-propagation phenomena, including ice riving and secondary-mineral riving, and are probably abraded by wind that is laden with ice crystals (on open ice sheets) or dust particles (if downwind from moraines). Chemical weathering proceeds by oxidation, hydration, carbonation, and solution and produces a variety of secondary minerals and mineraloids. Weathering proceeds at rates that are slower than in temperate climates but produces effects that may be distinctively different from those in non-Antarctic meteorite finds.

Differential Weathering Under Freezing Conditions. In general, the rates and styles of both physical and chemical weathering vary with the availability of liquid water, which controls solution, transportation, and precipitation processes. Minerals show differential susceptibilities to chemical attack that, to a first approximation, are correlated with values of the Gibbs free-energy changes that can be calculated for pertinent decomposition reactions. Because ice and vapor, rather than liquid, are the dominant forms of water in the Antarctic meteorite collection areas, differential weathering might be even more pronounced in Antarctica than in temperate latitudes.

Liquid water can survive in porous rocks at < 273 K either as "unfrozen" capillary water or as undercooled planar films on mineral surfaces [1]. It can be estimated (method of [2]) that for particle sizes and porosities that apply to stony meteorites, thermodynamically "liquid" water (> 15 molecular layers thick) should be expected at temperatures as low as 263–264 K (Fig. 1) although at deep-ice temperatures (250 K) unfrozen water thicknesses should be < 5 molec-
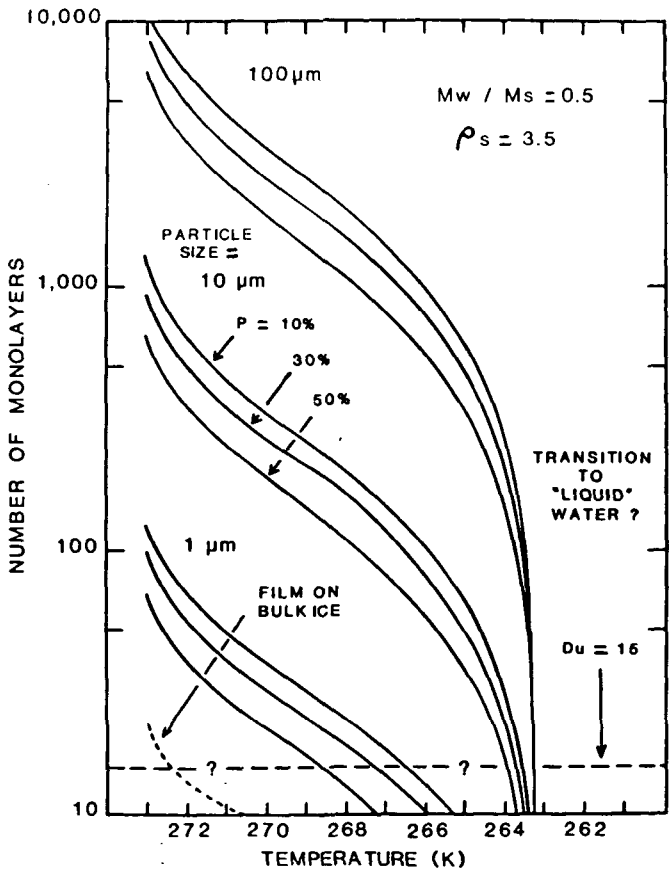

Figure 1.

Estimated thickness of "unfrozen" water layers in wet stony meteorites (water/rock mass ratio = 0.5) as a function of temperature, particle size, and porosity (P).

ular layers. Unfrozen water would form brines on hygroscopic phases (e.g., lawrencite) and, thereby, extend its own stability to even lower temperatures. Therefore, rust mantles on metal particles, which apparently form in liquid water [3], might develop while meteorites are ostensibly "frozen." The ability to nucleate ice from undercooled water varies significantly among minerals [1,4] and it might be expected that effective nucleators, which can immobilize water by freezing, should be less susceptible to weathering than are ineffective nucleators, which are less capable of immobilizing water. As shown in Fig. 2, a grid formed by conventional chemical-thermodynamic and ice-nucleation parameters might be useful in quantifying the relative susceptibilties of minerals to chemical weathering under "hydrocryo-genic" (cold water) conditions. Fig. 2 was constructed by calculating a "thermodynamic" ordinate and an "ice-nucleation" abscissa. For each mineral, the thermodynamic parameter represents the range of values obtained for the equilibrium constants of oxidation, hydration, and carbonation reactions for one mole of mineral reactant at the normal triple point of water. The ice-nucleation parameter represents the minimum crystallographic misfit, $/\delta/$, between the most favorable plane in the mineral substrate and the basal plane of the condensate, ice Ih, and is a measure of the favorability for epitaxial overgrowth of ice on the mineral. Although other determinative factors exist, the temperature at which a mineral can nucleate ice from undercooled water varies inversely with $/\delta/$ [5].
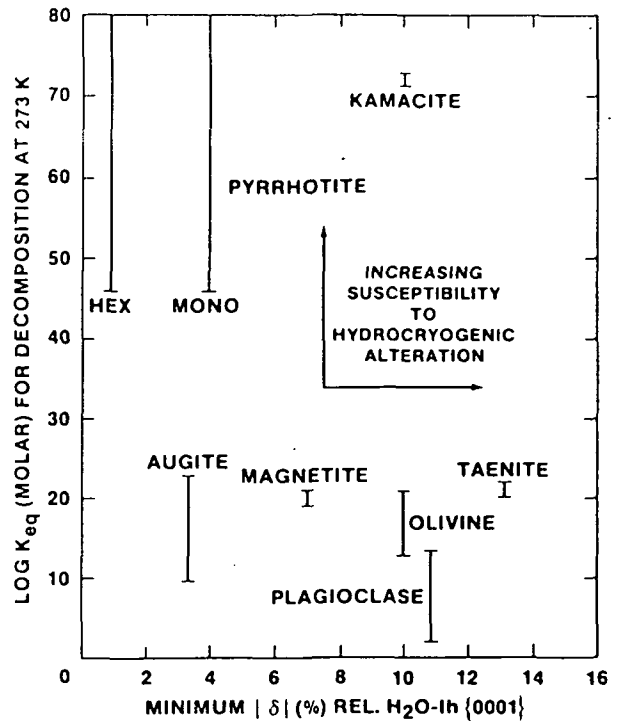

Figure 2.

Prediction of relative susceptibilities of meteoritic minerals to weathering under Antarctic conditions. Note that the x-axis parameter is unique to weathering under freezing conditions.

The relative susceptibilities of Fe-rich minerals to Antarctic weathering, as predicted in Fig. 2, are generally consistent with observations. Namely, pyrrhotite (or troilite) is less susceptible than is Ni-Fe metal, taenite is less susceptible than is kamacite, and silicates are less susceptible than are sulfides and metal. However, two less obvious predictions are also inherent in Fig. 2. First, due to its large value of $/\delta/$, plagioclase might be of similar or greater susceptibility to hydrocryogenic alteration than are pyroxene and olivine. Second, because of large values of both K_{eq} and $/\delta/$, glasses should be especially susceptible to weathering. Ignoring ice-nucleation effects (e.g., as in temperate-latitude weathering), plagioclase should possess a low susceptibility because of its low values for K_{eq}, relative to mafic silicates. However, under hydrocryogenic conditions, the susceptibility of plagioclase might be similar to that of olivine, because of the $/\delta/$ parameter (Fig. 2). Because the expected decomposition products of plagioclase (secondary aluminosilicates, carbonates, and oxides) would not be rusty in appearance, weathering of plagioclase could be easily overlooked during casual inspection of Antarctic meteorites. In the case of glasses, their higher susceptibilities relative to crystalline phases, as measured by

the K_{eq} parameter, would be further accentuated by their high (and effectively incalculable) $/\delta/$ values that result from the absence of long-range order in the glass structures. For example, the calculated thermodynamic coordinate for basalt glass (log K_{eq} = 15-30) indicates that it is more susceptible to chemical weathering than is augite. Although a meaningful value of $/\delta/$ cannot be calculated for basalt glass, it would undoubtedly be a very large number that would plot far to the right of augite in Fig. 2. In any case, the poor ice-nucleation properties of basalt glass have been confirmed experimentally. Under otherwise identical conditions, powdered basalt glass nucleated ice from undercooled water at a temperature that was 5.7 K lower than for the nucleation of ice by powdered augite [6]. A similar argument can be made for differences in susceptibility between plagioclase and plagioclase glass (e.g., maskelynite). Therefore, among the silicate portions of meteorites, glassy components should be the most susceptible to chemical weathering. It should be kept in mind that the overall susceptibility to weathering of a meteorite will be a function of the relative susceptibilities of its mineral components. Therefore, the wide range of phase compositions among meteorites should lead to a wide range in overall susceptibilities to weathering among meteorites.

Mineralogy of Weathering Products. Some samples, especially fusion-crusted surfaces, show clear evidence for etching (incongruent dissolution) of primary mineral grains and nearby deposition of secondary precipitates in voids and fractures, thereby confirming the role of liquid water during weathering of the Antarctic specimens (Fig. 3). "Metallic rust" is composed of oxidized Fe, Ni, and various amounts of S, Cl, and water whereas "sialic rust" is an Fe-rich, hydrous material that includes major to minor concentrations of Si, Al, and other lithophiles [3,7]. Metallic rust commonly occurs as veins and as mantles on Ni-Fe metal or troilite although sialic rust is typical of achondrites, especially in association with mafic silicates and spinels. Sulfates and carbonates occur both independently and along with other weathering products [3,8].

Figure 3.

SEM photomicrograph of a smectite-like clay mineraloid (SMEC) grown in a fracture in fusion crust of Antarctic shergottite EETA79001. Secondary mineral(oid)s contribute to disintegration of Antarctic meteorites through crack propagation. Scale bar is 10 μm.

Aluminosilicates, which may include clay minerals and zeolites, are abundant as decomposition products of glass and plagioclase in basaltic achondrites [3,7]. Rust can act as a pore-filling cement in a manner analogous to diagenetic cements in terrestrial sandstones. However, at tips of microcracks, specific-volume increases that accompany deposition of secondary mineral(oid)s cause widening of fractures and rock disintegration as exemplified by polygonal fracture patterns and pluck pits in fusion crust. Also, migration of water-soluble salts to free surfaces, with subsequent removal by wind abrasion, comprises a subtle but significant process of mass loss from the meteorites.
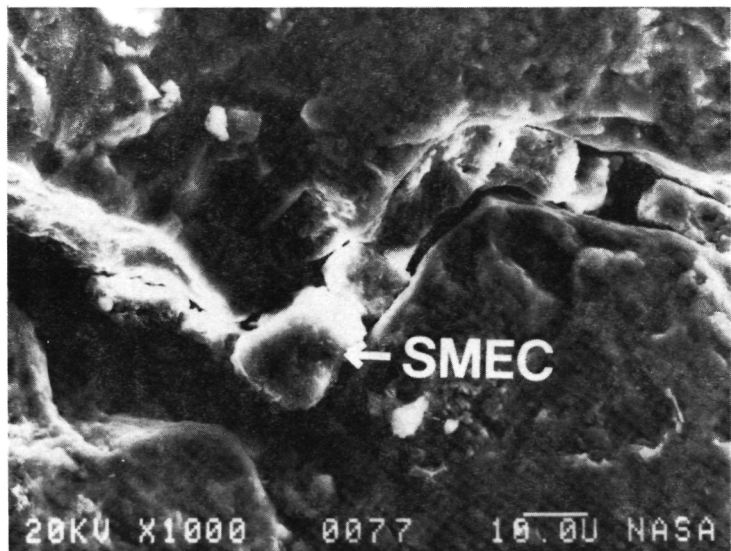
"Glacial" Weathering vs. "Periglacial" Weathering. The most likely time for exposure of a meteorite to liquid water should occur when a meteorite resides at a free surface (i.e., an ice/atmosphere or moraine/atmosphere interface) and is exposed to solar radiant heating. Such exposure can occur shortly after fall of the meteorite, before the rock is incorporated into the glacier, or after emergence of the rock from the glacier at a zone of ablation and accumulation. For convenience, weathering at a free surface (top of glacier or moraine) can be defined as "periglacial" whereas possible weathering during encasement in ice can be defined as "glacial." In the general case where a meteorite falls, is incorporated into a glacier, and then emerges again at a later time, the "glacial" weathering interval would lie between a "first periglacial" and a "second periglacial" weathering period.

Obviously, physical disintegration of a meteorite is not likely to be important as long as the meteorite is encased in ice. However, the existence of "unfrozen" water, as discussed above, might support initiation of chemical weathering during the first periglacial or glacial period that would set the trend for accelerated physical and chemical decomposition during the second periglacial period. From the standpoint of Antarctic geoscience, it would be desirable to recognize and quantify both glacial and periglacial weathering effects in each meteorite. Combined with data on terrestrial residence ages, data on the glacial and periglacial weathering histories of meteorites might reveal the histories of the ice sheets and the mechanisms by which meteorites are transported and concentrated. Important evidence that bears directly on this question occurs in ALH82102 (H5) which was found emerging from ice but which was already significantly rusted, even on its most deeply submerged side. However, it remains to be determined whether the rust in ALH82102 developed during the first periglacial or the glacial period of the meteorite's terrestrial history.

Figure 4.

Possible sources of interference in oxygen isotopic analyses of meteorites found in Antarctica. Large filled circle is SMOW and other points are for fresh, non-Antarctic meteorites [21]. The air clathrate composition is an estimate.

Detailed hydrogen, carbon, and oxygen stable-isotopic studies of weathered meteorites might provide one means of distinguishing glacial from periglacial weathering effects. During periglacial times, weathering probably depends on melted snow or ice as the principal source of water and on the atmosphere as the source of O_2 and CO_2. During glacial times, though, volatiles required for weathering might be derived from gas bubbles or clathrate ices that form in the ice at depths of 900-1300 m [9]. Trapped gas possesses atmospheric values of elemental and isotopic abundances, except for possible CO_2 enrichments and slightly positive values of $\delta^{15}N$ [10]. However, air clathrate should be significantly enriched in O_2 relative to air [11] and, by analogy with methane hydrate [12], H_2O in air clathrate should possess a higher $^{18}O/^{16}O$ ratio than that in free water, probably with values in the range between ice ($\delta^{18}O$ = - 35-43 o/oo) and air ($\delta^{18}O$ = + 23-24 o/oo) (Fig. 4). Therefore,
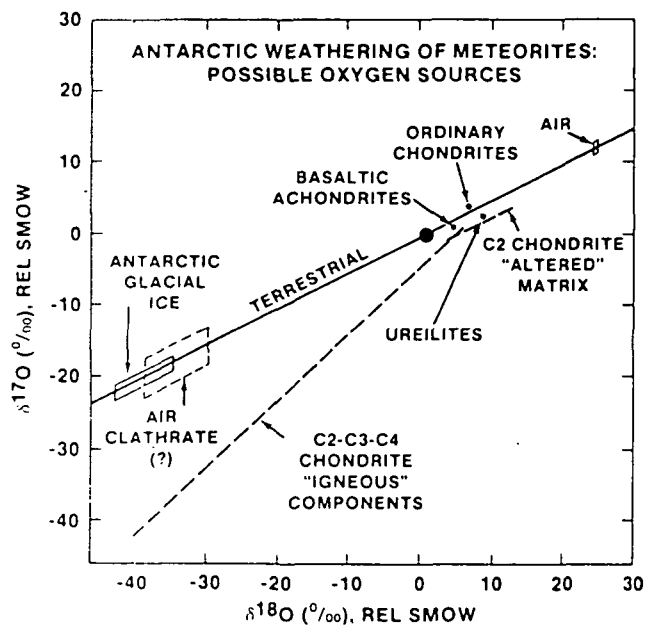
oxygen isotopic compositions of weathering products will depend upon relative contributions of oxygen from glacial ice, air clathrate, and air, as well as identities of the reactive species (i.e., O_2, H_2O, CO_2). From Fig. 4, it is clear that uptake of only small amounts of Antarctic oxygen from any of the three suspected reservoirs would be sufficient to perturb the oxygen isotopic compositions of meteorites.

"Weatherometers." A definitive correlation between degree of weathering and terrestrial residence age has not yet been found but may simply reflect absence of a quantitative scale for weathering, especially with regard to distinguishing glacial from periglacial weathering effects. Differential susceptibilities of meteoritic minerals to chemical weathering prevents application of a single weathering index to all types of meteorites. Although a single, "universal" weatherometer might not be possible, development of one or more weatherometers for each of the major groups of stony meteorites (carbonaceous chondrites, ordinary chondrites, eucrites, etc.) would represent a major element of progress toward deducing the terrestrial histories of the Antarctic meteorites. The most useful weatherometers should be relatively rapid, utilize modest quantities of samples, yet produce quantitative results that can be calibrated against other measurable parameters. A combination of x-ray diffractometry, reflectance spectrophotometry, and differential thermal analysis was previously found to be useful in quantifying relative degrees of weathering among small bulk samples of chondrites [3] and much more work along those lines is needed. Other petrographically-oriented weatherometers that should be investigated include rust haloes on metal particles (ordinary chondrites) and hydration rinds on glasses (unequilibrated chondrites and basaltic achondrites), both of which are expected to grow in thickness (at constant temperature) at log-linear rates, as previously demonstrated by studies in the fields of corrosion science and archeological obsidian dating, respectively. Indeed, little real utilization of weathering effects in meteorites as Antarctic geoscience tools can be made until quantitative weatherometers are discovered and calibrated.

Cosmochemical Interferences. Elemental fractionations clearly occur during weathering because compositions of some weathering products are very different from those of their progenitors. Although untreated aliquots that are isochemically weathered at the scale of sampling may appear undisturbed in bulk analyses (e.g., INAA), disturbances may become apparent in analyses that depend upon mineralogical, ion-exchange, or leachate separations (e.g., RNAA, radiochronometry) or gas extractions (e.g., noble gas studies) because phase locations, abundances, and site-retentivities of analyte species are subject to change by weathering. Fractionation of K from Na and of K from Ca are typical of aluminosilicate weathering products (Fig. 5), suggesting that other alkali/alkaline-earth fractionations (e.g., Rb/Sr) might also be important. In view of the unusual Eh-pH stability fields of Ce- and Eu-based species relative to other species based on rare-earth elements (REE)[13], fractionated REE patterns, and especially "Ce anomalies" [14], might reflect variable Eh-pH conditions during hydrocryogenic weathering. At least some of the Eh-pH conditions that favor REE fractionation should also favor magnetite (rather than hematite or goethite) formation during oxidation of Fe-bearing silicates. Therefore, absence of reddish rust from a sample might not guarantee that the sample was free of trace-element fractionations.

Meteorites can acquire trace-element contamination from atmospheric aerosols as demonstrated by contents of anthropogenic [137]Cs [15]. Because

[137]Cs has been a significant environmental pollutant only since the advent of atmospheric tests of nuclear weapons, its distribution among Antarctic meteorites might vary greatly with the periglacial "weathering ages" of the meteorites (i.e., lengths of time spent in contact with polluted air, ice or snow). Trace-element analyses of Antarctic meteorites should be screened for possible effects of weathering or aerosol contamination before new "cosmochemical" effects are reported.

Isotopic fractionations wrought by weathering are poorly understood because so few meteorites have been deliberately studied from that point of view. However, disturbances of both oxygen istopic systems [16] and K-Ar systems [17] have been reported for some analyses of Antarctic meteorites. Because some gas-absorbent weathering products (e.g., aluminosilicates and oxides) do not thermally decompose until > 1100 K, their volatile releases might trangress into temperature intervals that are assigned to "indigenous meteoritic" components in many analyses of cosmogenic volatiles. In fact, extraneous Ar trapped in weathering products has been blamed for an anomalously old ^{39}Ar-^{40}Ar age (4.6-4.9 Gy) obtained for ALHA76001 (L6) [18].

Trace-element and isotopic disturbances can be minimized by careful sample selection [e.g., 19], although much more work is needed before effects of the Antarctic environment on cosmochemical analyses are fully understood.
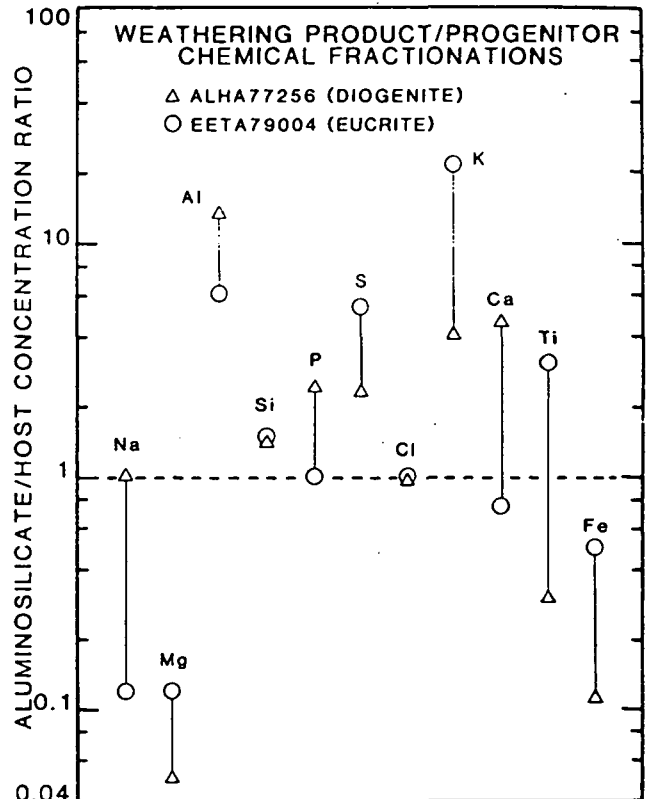

Figure 5.

Elemental fractionations in aluminosilicate weathering products relative to their hosts in Antarctic meteorites.

Martian and Cometary Analogs. Antarctic alteration of meteorites has occurred on timescales (10^4-10^6 y) that are unachievable in laboratory experiments but which approach those that are meaningful for planetary evolution. Accordingly, weathering of basaltic achondrites, especially shergottites, might be an excellent analog for weathering on Mars [20]. Furthermore, although pre-terrestrial alteration effects in carbonaceous chondrites are usually interpreted in terms of "hydrothermal" (hot water) processes on an asteroid or comet, remarkably similar features have evolved terrestrially in some Antarctic meteorites by phenomena that are clearly "hydrocryogenic" [4,7]. Therefore, terrestrially formed oxide, clay and salt minerals in Antarctic meteorites should be studied for possible petrogenetic insights into alteration processes on meteorite parent bodies. Furthermore, work toward quantifying weathering effects in Antarctic meteorites might provide insight into methods for quantifying pre-terrestrial aqueous alteration effects that occur in carbonaceous and other highly unequilibrated chondrites.

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COSMIC RAY RECORDS IN ANTARCTIC METEORITES
- A DATA COMPILATION OF THE COLOGNE-ZÜRICH-COLLABORATION -

S.Vogt[1], U.Herpers[1], R.Sarafin[1], P.Signer[2], R.Wieler[2], M.Suter[3] and W.Wölfli[3]

[1]Abteilung Nuklearchemie, Universität zu Köln
[2]Institut für Kristallographie u. Petrographie, ETH-Zürich
[3]Institut für Mittelenergiephysik, ETH-Zürich

The cosmogenic radionuclides ^{10}Be, ^{26}Al and ^{53}Mn and noble gases were determined in more than 28 meteorites from Antarctica by nuclear analytical techniques and static mass-spectrometry, respectively. The results are summarized in table 1 and table 2. (Some of the data were published previously (6-9)). The concentrations of ^{26}Al and ^{53}Mn (table 1) are normalized to the respective main target elements and given in dpm/kg Si_{eq} and dpm/kg Fe. The errors stated include statistical as well as systematical errors. For noble gas concentrations (table 2) estimated errors are 5% and for isotopic ratios 1.5%. Cosmic ray exposure ages T_{21} were calculated by the noble gas concentrations and the terrestrial residence times (T) on the basis of the spallogenic nuclide ^{26}Al. The suggested pairing (1o) of the LL6 chondrites RKPA 80238 and RKPA 80248 and the eucrites ALHA 76005 and ALHA 79017 is confirmed not only by the noble gas data but also by the concentrations of the spallation produced radionuclides. Furthermore, ALHA 80122, classified as H6 chondrite (1o), has a noble gas pattern which suggests that this meteorite also belongs to the ALHA 80111 shower.

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Meteorite	Class	Sample	^{10}Be[+] [dpm/kg]	^{53}Mn^{+} [dpm/kg Fe]	Sample	^{26}Al^{+} [dpm/kg Si$_{eq}$]	T [10^5 y]
ALHA 76oo5	Euc	.56	22.8 ± .8	512. ± 74.		266. ± 26. 2)	
ALHA 77oo9	H4	.11	13.9 ± 1.o	3o2. ± 28.		167. ± 11. 2)	2.7 ± 1.8
ALHA 77o15	L3	.31	14.4 ± 1.2	145. ± 13.		172. ± 2o. 1)	5.3 ± 2.2
ALHA 77216	L3	.45	21.1 ± .8	379. ± 34.		191. ± 15. 2)	3.1 ± 1.8
ALHA 77257	Ure	.69	21.2 ± .8	271. ± 56.	.14	165. ± 7. 2)	
ALHA 77258	H6	.25	2o.2 ± 1.o	478. ± 52.		151. ± 11. 2)	8.o ± 2.o
ALHA 77261	L6	.21	22.7 ± 1.4	271. ± 21.		172. ± 2o. 2)	3.4 ± 2.1
ALHA 77272	L6	.37	15.9 ± .6	245. ± 32.		168. ± 19. 2)	3.7 ± 2.5
ALHA 77285	H6	.14	16.8 ± .8	41o. ± 38.		198. ± 21. 2)	3.5 ± 2.1
ALHA 77297	L6	.25	25.o ± .9	419. ± 37.		335. ± 33. 2)	≤ .2
ALHA 78o43	L6	.2o	19.4 ± .7	442. ± 35.		158. ± 15. 2)	6.6 ± 1.9
ALHA 78o84	H4	.26	16.9 ± .7	33o. ± 34.	.19	246. ± 7.	≤ 1.7
		.34	18.4 ± 1.2	314. ± 32.	.45	224. ± 7.	
		.43	18.3 ± .7	299. ± 3o.	.84	239. ± 7.	
		.62	17.5 ± .7	34o. ± 34.			
		.66	18.2 ± .6	356. ± 35.			
		.68	18.2 ± 1.o	323. ± 31			
		.7o	17.6 ± 1.o	326. ± 33.			
		.76	18.6 ± .7	3o4. ± 32.			
		.8o	18.2 ± .8	359. ± 36.			
		.83	19.o ± .9	322. ± 34.			
ALHA 78102	H5	.15	19.6 ± .7	327. ± 37.		182. ± 16. 2)	2.9 ± 2.1
ALHA 78113	Aub	.47	19.o ± 1.o		.32	327. ± 23. 2)	
ALHA 78114	L6	.19	16.8 ± .6	38o. ± 34.		182. ± 16. 2)	3.6 ± 1.8
ALHA 79o17	Euc	.52	23.8 ± .8	53o. ± 75.	.51	288. ± 14.	
ALHA 8o111	H5	. 6	19.1 ± .6	285. ± 28.	. o	237. ± 9.	4.7 ± 1.4
ALHA 8o122	H6	. 6	2o.7 ± 1.o	364. ± 34.	. o	315. ± 14.	≤ 1.4
ALHA 8o124	H5	. 3	17.3 ± .7	288. ± 28.	.2/3	377. ± 3o.	≤ 1.9
EETA 79oo1	Sher	(A)	5.3 ± .4	62. ± 42.	(A)	119. ± 6.	3.2 ± 1.7
EETA 79oo2	Dio	.42	23.o ± .8	357. ± 73.	.16	287. ± 11.	
EETA 79oo4	Euc	.67	22.2 ± .8	344. ± 67.	.58	266. ± 13.	
EETA 79oo5	Euc	.65	23.o ± .8	419. ± 7o.	.13	286. ± 1o.	
EETA 79oo6	How	.31	23.8 ± .8	436. ± 72.	. 2	273. ± 16.	
RKPA 78oo2	H4	.38	17.9 ± 1.2	335. ± 29.	.35	3o5. ± 13.	≤ 1.6
		.41	17.3 ± .8	34o. ± 31.	.4o	273. ± 12.	2.o ± 1.4
		.48	17.5 ± .9	348. ± 32.	.46	3o3. ± 9.	2.1 ± 1.2
RKPA 8o2o1	H6	.11	18.1 ± .6	286. ± 26.	.1o	2o3. ± 8.	2.9 ± 1.3
		.14	2o.5 ± 1.o	327. ± 3o.	.13	2o6. ± 9.	3.8 ± 1.4
		.16	13.o ± 1.c	3oo. ± 27.	.15	245. ± 1o.	1.8 ± 1.3
RKPA 8o213	H6	. o	14.5 ± 1.o	24o. ± 24.	. o	284. ± 3o.	≤ 1.7
RKPA 8o238	LL6	. o	19.7 ± 1.o	357. ± 34.	. o	267. ± 14.	≤ .4
RKPA 8o248	LL6	. 7	19.2 ± .9	338. ± 33.	.o/7	2o3. ± 18.	≤ 3.3

+Average saturation activity : ^{10}Be = 19.o ± o.7 dpm/kg meteorite ,
^{26}Al calculated according to (11), ^{53}Mn calculated according to (12) and (3)

Table 1 : ^{10}Be-, ^{53}Mn- and ^{26}Al-concentrations and terrestrial residence times
of Antarctic meteorites

sample	class	3-He	4/3	20-Ne	21-Ne	22/21	20/22	38-Ar	36/38	40-Ar	T_{21}	T_{38}
		(Concentrations in 10^{-8} cm^3STP/g)									(Ma)	
ALHA76005	Euc	12.3	85.7	2.09	2.16	1.15	.84	1.79	.69	930	11.5	13
ALHA77009	H6	20.5	82.7	3.96	4.16	1.14	.84	.64	1.92	3530	16	
ALHA77015	L3	3.60	283.	2.56	.82	1.34	2.33	15.5	5.29	2600	2.3	
ALHA77216	L3	74.2	>1620	926	12.0	7.78	9.91	6.38	4.22	3750	-29	
ALHA77257	Ure	14.9	47.1	14.3	2.87	1.52	3.28	358	5.29	600	-6.5	
ALHA77258	H6	61.6	35.1	11.4	12.5	1.09	.84	2.10	1.69	2340	40	
ALHA77261	L6	12.1	58.6	3.63	2.12	1.23	1.39	.34	1.58	990	8.0	
ALHA77272	L6	8.32	29.9	1.65	1.31	1.25	1.00	.27	2.03	1520	6.5	
ALHA77285	H6	53.1	24.2	11.5	12.6	1.08	.85	1.50	.89	2490	37	
ALHA77297	L6	74.4	10.1	15.0	16.4	1.09	.84	2.17	1.23	3640	48	
ALHA78043	L6	30.9	13.2	7.32	6.56	1.13	.99	.90	.93	1910	21	
ALHA78102	H5	19.5	86.1	2.90	2.98	1.18	.82	.51	1.29	3410	13.5	
ALHA78113	Aub	35.6	12.0	10.6	11.5	1.09	.84	.53	1.46	1220	-23	
ALHA78114	L6	32.0	11.6	7.51	5.98	1.16	1.08	.87	.93	1790	20	
ALHA79017	Euc	12.4	167.	2.03	2.07	1.15	.86	2.12	.71	2110	11	15
ALHA80111	H5	6.35	407.	5.60	1.24	1.38	3.24	.39	3.32	5580	-4.0	
ALHA80122	H6	6.53	682.	9.37	1.29	1.58	4.57	.39	3.11	5450	-4.0	
ALHA80124	H5	5.34	377.	5.15	1.22	1.35	3.11	.47	3.51	4740	-4.0	
EETA79001(A)	Sher	1.00	39.3	.168	.138	1.27	.96	.076	2.21	105	.5	
EETA79002	Dio	39.8	4.9	5.96	6.09	1.18	.83	.47	.73	10	-17	
EETA79004	Euc	20.2	235.	4.33	4.65	1.17	.79	2.96	.75	1290	25	21
EETA79005	Euc	31.1	109.	4.61	4.67	1.18	.84	3.60	.77	1330	25	25
EETA79006	How	15.9	103.	4.08	4.12	1.18	.84	3.11	.77	1000	-15	
RKPA78002,38	H4	9.73	148.	2.54	2.38	1.09	.98	.46	2.67	5550	7.0	
RKPA78002,41		9.41	137.	2.31	2.00	1.12	1.03	.43	2.44	5140	6.5	
RKPA78002,48		9.27	118.	2.60	1.89	1.12	1.21	.46	2.24	4600	5.5	
RKPA80201,11	H6	11.6	106.	2.03	1.86	1.14	.96	.45	1.88	5460	7.0	
RKPA80201,14		12.0	101.	2.13	2.05	1.13	.92	.42	1.80	5740	7.5	
RKPA80201,16		11.5	117.	2.06	1.82	1.13	1.00	.44	1.75	5210	6.5	
RKPA80213	H6	55.4	3092	1076	4.19	21.5	12.0	31.8	5.35	3650	-5	
RKPA80238	LL6	35.7	44.9	7.07	5.76	1.20	1.02	.96	1.30	5360	24	
RKPA80248	LL6	38.7	41.5	6.02	5.83	1.20	.86	.93	1.07	5600	25	

Table 2: Concentrations and isotopic ratios of noble gases and noble gas exposure ages of Antarctic meteorites.

Sample weights ranged between 130 - 250 mg. Shielding corrected 21-Ne exposure ages for chondrites are calculated, after correction for trapped gas contributions, according (3), except for the values marked by "~", where trapped gas concentrations were too high. For these samples, $(22\text{-Ne}/21\text{-Ne})_{cos}=1.1$ and $(22\text{-Ne}/21\text{-Ne})_{tr}=32$ were assumed. 21-Ne exposure ages for achondrites were estimated with the elemental production rates given in (4), assuming mean chemical composition for the respective meteorite classes (5). The 38-Ar exposure ages of the eucrites are calculated with the production rates given in (4).

RADIOCARBON DATINGS OF YAMATO METEORITES : K.Kigoshi and
E.Matsuda , Department of chemistry, Gakushuin University,
Mejiro,Toshima-ku, Tokyo

The terrestrial ages of five Yamato Meteorites have been
measured by their contents of cosmic-ray-produced carbon-14.
Among them three Yamato Meteorites Y-74013,Y-74097, and Y-74136
which are all diogenites, were found at sites apart from one to
two kilometers each other on the bare ice sheet.   They are
considered [1] to be a single meteorite from their apparent
shapes and unique texture.

This paper presents an evidence for these three meteorites
being a single meteorite. And also presents a method adopted
in our experimental procedure which includes a check for modern
carbon contamination in the meteorites.

The meteorite sample was pulverized in an airtight alumina
crusher for 10 hours. The powdered sample in a platinum boat
was put into a quartz tube and was evacuated for a few hours
at 100°C. The sample was then heated at 600°C for 5 hours under
vacuum(10^{-5}-10^{-6} Torr) to remove terrestrial contaminants. The
evolved gases were passed through a liquid nitrogen trap, where
CO_2 and other condensable gases were recovered. Noncondensable
gases mainly CH_4 and CO, were then passed through the CuO
furnace heated at 450°C-550°C, where CO was converted to CO_2,
and were recovered in a molecular sieve 4A cooled in liquid
nitrogen. The CO_2 condensed in a liquid nitrogen trap was
purified from SO_2 and H_2O by distillation at -150°C. The temperature
of the molecular sieve 3A was raised to dryice-methanol temperature.
The gas recovered from the molecular sieve 4A was circulated through
the CuO furnace at 800° for 40 minutes to oxidize CH_4 to CO_2 and
added to the previously recovered CO_2.

The sample in the quartz tube was then heated at 1200°C for
5 hours under vacuum. Evolved CO_2 gas was recovered with the
same procedure as in the case of 600°C. The residual sample was
heated again at 1200°C for 3 hours in oxygen atmosphere. The
CO_2 evolved in this step was collected as 1200°C fraction
together with the previous one.   The amounts of carbon

recovered at 600°C and 1200°C were measured volumetrically as CO_2 gases.

The CO_2 gases of both fractions were converted to acetylene through lithium carbide which was prepared by the reaction between metalic lithium and CO_2. The reaction of lithium carbide with tritium free water gave acetylene. The acetylene was purified by the adsorption in the molecular sieve 4A at 0°C and the desorption at 100°C. The molecular sieve 4A used here was prepared from radium free sodium aluminate and sodium silicate, and it gave no measurable amount of radon in the desorpted gases. The carbon-14 in the acetylene was counted in a proportional counter of 53.0 cm^3 which has a background of 0.373 $\pm$ 0.016 cpm.

As shown in Table 1, all 600°C fractions of recovered carbon have specific radiocarbon concentrations of nearly the same level to that of atmospheric carbon dioxide. This indicates that the 600°C fractions are mainly composed of the carbon of recent contamination on the earth. The terrestrial ages listed in Table 1 are calculated from the C-14 activities in the 1200°C fractions and that of of modern standard which is a mean value of measured C-14 activities of Allende and Bruderheim.

The terrestrial ages of Y-75102,Y-74459, and Y74013 are consistent with the measured values by Fireman[2] The agreement of the terrestrial ages of Y-74013,Y-74097, and Y-74136 supports the view that these are a single meteorite.

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RADIOCARBON DATINGS

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Table 1. Terrestrial ages and vacuum extraction
of carbon and C-14.

Meteorite (Wgt)	Type	Temp. (°C)	Recovered carbon (mg)	^{14}C (dpm/kg)	^{14}C Specific activity (dpm/g C)	Terrestrial age (10^3 yr)
Y-75102 (21.53 g)	L6	600	2.40	3.7 ± 1.5	19 ± 8	
		1000	0.82	20.2 ± 1.7	305 ± 25	2.0 ± 0.6
		1200*		18.2 ± 1.8		
Y-74459 (13.17 g)	H6	600	6.70	3.9 ± 1.8	8 ± 2	
		1000	0.68	< 1.4		19 ± 2
		1200*		3.6 ± 1.4		
Y-74013 (16.9 g)	DIO	600	1.31	1.9 ± 0.8	24 ± 11	
		1200	0.54	7.1 ± 1.0	222 ± 31	16 ± 1
Y-74097 (15.8 g)	DIO	600	1.41	3.3 ± 1.1	37 ± 12	
		1200	0.67	5.3 ± 1.1	120 ± 30	19 ± 2
Y-74136 (14.9 g)	DIO	600	1.44	2.1 ± 1.1	22 ± 12	
		1200	0.81	6.7 ± 1.5	123 ± 28	17 ± 1
Allende	C3	600	13.5	14.0 ± 1.5	20 ± 3	
		1200	35.4	49.1 ± 1.8	25 ± 1	Modern
Bruderheim	L6	1200		52.9 ± 2.3		Modern

* In this case ,sample was recrushed and small amount of
graphite was added.

ELEMENT DISTRIBUTION AND NOBLE GAS ISOTOPIC ABUN-

DANCES IN LUNAR METEORITE ALLAN HILLS A81005

U. Krähenbühl, Laboratorium für Radiochemie, An-
organisch chemisches Institut and O. Eugster and
S. Niedermann, Physikalisches Institut, Universi-
ty of Bern, Switzerland. βN790295

Antarctic meteorite ALLAN HILLS A81005, an anorthositic brec-
cia, is recognized to be of lunar origin [1]. Bogard and John-
son [2] analyzed the noble gases in this meteorite and found
solar-wind implanted gases, whose absolute and relative concent-
rations are quite similar to those in lunar regolith samples.

We obtained an 0.279 g sample (A81005,51) of this meteorite
for the analysis of the noble gas isotopes, including ^{81}Kr, and
for the determination of the elemental abundances. In order to
better determine the volume derived from the surface cor-
related gases, grain size fractions were prepared. After
crushing the sample using a stainless steel mortar 0.022 g ma-
terial was used for bulk analyses. The remaining mass was sepa-
rated by sieving in acetone into the following grain size frac-
tions: <15μm (0.0031g), 15-35μm (0.0048g), 35-74μm (0,010g), 74-149μm
(0.0216g) and >149μm (0.1925g).

Chemistry. About 20% of each size fraction was irradiated in
suprasil quartz vials for 4 days at 10^{14}n cm^{-2}s^{-1}. The results of
the instrumental measurements of the gamma radiation are given
in Table 1.

Table 1. Major and trace elements in grain size fractions of
         A81005,51. One sigma errors are ± 5% for Na, Fe, Cr,
         Co and Sc; ±5-10 % for Ca, La, Eu and Hf.

fraction	sample weight mg	Na %	Ca %	Fe %	Cr ppm	Co ppm	Sc ppm	La ppm	Eu ppm	Hf ppm
<15μm	0.91	0.24	10.5	–	780	18	9.2	–	0.50	0.60
15-35μm	1.21	0.24	11.8	3.95	800	18	9.4	1.90	0.53	0.55
35-74μm	2.48	0.27	12.4	4.75	770	17	10.3	1.60	0.61	1.05
74-149μm	5.22	0.22	11.6	3.25	750	19	8.5	1.70	0.63	0.60
>149μm	50.14	0.22	10.5	3.60	710	17	8.8	2.2	0.61	0.60

Concentrations were calculated relative to those in the refe-
rence sample IAEA soil-5 and in USGS standard BHVO-1. Our data
agree well with those reported by Laul et al. [3] and by Palme
et al. [4]. The anorthositic composition of this Antarctic me-
teorite is indicated by the high Ca value, the rather low Fe
concentration and the typical values for La and Eu compared with
the ones found in chondrites. All the five fractions show essen-
tialy the same distribution pattern. That means we have not
produced a major mineral fractionation by the grain size sepa-
ration. In order to determine the blank levels a sample of
suprasil quartz powder was subjected to the same grinding and
sieving scheme as the meteorite sample. High contamination was
observed for Ba and Br; therefore, no values are reported for
these two elements. Blanks for Na, Fe, Co, Sc, Cr and La amount
to less than 3% in the 35-74μm fraction. Blank corrections for
the <15μm fraction are about 10 times larger than for the 35-74μm
fraction (smaller sample weight, longer and more thorough contact
with sieving apparatus and acetone).

For Fe and La, blank corrections for the finest material are
larger than 60%; therefore, no values are reported. For Ca, Eu
and Hf blank corrections are negligibly small.

Production rates for cosmogenic noble gas nuclei

Because this meteorite spent less than 1 my in space as a small body [5] it must have resided in the lunar regolith during most of its cosmic ray exposure time. The shielding depth within the lunar regolith was determined from the ratio of cosmogenic ^{131}Xe/ ^{126}Xe = 4 ± 1, which corresponds to an average shielding depth of <50 g/cm^2. Production rates for cosmogenic noble gases were calculated from the data given by Regnier et al. [6] and Hohenberg et al. [7] for 2π irradiation at a shielding depth of 40 g/cm^2 using the target element abundances given in Table 1. For Mg, Al, Si, K and Ti values reported by Plame et al. [4] were used. Zirconium concentrations were calculated from Hf values using a ratio Zr/Hf of 31.8. The resulting production rates are given in Table 2.

Table 2. Concentrations of cosmogenic noble gases, production rates and exposure age of A81005.51 (preliminary data).

	^{3}He	^{21}Ne	^{38}Ar	^{83}Kr	^{126}Xe
Concentration (10^{-8}cm^3 STP/g) av. for bulk and grain size fractions	18	36	66	1.5×10^{-2}	1.55×10^{-3}
Production rate (10^{-8}cm^3 STP/g, my)	1.24	0.118	0.113	2.8×10^{-5}	2.8×10^{-6}
Exposure age (10^6 y)	15	305	584	536	554

Lunar surface residence time.

From the amounts of cosmic ray produced noble gases and respective production rates, the lunar surface residence times were calculated (Table 2). The ^{21}Ne exposure age and, in particular, the ^{3}He

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exposure age are erroneously low due to diffusion loss of these
noble gases, as typically observed for lunar rocks and soils.
From the fact that a plateau is obtained for three heavier noble
gases we conclude that the lunar surface residence time is about
half a billion years. More detailed results, including the terrest-
rial age of A81005 calculated from the ^{81}Kr concentration, will be
given in a later publication.

Acknowledgments.

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THERMOANALYTICAL CHARACTERIZATION OF SEVERAL ANTARCTIC METEORITES

B. Lang, Warsaw University, Department of Chemistry, 02-089 Warsaw, A. Grodziński, Institute of Electronic Materials, 02-075 Warsaw, L. Stoch, Technical University of Mining and Metallurgy, 30-059 Cracow

Following our first attempts to get thermoanalytical data for a number of meteorites [cf. Lang et al., 1981] we focused our attention on several meteorites from Antarctica: 5 achondrites, 2 chondrites and 1 iron. Received from the National Institute of Polar Research Tokyo they were:

achondrites :	Yamato-74010, diogenite
	Yamato-74013, diogenite
	Yamato-7308, howardite
	Yamato-74450, polymict eucrite
	ALH-765, polymict eucrite
chondrites :	Yamato-75102, L 3
	Yamato-74662, C 2
iron :	DRP-78007

We realize that our few data [cf. Lang et al., 1983, 1985; Żbik et al., 1984] are too preliminary and scarce to offer any valuable conclusions. The reported here few observations are expected to be useful in the future research of Antarctic meteorites including thermoanalytical study.

The thermochemical response to heating in air is observed distinct on the differential thermal /DTA/ and thermogravimetric /TG/ curves. However, within the heating range up to $1000°C$ exothermic peaks from oxidation are often seen on the DTA-curves accompanied by a mass increase on the TG-curves. Our experience suggests that in meteorites remarkable oxidation events are due - in the first approximation at least - possibly to iron. Wüstite FeO can be obtained from conversion of free iron or decay of nickel-iron to be further oxidized to magnetite Fe_3O_4 or even hematite Fe_2O_3. The final possible oxidation of free iron to hematite results in mass increase of ∿43%. The intermediate steps leading to ultimate oxidation of iron can eventually be seen on the DTA-curves as more or less resolved exothermic peaks.

Assuming an extremely simplified model of oxidation of iron to hematite, covering free iron, nickel-iron and iron sulfides, with TG-data we can estimate the oxidable part of the total iron. The term "oxidable" refers here to temperatures not exceeding $1000°C$. We received :

	Y-74013	ALH-765	Y-74450	Y-7308	Y-75102
Fe total wt%	13.77	16.42	15.21	13.45	22.24
mass increase wt%	0.64	1.4	2.6	2.6	2.1
Fe oxidized %%	3.1	6.06	11.42	12.92	6.26

For Derrick Peak-78007 iron the mass increase as low as ∿3.5% proves by far incomplete oxidation during heating in air. Similar result was received by us for the Sikhote Alin iron (3.88%).

The effects of oxidation processes can often be better identified by comparing the DTA-curves for heating in air with those as obtained for heating in oxidation-suppressing atmosphere of

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argon. Unfortunately in the latter case the TG-data were unavailable. Meandering of the DTA-curves is another feature of the applied thermoanalytical techniques making difficult the analysis of the curves.
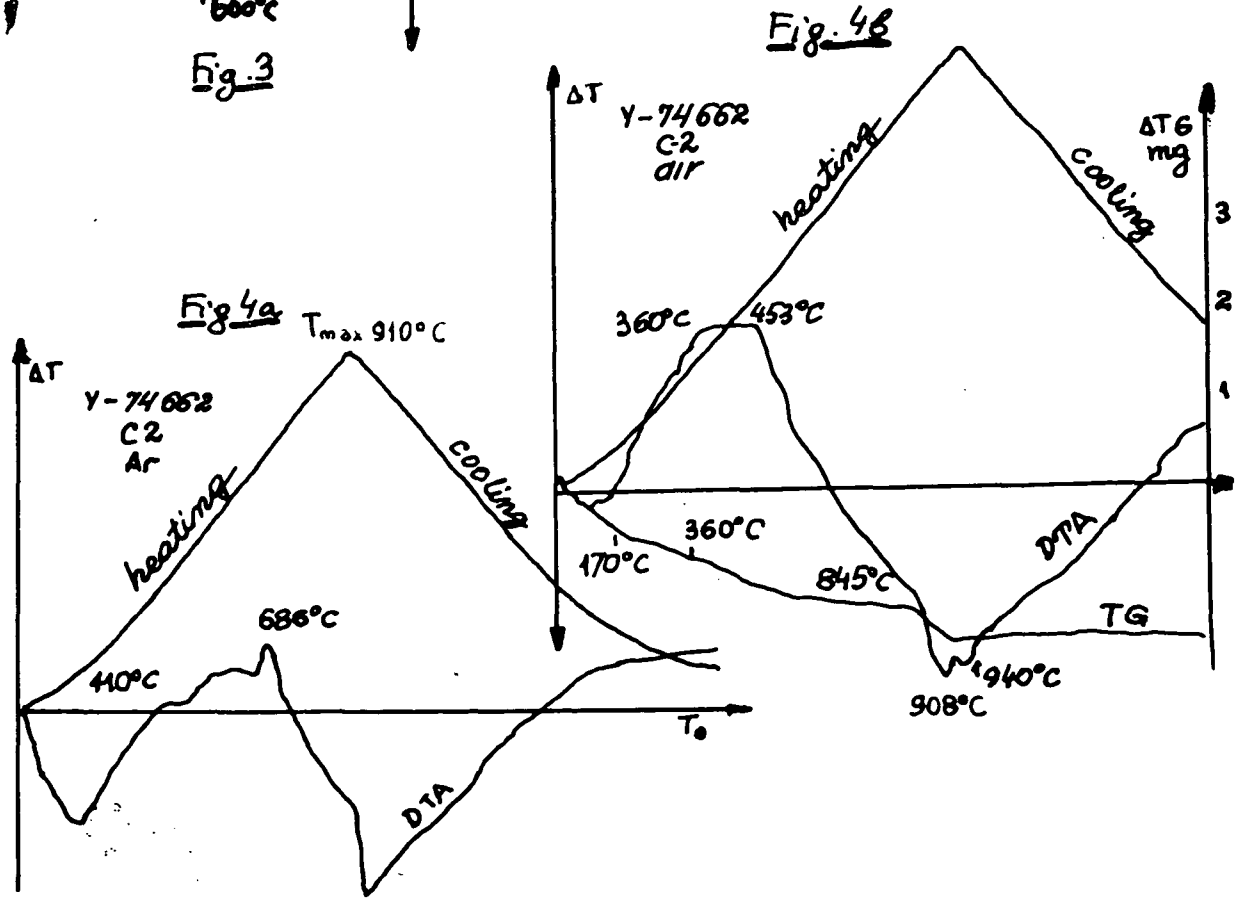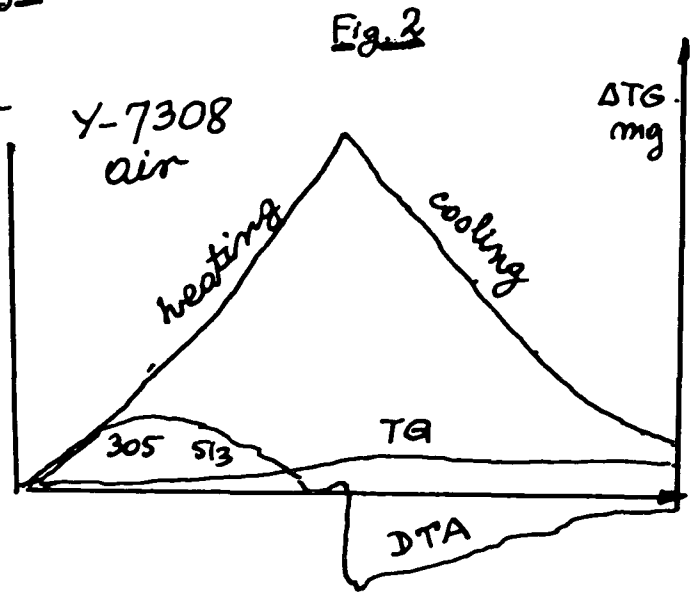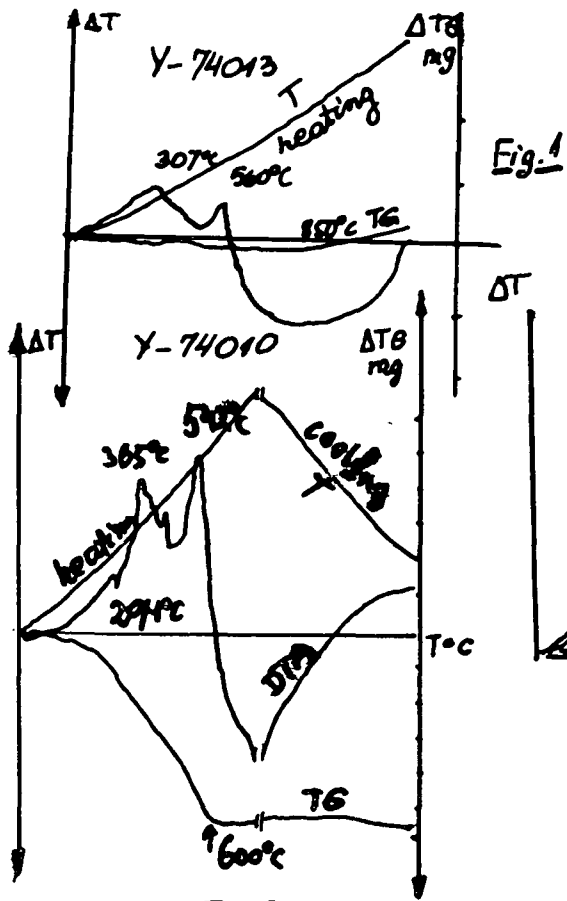
Thermoanalytical method can be helpful in determining the degree of weathering of meteoritic material. With this purpose it was applied by Gooding [1981] . Weathering results in appearance of mineral forms which at least partially volatilize even at non-elevated temperatures. In the case of the Antarctic meteorites such behavior of meteoritic material is not observed. The thermogravimetric losses are small - they do not differ from those of non-Antarctic meteorites.However, in the case of the Yamato diogenites -74010 and -74013 we analyzed samples stored without any special precaution in test tubes for a couple of years: we obtained thermoanalytical curves remarkably changed [see Lang et al., 1983] . This observation seems to argue that natural conditions in Antarctica where the meteorites were found do not favour significantly their weathering. Naturally, such a conclusion needs further examination of Antarctic meteorites accounting the problem.

A distinct behaviour during heating in air was identified in the case of the Yamato-74662 carbonaceous chondrite C 2. Heated in air it lost rather smoothly $\sim 9.3\%$ of its original mass. We attributed these thermogravimetric losses to joint volatilization of water and carbon compounds. An unique feature of this meteorite is seen on the DTA-curve for heating in argon. The remarkable exothermic peak at $686^\circ C$ - similar in shape to oxidation peaks - should be referred presumably to formation of a new mineral form possibly of remnants of phyllosilicates affected by heating while being a major component of the original meteorite.

In Fig.1 and 2 are given the thermoanalytical curves for Yamato-74013 diogenite and Yamato-7308 howardite respectively. In Fig.3 is demonstrated the effect of storage of powdered diogenite Yamato-74010 for two years in a test tube. In Fig.4a and 4b are shown the curves for the Yamato-74662 for heating in argon and in air respectively.

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Fig.1 — Y-74013 T heating, 307°, 560°c, 850°c TG

Fig.2 — Y-7308 air, heating, cooling, 305, 513, TG, DTA

Fig.3 — Y-74010, heating, 365°c, 540°c, 294°c, DTA, TG, 600°c

Fig.4a — Y-74662 C2 Ar, Tmax 910°C, heating, cooling, 686°C, 440°C, DTA

Fig.4b — Y-74662 C-2 air, heating, cooling, 360°C, 453°C, 170°C, 360°C, 845°C, DTA, TG, 940°C, 908°C

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TRACE ELEMENTS IN ANTARCTIC METEORITES: WEATHERING AND GENETIC INFORMATION; M. E. Lipschutz, Dept. of Chemistry, Purdue University, W. Lafayette, IN 47907 USA.

Antarctic meteorite discoveries have created great scientific interest due to the large number of specimens recovered (~7000 so far) and because they include representatives of hitherto rare or unknown types. Some can be paired, on average 2-6/event [1]: these 1200-3500 separate Antarctic meteorites form a population comparable to the 2611 known non-Antarctic meteorites [2]. Antarctic meteorites are so abundant because they have fallen over long periods ($\leq 7 \times 10^5$ years, averaging 3×10^5 years in Victoria Land) and have been preserved, transported and concentrated by the ice sheet [3].

Differences between the Antarctic and non-Antarctic sample populations are evident at various subtlety levels, even at the least subtle (Table 1) [4]. Antarctic meteorites are therefore a potentially unique source of genetic information provided that weathering during terrestrial residence in or on the ice sheet can be accounted for or is negligible.

Antarctic meteorites (stones, in particular) are classified by macroscopic (and fracturing) characteristics into 3 types, A-C, ranging from essentially unaltered to very heavily weathered. Meteoritic compositions should reflect terrestrial weathering unless it occurs in situ so that elements are neither gained nor lost, i.e. the system is closed. Trace element contents should be particularly instructive since even a small absolute amount of chemical transport should result in large relative compositional changes.

The few studies thus far indicate that Antarctic meteorite weathering essentially involves closed systems. Lipschutz [5] reviewed data published in 1980 and earlier - mainly for uncommon meteorites of weathering types A and B. Provided that interior samples (>0.5 cm below the meteorite's surface) are used, compositions of Antarctic finds and non-Antarctic falls of uncommon type accord well, although analytical ranges for the falls can be extended by data for Antarctic finds.

More recently, weathering effects on trace element contents of H5 chondrites have been studied in detail [4,6]. Of 13 elements studied, 5 are more abundant in weathering type A and B H5 chondrites than in those of type C: Bi and Cs differ at significant (>95% confidence) levels, Co, Sb and Tl at possibly significant (90-94%) ones. For 3 samples with weathering rinds, interior samples contain signficantly more Cs and possibly Te than do rinds: these seem attributable to chance. ALH A82102, an H5 chondrite caught emerging from the ice, reveals no systematic difference between exposed and submerged portions beyond that attributable to chance. As proposed earlier [5], these more recent data suggest leaching as the primary Antarctic weathering process for H5 chondrites and, presumably, others. The effects are, however, minor and, with proper precautions, data from Antarctic meteorites are as reliable as those obtained from non-Antarctic falls [5]. Interestingly, trace and major element dispersion is generally smaller in Antarctic samples than in non-Antarctic falls [4, 6-8].

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Table 1. Comparative numbers of selected meteorite types *
found in Victoria Land and falling in non-Antarctic regions

Meteorite Type	Victoria Land		Non-Antarctic	
	No.	Pct.	No.	Pct.
Chondrites	756	92.4	784	86.6
H	*542*	*66.3*	*276*	*30.5*
L	*167*	*20.4*	*319*	*35.2*
LL	*24*	*2.9*	*66*	*7.3*
Achondrites	45	5.5	69	7.6
Irons	14	1.7	42	4.6
Stony Irons	3	0.4	10	1.1
Total	818	100.0	905	100.0

*Data from sources listed by Dennison et al. [4]. Queen Maud
Land (Yamato) samples and non-Antarctic finds also exhibit
the same trends: deficiencies of LL chondrites, irons and
stony-irons and a very high H/L chondrite ratio in Antarctic
meteorites compared with non-Antarctic ones [4].

Table 2. Comparison of statistically significant differences in H5
and L6 chondrites from Victoria Land, Antarctica with
contemporary non-Antarctic falls [4,8].

Element	H5[†]			Element	L6[†]		
	Ant.(23)	Non(20)	Sig.		Ant.(13)	Non(25)	Sig.
				Co(ppm)[*]	480	600	97
				Au(ppb)[*]	140	160	*90*
Sb(ppb)[*]	83	69	97				
Se(ppm)	9.0	8.2	99				
Rb(ppm)	2.0	2.5	97	Rb(ppm)	2.6	2.2	95
				Cs(ppb)	4.02	12.4	99
				Te(ppb)	340	380	*90*
Bi(ppb)	2.8	1.1	98	Bi(ppb)	0.58	2.7	99
				Ag(ppb)	45	71	97
In(ppb)	0.21	0.49	97				
Tl(ppb)[*]	0.81	0.24	96				
Zn(ppm)	43	53	96				
Cd(ppb)	0.72	3.7	99	Cd(ppb)	1.6	14.2	99

*Arithmetric means: all others are geometric means.

†Column headings: Ant - Antarctic chondrites from Victoria Land; Non -
Non-Antarctic chondrite falls; Sig. - Significance level at which it
may be concluded that the respective sample populations do not derive
from the same parent population. Numbers in parentheses are number of
samples analyzed in that population.

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Properties of Antarctic finds and non-Antarctic falls differ to degrees well beyond those expected to arise from weathering [4]. Differences more subtle than those in Table 1 are apparent when trace element contents of H5 or L6 chondrites from Victoria Land are compared with respective non-Antarctic falls. Using normal or lognormal distributions and standard statistical tests, 8 of 13 elements differ at >90% confidence level in each population (Table 2). [Furthermore, the differences are apparent in all equilibrated H and L chondrites, at least.] While elements that differ overlap to some extent, those that do differ in direction. From these and other data cited earlier, we can show that differences do not reflect Antarctic weathering or incidental causes (sample selection bias, compositional modeling, analytical bias or chance) [4,8].

We interpret compositional differences as reflecting derivation of Antarctic meteorites predominantly from parent sources or regions different than those from which contemporary falls derive. Hence, the near-earth meteoroid complex sampled by Victoria Land 3 x 10^5 years ago differed from that sampled today [4]. For example, the Victoria Land L6 chondrite sample population predominantly derived from a body or region much more heavily shocked, on average, than the one(s) we now study through contemporary L chondrites [8]. Antarctic meteorites truly constitute a solar system snapshot in time and/or space.

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TERRESTRIAL AND EXPOSURE HISTORIES OF ANTARCTIC METEORITES: K. Nishiizumi,
Dept. of Chem., B-017, Univ. of Calif., San Diego, La Jolla, CA 92093 (U.S.A.)

Records of cosmogenic effects (noble gases, radionuclides, and cosmic ray
tracks) have been studied in a large suite of Antarctic meteorites. The cosmo-
genic nuclide measurements together with cosmic ray track measurements (if pos-
sible) on Antarctic meteorites provide us with information such as exposure age,
terrestrial age, size and depth in meteoroid or parent body, influx rate in
the past, pairing, and so on. The first two ages are of special interest.
The exposure age is the time period between meteorite ejection from its parent
body and capture by the earth. The cosmogenic nuclides are produced during
this period by interraction of cosmic rays in space. The terrestrial age is
the time period between the fall of the meteorite on the earth and the present.
To define both ages, two or more nuclides with different half-lives and pos-
sibly noble gas data are required.

In the present work, we emphasize the terrestrial age of Antarctic mete-
orites based on their cosmogenic radionuclides. The cosmogenic radionuclides
for this study are ^{14}C ($t_{1/2}$ = 5740 years) [e.g. 1,2,3], ^{81}Kr (2.1×10^5 years)
[e.g. 4,5], ^{36}Cl (3.0×10^5 years) [e.g. 6,7,8], ^{26}Al (7.05×10^5 years) [e.g. 9,
10], ^{10}Be (1.6×10^6 years) [e.g. 11,12], ^{53}Mn (3.7×10^6 years) [e.g.13,14,15] and
^{40}K (1.28×10^9 years) [e.g. 16].

Terrestrial age: Figure 1 is a histogram of terrestrial ages of Yamato,
Allan Hills, and other Antarctic meteorites. The figure shows the average age
for same fall (pair) meteorites and does not include the so-called 3.5×10^4
year peak for ^{14}C age [2]. This figure indicates several features. The ter-
restrial ages of Allan Hills meteorites are widely distributed between 1×10^4
and 7×10^5 years and clearly show longer ages than both Yamato and non-Allan
Hills meteorites. This is expected because the meteorite surface density on
the Allan Hills blue ice is much higher than that at the Yamato mountain area.
All six Meteorite Hills meteorites which we have so far measured show terres-
trial age less than 1×10^5 years. The shape of the two distributions is dif-
ferent. The terrestrial ages of Allan Hills meteorites show poisson distri-
bution and others show exponential distribution. It is not clear that the
difference is due to different accumulations mechanisms or sampling bias for
measurements. For Allan Hills meteorites, there is no clear correlation be-
tween the terrestrial age and their weathering features. It may be that wea-
thering is mainly dependent on exposure time at the ice surface. Meteorites
found on the west and north part of the Allan Hills blue ice region have shor-
ter terrestrial ages than meteorites found on the south and east part. This
trend is similar to the flow direction of the surface ice. Figure 1 also in-
dicates that the terrestrial ages of Allan Hills L-chondrites are widely dis-
tributed up to 7×10^5 years compared to other types of meteorites. We are not
confident that this indicates a different influx rate of L-chondrites in the
past, because of inadequate statistics and sampling artifacts which were the
result of non-random selection of samples for measurement of terrestrial age
determination. Additional studies are required to clarify this.

Cosmic ray exposure history: There is no distinguishable difference be-
tween Antarctic meteorites and non-Antarctic meteorites with regard to expo-
sure age. The distribution of ^{21}Ne exposure ages of Antarctic meteorites
[e.g. 17,18,19] is very similar to that of non-Antarctic meteorites [20].
Figures 2-a and 2-b show the histogram of ^{53}Mn results in L-chondrites (2-a)
and H-chondrites (2-b) of both Antarctic and non-Antarctic meteorites. The

values have not been corrected for undersaturation. These two histograms for both classes of meteorites are surprisingly similar to each other. It is completely different from the histogram of nuclides with shorter half-lives, [26]Al [9,10] and [36]Cl. Figures 2-a and 2-b indicate that the terrestrial ages of the Antarctic meteorites are usually short compared to the half-life of [53]Mn, and also that the [53]Mn contents of Antarctic meteorites are useful for the study of meteorite exposure history. We found several interesting exposure histories among Antarctic meteorites, for example, two stage irradiations for ALHA 76008, Yamato 7301, 74028 and 74116 [6,14] and Solar Cosmic Ray effects for ALHA 77005 [unpublished]. These discussions will be described elsewhere. In general, we found no distinguishable differences between the average exposure histories for the two sources of meteorites.

New methods: We have started two new dating methods for measuring terrestrial ages of Antarctic meteorites and the history of the glacier. The cosmogenic nuclide [41]Ca with half-life of 1.0×10^5 years can fill the gap between ^{14}C and [81]Kr, also [36]Cl for measurements of the terrestrial age of Antarctic meteorites. The [41]Ca in the metal phase is produced by high energy spallation such as [36]Cl in the metal phase. The production rate of [41]Ca is insensitive to size and depth for a meteorite of normal size. The first accelerator mass spectrometry measurement of this nuclide in the Bogou iron meteorite [21] demonstrates that [41]Ca can be measured in 100-200 mg of meteoritic metal. The sample size will be reduced after improvements of the ion source of the accelerator. We also demonstrated in situ production of [10]Be and [26]Al in quartz samples [22]. The concentrations of both nuclides and the ratio show the erosion rate and cosmic ray exposure age of the quartz on the earth's surface [23]. The measurement of this pair in Antarctic quartz indicates that how long the quartz was exposed on ice or snow. The first measurements of [10]Be and [26]Al in a quartzite which was collected at the peak of Allan Hills shows that the top of Allan Hills was not covered by ice for the last 1 million years [22]. The measurements of [10]Be and [26]Al in other quartz collected at different locations are in progress.

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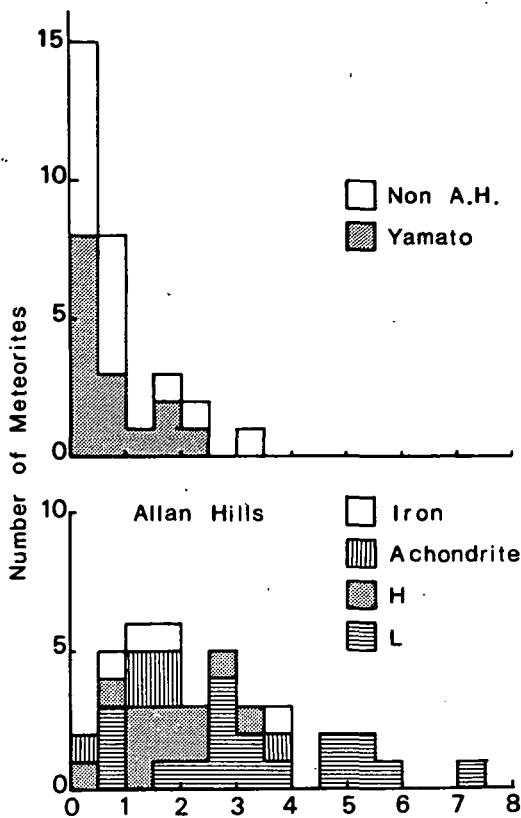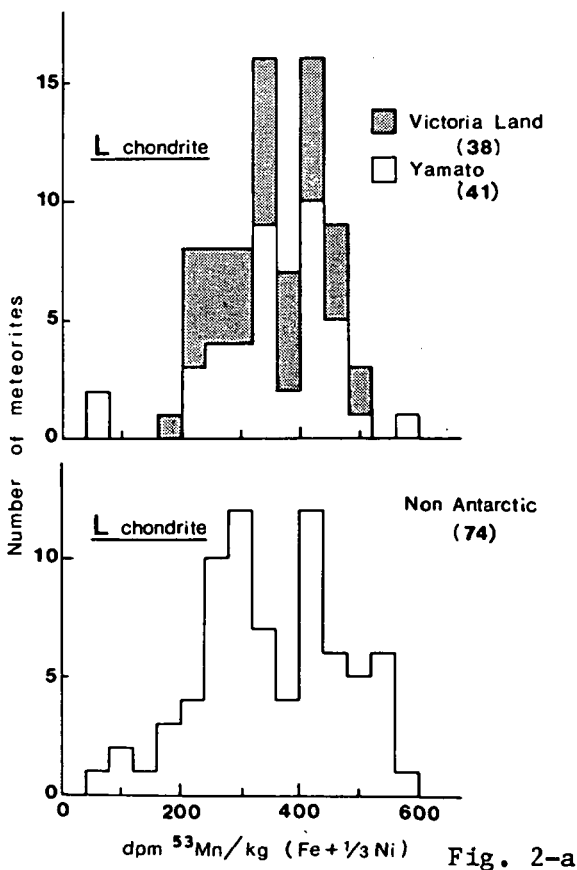
Fig. 1 Terrestrial Age (10⁵y)

Fig. 2-a

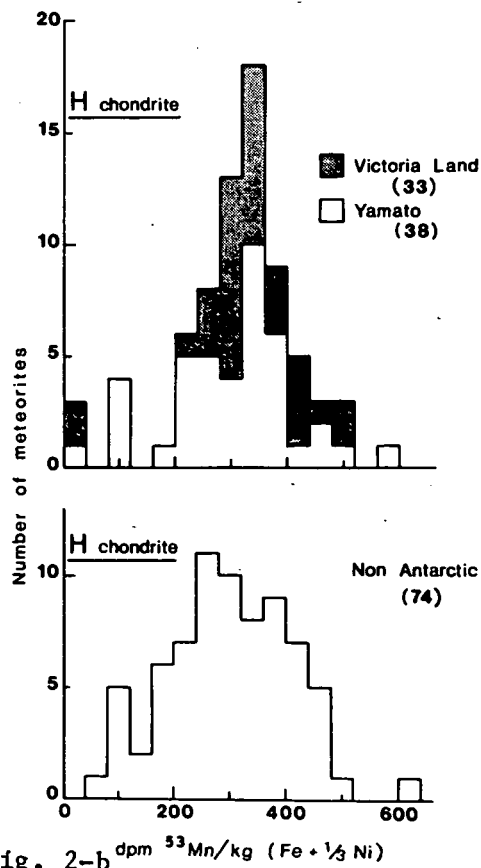Fig. 2-b

WEATHERING EFFECTS AND SOLAR COMPONENTS IN TWO ALLEN
HILLS CHONDRITES. J.T. Padia and M.N. Rao, Physical
Research Laboratory, Ahmedabad, India 380 009.

We have studied two Allen Hills chondrites, ALHA 77252
and ALHA 77215 belonging to the L-group, by stepwise
heating mass spectrometric methods for elemental and isoto-
pic composition of noble gases.

The neon data points representing 600°C, 900°C, 1200°C
and 1600°C temperature fractions are plotted in the three
isotope neon diagram, Fig. 1. All the data points, in-
cluding the first temperature fractions (i.e. 600oC) fall
much below the solar wind point (SW) in Fig. 1, clearly
indicating the complete removal of solar wind from these
samples. These two ALHA samples were found to contain
irradiated track-rich grains (1) and hence are considered
to be gas-rich meteorites. It may be noted here, that prior
to performing the mass spectrometric analysis, we have not
given any chemical etching treatment to these samples in
our lab. The distribution of the data points of ALHA 77252
and ALHA 77215 samples in Fig. 1 suggests that the surface
sited loosely bound solar wind was driven away from the irra-
diated grains by some natural etching process. As these
Allen Hills chondrites were lying in Antarctic ice for
several thousands of years and while most of the interior
metal grains in these samples show signs of weathering, it
is likely that the weathering process could have resulted
in chemical etching of the grain surfaces over long periods
of time, driving away the implanted SW from these grains.

In the case of the etched mineral residues, (after the
solar wind removal) the data points represent varying mix-
tures of implanted solar flare neon and combined GCR and
SCR spallation depending on their cosmic ray exposure
history. For a given sample, the data points could be
fitted to a best-fit line (not shown in Fig. 1). In the
case of ALHA 77215, this line when extrapolated upwards
will intersect the SW-SF-A-P (solar wind-solar flare-
Atmosphere-Planetary) line at 11.6 ± 0.2 for the Ne-20/Ne-22
ratio for a 21/22 ratio of 0.031 ± 0.002. The data set
belonging to the ALHA 77215 is found to be free from experi-
mental problems compared to ALHA 77252. The value obtained
for ALHA 77252 agrees with that given above within experi-
mental errors.

The ^{3}He/^{4}He value obtained in the case of ALHA 77215
is about 8.5×10^{-4} (total) and in the case of ALHA 77252
it is about 1.3×10^{-3} (total). These are the tentative
values,

Further, a method to resolve the SCR-proton produced neon
component from these two gas-rich chondrites is discussed
briefly.

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Figure Caption: Fig. 1. Neon diagram in which the
data of ALHA 77252 and ALHA 77215 are plotted. Though
the Kapoeta data are plotted for comparison, they are
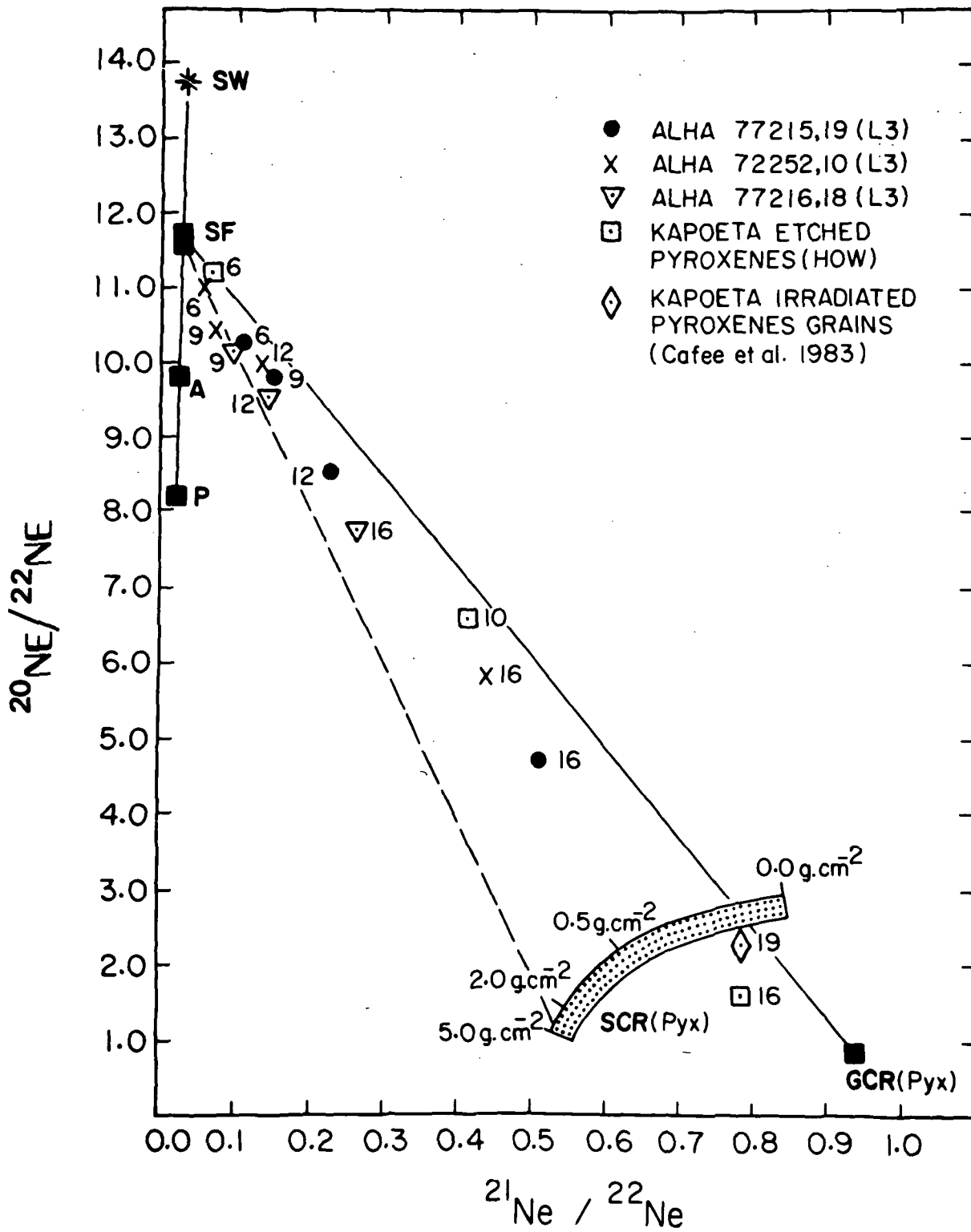discussed elsewhere.

Fig.1

RARE AND UNIQUE METEORITES FROM ANTARCTICA

H. Palme, Max-Planck-Institut für Chemie, 65 Mainz, F.R. Germany

Among the several thousand meteorite specimens recovered from Antarctic ice-fields, there is a certain number of meteorites, that deserve special attention. They either belong to meteorite classes with only few members or they are unique in the sense that they do not fit into any of the existing meteorite groups. The importance of some of these meteorites cannot be overestimated. For example, the detection of Antarctic meteorites of Lunar and perhaps Martian origin, belongs to the most important discoveries in planetology during the last years. The prospect of finding more of these meteorites should be incentive enough to continue the collection of Antarctic meteorites for the next decade.

Lunar Meteorites:

On January 18, 1982 an, by appearance, unusual meteorite was collected in Antarctica (1). The specimen weighed 31.4 grams and was designated ALHA 81005. By the time of the 14th Lunar and Planetary Conference in March 1983 it was unanimously agreed by the scientific community, that this meteorite represents ancient lunar highland crust (2).

In 1985, papers given at the 10th symposium on Antarctic meteorites in Tokyo described a lunar meteorite from the Yamato mountains (3). This meteorite (Y-791197, 52.4 grams) was only recently recognized as a lunar rock, although it was collected in 1979, 2 years before the Allan Hills Lunar meteorite. Still another lunar meteorite Y-82192 (36.7 grams) was identified in the Japanese collection (4). The two lunar meteorites investigated so far, ALHA 81005 and Y-791179, are very similar in texture, mineralogy and chemical composition. Both meteorites are anorthositic regolith-breccias with solar wind implanted rare gases (4, 5). The two lunar meteorites contain abundant lithic and mineral clasts, similar to those from Apollo highland breccias (6, 7). The absence of KREEP, a component rich in incompatible elements in front-side Apollo highland rocks, and the pattern of siderophile elements suggest that both meteorites sample the old lunar crust (older than 4 b.y.) some distance away from the large basins on the front side. They are perhaps samples from the far-side of the Moon. A closer inspection, however, reveals significant differences between ALHA 81005 and Y-791179. The Yamato lunar meteorite has a higher Fe/Mg ratio and a higher content of Sc, than the Allan Hills meteorite and most of the Apollo highland rocks (7, 8). Therefore the composition of the Y-791179 meteorite does not fit into the mixing diagram that has been successfully established for lunar highland samples from the Apollo missions (9). The ALHA 81005 meteorite does marginally lie within compositions of the mixing diagram (10). The major and trace element chemistry of the front-side samples was established by large basin forming impacts 3.9 to 4 b.y. ago. These samples probably contain material from deeper stratigraphic levels. Impacts on the far side did not penetrate the crust (because of its larger thickness). Therefore, meteorites such as Y-791179, which is likely to come from the far side may provide the opportunity to study the composition of the earliest lunar crust. Another important signature of the Y-791179 meteorite is its high content of volatile elements, which is in some cases comparable to the volatile rich rusty rock 66095 (11). Similar high Ga contents, as those found in some fragments of ALHA 791179 have never been observed in other highland samples (7, 11). Since Ga enrichment is accompanied by enrichments of other volatiles (11) there is no doubt that the high Ga is a result of a general enhancement in volatile elements. Redistribution of volatile elements may

therefore be a moon-wide phenomena. There is, abundant evidence for these processe to have occurred on the front side 3.9-4.0 b.y. ago. The Yamato lunar meteorite clearly demonstrates the importance of of mobilisation of volatile elements on a more Moon-wide basis. Some preliminary age data suggest that volatilisation and recondensation may have occurred around 3.9 b.y. at the same time as on the front side (12).

With these questions in mind one may well anticipate that additional lunar meteorites will considerably enhance our knowledge of the formation of the lunar highland crust. Some 5 to 10 more lunar meteorites could solve some important questions of lunar geochemistry. We would then presumably know the average far-side composition. With this knowledge better models for the early differentiation of the Moon, including formation of an anorthositic crust, could be set up.

Meteorites from Mars?

An important consequence of the discovery of lunar meteorites (without noticeable shock features) is the increasing readiness of researchers to accept the proposition that the SNC-meteorites (Shergottites, Nakhlites, Chassignites) are impact ejected Mars rocks. Some of the most convincing evidence is obtained from nitrogen isotope determinations and rare gas abundance measurements on samples from the Antarctic meteorite EETA 79001 (13, 14). This meteorite and the Allan Hills A 77005 have increased the number of potential Mars meteorites by some 30 %. There is, of course, the hope to find more SNC-meteorites by future Antarctic expeditions or even identify SNC-meteorites in the present Antarctic meteorite collections. Any new SNC-meteorite may provide the crucial evidence for a Martian origin of the SNC-group. In contrast to the time before the detection of Antarctic meteorites we are now in the position to actively pursue these questions by further searching for those meteorites.

Meteorites from the parent body of basaltic achondrites:

A comparatively large number of eucrites, howardites, and diogenites were recovered from the Antarctic. These samples from the third differentiated planet, aside from the Earth, provide important evidence for accretion and differentiation of a small planet under reducing conditions. For unknown reasons eucritic samples from the Antarctic are dominated by polymict eucrites, sampling a variety of compositionally different basaltic clasts (15). We have in our laboratory, for example, analysed clasts from a polymict eucrite (Y-790266). One of these clasts contains abundant sulfides with high contents of Ni, Co, Ir and other siderophile elements (16). This kind of evidence may have some bearing on the evolution of a metal-sulfide core of the eucrite parent body. The Antarctic samples from the eucrite parent body will certainly help deciphering the still controversial story of the evolution of this small planet.

Chondritic meteorites:

The relatively large number of C2 and C3 meteorites from Antarctica may contain a wealth of information on early solar system processes. Detailed investigation of these meteorites is just beginning. We are still expecting the first C1 chondrite.

An unusual chondritic meteorite ALHA 77081 was recovered in 1977 (17). It has chondritic composition and achondritic texture. With its high content of volatile elements and its reduced mineral chemistry, this meteorite belongs to the same group as Acapulco, Winona, silicate inclusions in IAB etc. (18). Such a small meteorite (8.56 g) can only be spotted on a white ice-field. There may

probably be more unusual meteorites among the not yet fully investigated small meteorites.

There are also rare unequilibrated enstatite chondrites among Antarctic meteorites (19). In one of the Antarctic enstatite chondrites solar type rare gases were detected, indicating for the first time the existence of regolith on an enstatite chondrite parent body (20).

In the 10th symposium of Antarctic meteorites a lodranite was described (21). Texture and chemistry of this meteorite (Y-79149) suggest that it is a cumulate rock. Although probably because of a parent body with a small gravity field, there was no separation of metal, sulfide, and silicate. Evidence such as this provides important information on the initial differentiation of small planets. It may in addition be possible to extract from these assemblages data on metal- silicate and sulfide-silicate partitioning of trace elements, such as Ni, Co etc. These data are essential in modelling the early differentiation of the Earth.

In summary, there is such a wealth of new information on differentiated and undifferentiated planetary bodies deduced from Antarctic meteorites that it is at present not possible to even qualitatively foresee the impact that these meteorites will have on our understanding of the formation and differentiation of large and small planets in our solar system.

In the past years considerable efforts have been devoted to search for presolar material. Inclusion of Antartic meteorites into these programs has not even started. There is no doubt, in my opinion, that it will not take very long, when new existing evidence will be provided by these meteorites. And if it is for no other reason than the large number of unequilibrated carbonaceous and ordinary chondrites among the Antarctic meteorite collections.

Lit.:
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TERRESTRIAL AGES OF ANTARCTIC METEORITES: IMPLICATIONS FOR CONCENTRATION MECHANISMS. Ludolf Schultz, Max-Planck-Institut für Chemie, 65 Mainz, FRG.

Antarctic meteorites differ from meteorites fallen in other places in their mean terrestrial ages. BOECKL (1) estimated the terrestrial "half-life" for the disintegration of stone meteorites by weathering under the climatic conditions of the Western United States of America to about 3600 years. Antarctic meteorites, however, have terrestrial ages up to $7 \cdot 10^5$ yrs, indicating larger weathering half-lifes.

The terrestrial ages of meteorites are determined by their concentration of cosmic-ray-produced radionuclides with suitable half-lives. ^{14}C, ^{26}Al and ^{36}Cl have yielded reliable ages of Antarctic meteorites. A summary of the results is given by NISHIIZUMI (2). Because of the long half-life of ^{26}Al ($t_{1/2} = 7 \cdot 10^5$ yrs) this isotope is only useful for terrestrial ages greater than about $3 \cdot 10^5$ yrs. On the other hand, ^{14}C-terrestrial- ages can only be measured when the age is less than about $4 \cdot 10^4$ yrs. The gap between these limits is partly closed by measurements of ^{36}Cl. This isotope must be measured in the metal phase of meteorites because the production of cosmogenic ^{36}Cl in silicate phases is highly variable. To determine also terrestrial ages of achondrites, which do not contain any metal phase, we have used ^{81}Kr ($t_{1/2} = 2 \cdot 10^5$ yrs) combined with cosmogenic ^{38}Ar (3-5). A summary of these results is given in Tab. 1.

From these measurements and also from mineralogical investigations (6) it became clear that many Antarctic achondrite specimens are paired or even multiple falls. Most of the Yamato polymict eucrites belong to two falls only; the same is true for the Elephant Moraine eucrites. Also all investigated Allan Hills polymict eucrites are parts of one fall. Therefore, from 17 meteorites investigated only ten individual terrestrial ages are obtained.

Fig. 1 shows the distribution of terrestrial ages of Allan Hills and Yamato meteorites. To discuss the distribution of terrestrial ages of Allan Hills meteorites the following assumptions are made:
- Since more than $7 \cdot 10^5$ yrs a "steady-state" situation is present concerning ice movement. ablation, meteorite infall rate etc.
- The sink for meteorites is physical weathering. Weathering (= destruction) takes place only for meteorites sitting on the surface of the ice. The destruction is proportional to the number of meteorites exposed. The removal of meteorites by strong winds or meteorite hunters is not important for this discussion.
- Allan Hills meteorites are direct falls and meteorites transported within the ice to their place of recovery.
- Meteorites with terrestrial ages less than 10^5 yrs are direct falls.

Fig. 2 shows the expected distribution of terrestrial ages which was constructed with a destruction half-life of $1.6 \cdot 10^5$ yrs and a transport time of the meteorites within the ice (without weathering) of $1.5 \cdot 10^5$ yrs. The ratio of local falls to transported meteorites is 1:1 which is anticipated by transport models (7). The agreement between the calculated distribution of terrestrial ages and observation is reasonably good, although the number of dated meteorites is still rather small.

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Most of the Yamato meteorites have shorter terrestrial ages than the Allan
Hills meteorites (see Fig. 1). This difference has been noted earlier by HON-
DA (8), NISHIIZUMI et al. (9), FIREMAN (10), and JULL et al. (11). If these
meteorites are direct falls only the weathering half-life must be greater
compared to Allan Hills conditions. This, however, seems not to be likely.
JULL et al. (11) explain the absence of Yamato meteorites with greater ter-
restrial ages by the removal of these stones by ice flow through the block-
ing system of the Yamato Mountain barrier. However, it seems to be also pos-
sible that the Yamato ice field is not stagnant for a sufficient long time.
Direct falls dominate the Yamato meteorites; accumulation took place not long
enough to build-up the pattern of weathering in the distribution of terres-
trial ages. This model implies that the Yamato ice field has an age of less
than 10^5 yrs and that the concentration mechanism by ice movement plays only
a minor role. Absolute ages of ice could help to clarify this problem.

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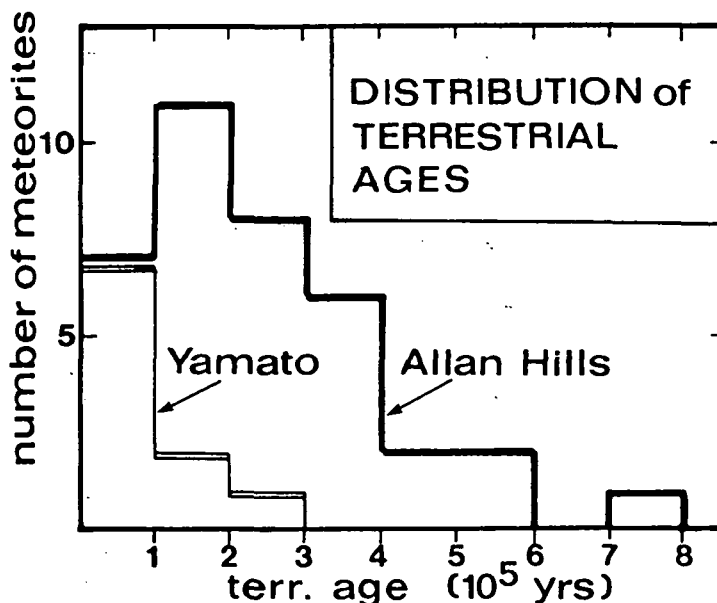Lunar Planet. Sci. Conf. 15th, in J. Geophys. Res. 89, p. C329-C335.

Fig.1: Distribution of terrestrial ages of Allan Hills and Yamato meteorites
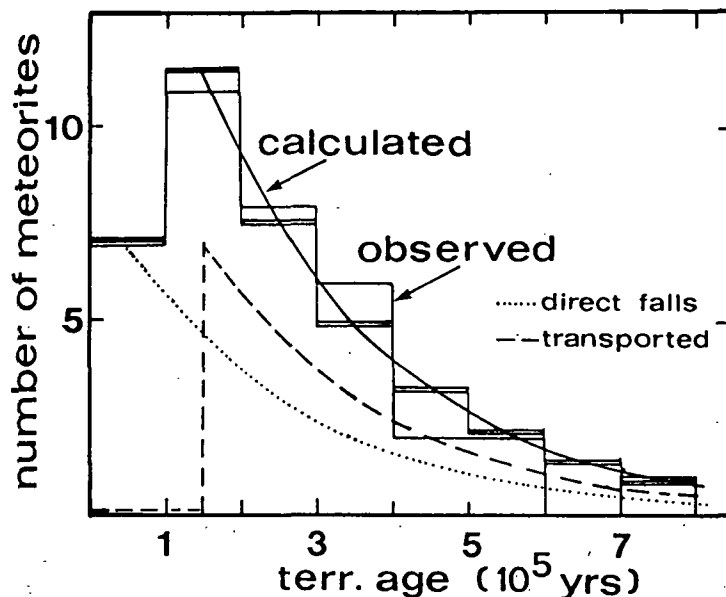   (2,11,Tab.1). Possible paired falls are counted only once.

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Fig.2: For Allan Hills meteorites the distribution of terrestrial ages is cal-
culated from direct falls and transported meteorites. The "weathering"
half-life on the surface of the ice is $1.6 \cdot 10^5$yrs and the transport
time within the ice is about $1.5 \cdot 10^5$ yrs.

Tab. 1: Terrestrial ^{81}Kr and exposure ages of Antarctic achondrites.
Brackets indicate paired falls.

Sample	Class	Terrestrial age (10^3yrs)	Exposure age (10^6yrs)
ALH 78132	Euc	121 ± 52	16.1 ± 1.2
ALH 79017	Euc	117 ± 51	15.5 ± 1.7
ALH 81009	Euc	115 ± 92	14.5 ± 1.6
ALH 77005	She	190 ± 70	3.6 ± .4
EET 79004	Euc	250 ± 23	21.6 ± 2.1
EET 79005	Euc	185 ± 41	27.6 ± 1.7
EET 79006	Euc	190 ± 39	26.2 ± 1.6
EET 82600	Euc	173 ± 29	26.3 ± 1.9
TIL 82403	Euc	≤32	28.5 ± 1.8
PCA 82502	Euc	309 ± 31	21.9 ± 1.5
Y 74450	Euc	≤44	73.3 ± 6.5
Y 790007	Euc	≤34	73.5 ± 7.2
Y 790122	Euc	111 ± 31	24.4 ± 1.8
Y 790260	Euc	140 ± 32	21.6 ± 1.7
Y 790266	Euc	150 ± 33	22.0 ± 2.0
Y 75032	Dio	22 ± 56	17.2 ± 1.6
Y 790727	How	225 ± 58	12.7 ± 1.2

THERMOLUMINESCENCE AND ANTARCTIC METEORITES

DEREK W.G. SEARS AND FOUAD A. HASAN
Department of Chemistry and Biochemistry
University of Arkansas
Fayetteville, Arkansas 72701   A4007697

Abstract

The level of natural thermoluminescence (TL) in meteorites is the result of competition between build-up, due to exposure to cosmic radiation, and thermal decay. Antarctic meteorites tend to have lower natural TL than non-Antarctic meteorites because of their generally larger terrestrial ages. However, since a few observed falls have low TL due to a recent heating event, such as passage within ~0.7 astronomical units of the Sun, this could also be the case for some Antarctic meteorites. Dose rate variations due to shielding, heating during atmospheric passage and anomalous fading also cause natural TL variations, but the effects are either relatively small, occur infrequently, or can be experimentally circumvented.

The TL sensitivity of meteorites (TL emitted after the natural TL has been removed and the sample administered a standard radiation dose) reflects the abundance and nature of the feldspar. Thus intense shock, which destroys feldspar, causes the TL sensitivity to decrease by 1-2 orders of magnitude, while metamorphism, which generates feldspar through the devitrification of glass, causes TL sensitivity to increase by a factor of $\sim 10^5$. The TL-metamorphism relationship is particularly strong for the lowest levels of metamorphism. The order-disorder transformation in feldspar also affects the TL emission characteristics and thus TL provides a means of paleothermometry.

1. Introduction

Measurement of the thermoluminescence (TL) properties of meteorites provides certain clues into diverse aspects of their history and that of the ice on which they are found. The present article describes the theoretical and experimental background to TL measurement of meteorites and summarizes current understanding of the factors which determine their TL properties. It ends with a summary of the main points with particular reference to the value of including TL in the routine preliminary survey of Antarctic meteorites.

2. Theory

As first pointed out by Randall and Wilkins (1945) and Garlick and Gibson (1948), the band model provides a reasonable framework for understanding TL in semi-conductors, although for most phosphors details are known only in a fragmentary way (Fig. 1). Any ionizing radiation promotes electrons from the valence band (V.B) to the normally unoccupied conduction band (C.B) where they pass freely through the lattice. Located through most crystals are intrinsic and impurity produced defects which provide sites (e.g. T and L) for metastably
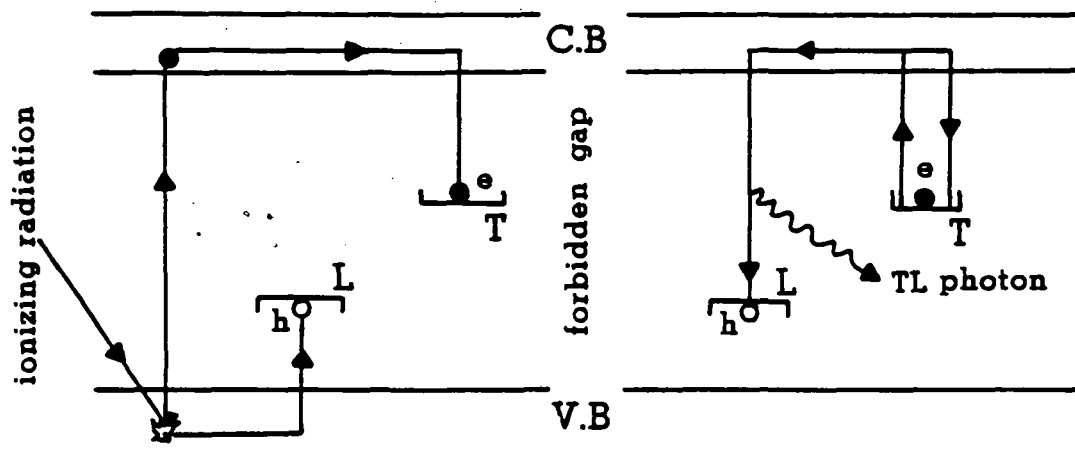
Figure 1: Band model for a semi-conductor crystal lattice explaining the main features of thermoluminescence. Ionizing radiation excites an electron from the valence band (V.B) to the conduction band (C.B) where it moves through the lattice until trapped at a site (T) ~1 eV below the C.B. Thermal stimulation enables the trapped electron to escape the trap and return to the ground state via a luminescence center (L) at which it releases some of the excitation energy in the form of a visible photon. The process may also involve recombination of the electron and the positive hole that was created by ionization (h).

trapping the excited electron at various energies, but typically ~1 eV, below the conduction band. The rate of trap filling can be represented by a relationship such as

$$\frac{dn}{dt} = \alpha R(N-n) \tag{1}$$

where n is the number of trapped electrons, N is the number of available traps, R the dose rate, t is time and α a rate constant. For a meteorite the major sources of ionizing radiation are primary and secondary cosmic rays for which dose rates are thought to be on the order of ~1 rad/year.

The trap depth constitutes an activation barrier to decay of excited electrons which can be overcome by heating the sample to the appropriate temperature. Once released from the traps the electrons may become retrapped at the same or other defects, or fall back to the valence band by a number of pathways. It is those which involve radiative transitions at visible wavelengths that are responsible for the TL phenomenon. This part of the TL mechanism can also be modeled quantitatively. Assuming first order decay kinetics, the rate of decay of excited electrons is given by

$$\frac{dn}{dt} = -\beta n \tag{2}$$

where β is the first-order decay constant. The relationship between β and the trap depth (E) and temperature (T) is given by the Arrhenius equation so that

$$\frac{dn}{dt} = -Sn \exp(-E/kT) \qquad (3)$$

where S is the Arrhenius or pre-exponential factor, and k is the Boltzman constant.

Cosmic ray exposure ages for meteorites are ~10^7 year, so that equilibrium will be achieved for the electrons in most traps. Setting the rate of decay equal to the rate of build-up, and re-arranging, the relationship between number of trapped electrons, and therefore the level of TL, and the dose-rate and ambient temperature is given by

$$n = \frac{N}{1 + [S/\alpha R \exp(-E/kT)]} \qquad (4)$$

There are many such quantitative models for the TL process, most of greater sophistication, and it is not clear which is applicable to meteorites. There is strong evidence that the decay kinetics of the TL or ordinary chondrites is second order (McKeever, 1980). However, all models predict that the level of TL naturally present in a meteorite will normally be at an equilibrium and that the level will be related directly to dose rate and reciprocal temperature. It is also possible, in principle, for the TL level to be out of equilibrium if the traps are all filled or if insufficient time has elapsed since the system was last drained for equilibrium to have been re-established. Insertion of plausible values into equations 1 and 3 suggests that it may take ~10^5 y to achieve equilibrium, so that it may be feasible to empirically determine the time taken to reach TL equilibrium by looking for a relationship between natural TL and exposure age for the dozen or so meteorites with extremely short exposure ages.

Thermoluminescence can be induced in the sample after the natural TL has been removed, by, for instance, momentary heating to ~500°C, by irradiation in the laboratory. The level of induced TL depends on the number and type of traps, and the details of the induced TL emission depend on such factors as the crystallography of the phosphor.

3. Apparatus and Procedures

Samples are heated on a nichrome strip in a nitrogen atmosphere at carefully controlled linear heating rates of 5-20°C/sec; a signal from a chromel-alumel thermocouple placed under the center of the heating strip provides a temperature feedback to the control unit (Fig. 2). The emitted TL is detected with a specially designed electronically and magnetically shielded photomultiplier tube behind a heat filter and a blue filter (Mills et al., 1981). The blue filter and an aperture keep to a minimum the red black-body radiation from sample and heating strip. Rate counting electronics provide a high signal-to-noise input for storage by a microprocessor or feeding directly to the Y-axis of an X-Y plotter with temperature on the X-axis. The resulting plot of TL against temperature, termed a glow curve, contains a number of peaks corresponding to the number of discrete trap levels. For natural meteorite samples, there is a relatively sharp peak at ~250°C and a broader peak at ~450°C. For the induced TL there is a broad peak between 100-300°C. In fact, all the "peaks" referred to are, in fact, composites of many smaller peaks.
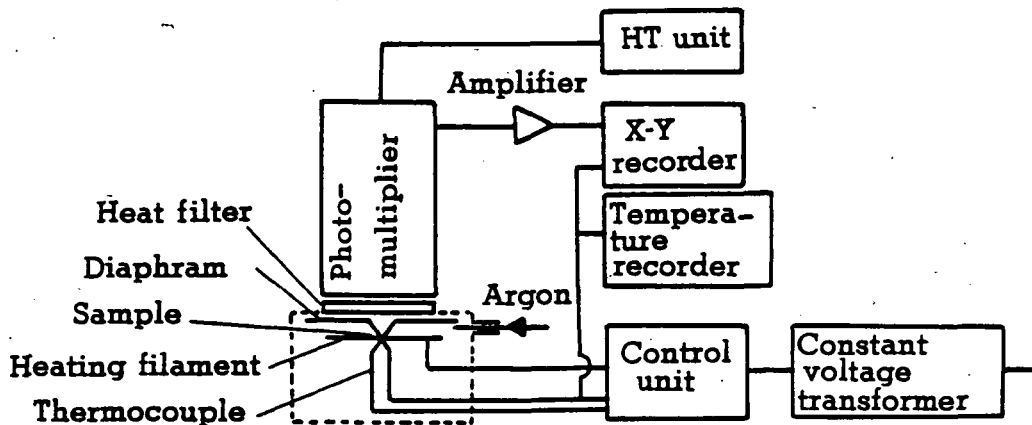
Figure 2: Schematic diagram of apparatus for the measurement of thermo-
luminescence. The function of the recorders and the control units are often
performed by a microprocessor.

Samples are prepared either as powders by removal of the metal with a hand
magnet and grinding so as to pass through a 100 mesh sieve, or as ~1 μm grains
deposited from an acetone suspension into a 1 cm Cu disks. The powders are
placed in Cu pans for TL measurement, whereas the disks can be measured directly
and are in a convenient form for storage. Typically each sample is measured in
duplicate and the TL of each duplicate measured 4-6 times; the natural TL is
first measured, and thus drained, and then the sample irradiated with a Co-60 or
Sr-90 source (typically to 25 krad) and the induced TL measured 3-5 times,
depending on reproducibility. At the beginning and end of a days measurements,
samples of the Dhajala meteorite are run as a normalization standard. Dhajala
has a TL sensitivity in the middle of the observed range and is available in
reasonable quantities. Its use as a standard enables interlaboratory comparison
of data.

4. Data Reduction

The information available from the measurement of natural TL and from the
induced TL is very different and this is reflected in the means of data reduc-
tion (Fig. 3). The main object in measurement of natural TL is to assess the
level of natural TL in a way which removes the effects due to variations not
related to R and T, such as sample heterogeneity or considerable variations in
the number of available traps. The two methods available are (1) to measure the
ratio of the low temperature peak (LT) to the high temperature peak (HT) (Fig.
3a), and (2) to measure the ratio of the natural TL to the induced TL at a given
glow curve temperature; this ratio can be multiplied by the test dose and
resulting quantity has the units of dose and is termed the "equivalent dose".
The first method presupposes that HT and LT are equally sensitive to the inter-
fering effects, and the second is subject to greater experimental errors such as
thermal lag between sample and heating strip (Sears and McKeever, 1980). A plot
of equivalent dose against glow curve temperature permits a convenient means of
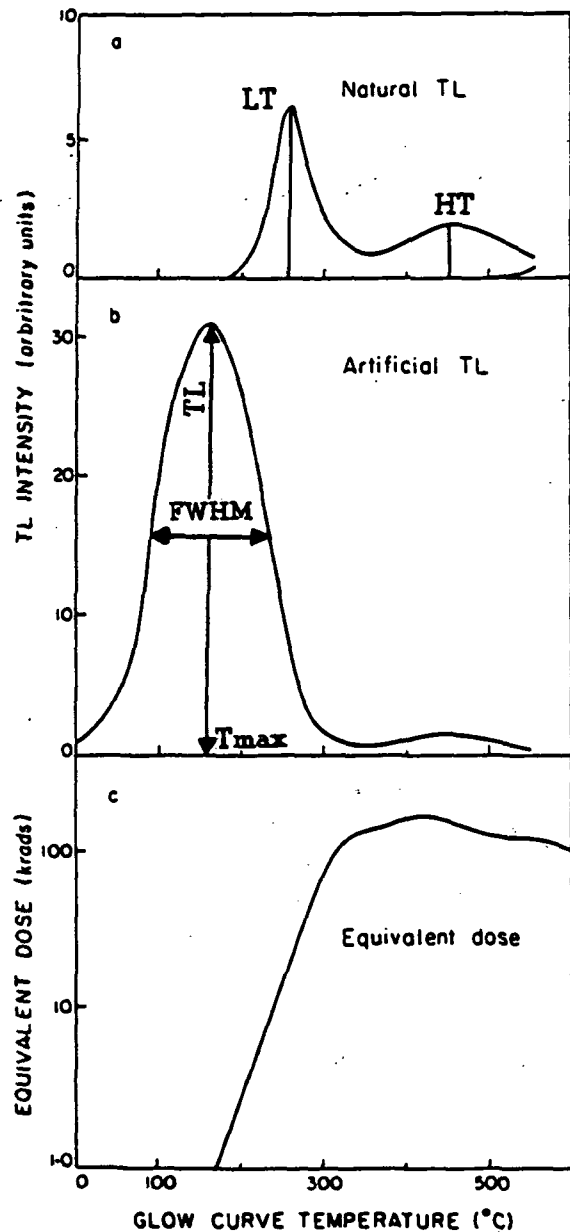examining the extent of thermal draining (Fig. 3c).

Figure 3: Methods of data reduction for (a) natural TL and (b) induced TL (artificial TL). (c) The rates of the curves for natural and induced TL (artificial TL) (after Melcher, 1981a).

Three measurements may be usefully made from the glow curve for the induced TL: 1) the height of the peak at maximum emission, which is referred to as TL sensitivity and is frequently normalized to that of the Dhajala meteorite; 2) the width of the peak at half maximum (FWHM or simply peak width); 3) the temperature of maximum TL emission (or peak temperature) (Fig. 3b).

5. Natural TL Levels in Meteorites

The levels of natural TL in a number of ordinary chondrites is shown in histogram form in Fig. 4. Slightly different distributions are displayed by the observed falls and the finds. The falls have preferred values between 2 and 7,
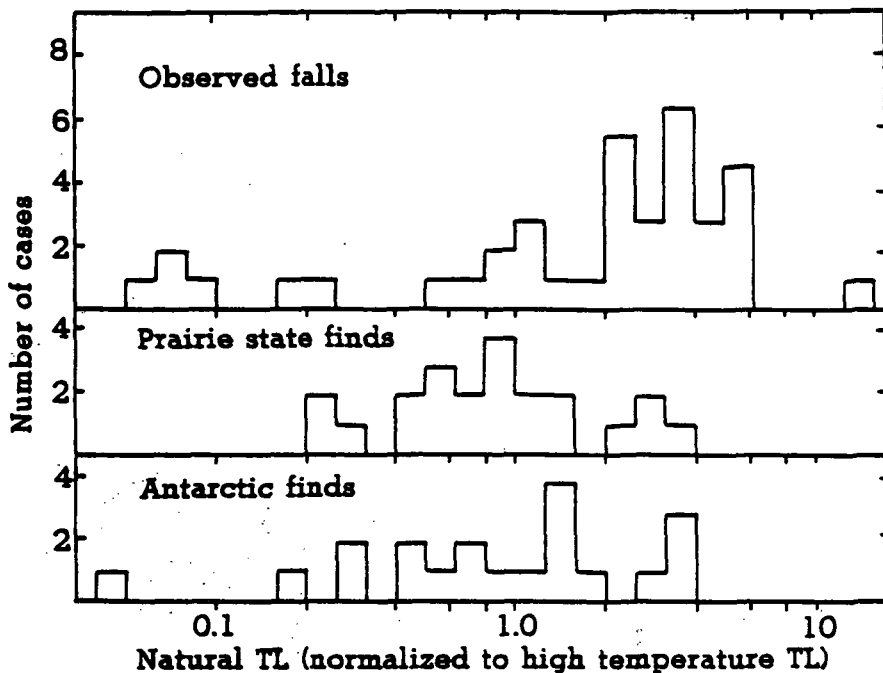
Figure 4: Histograms of the natural TL levels in meteorites that were observed to fall within the last 250 years (top, McKeever and Sears, 1980), meteorites that were found in the Prairie States of the U.S.A. (middle, Sears and Durrani, 1980) and those that were found in the Antarctic (bottom, present study).

but spread over 2 orders of magnitude and extend down to peak height ratio values of less than 0.1. The Antarctic and Prairie State finds also show considerable spread which is similar for the two sources and skewed to lower values than for the falls (~0.2 to ~3) (Sears and Durrani, 1980; McKeever and Sears, 1980).

The difference in TL between the falls and finds, which is an order of magnitude, is probably associated with differences in terrestrial age. The Al-26 activity of Antarctic meteorites is about 20% lower than non-Antarctic meteorites (Fig. 5) and since there is no evidence from other cosmogenic isotopes that Antarctic meteorites have suffered significantly different exposure histories, this must reflect terrestrial ages which are a significant fraction of the half-life of Al-26 (Evans et al., 1982). The extensive measurements, based on other cosmogenic nuclides, by Nishiizumi et al. (1979, 1981) have shown that the terrestrial ages of Antarctic meteorites are often ~10^5 y. Theoretically, a relationship between natural TL and terrestrial age is to be expected, since the cosmic ray dose rate decreases and the ambient temperature increases, after a meteorite falls to earth. The equilibrium TL level has therefore to adjust to a new low level. Fig. 6a shows the decrease in natural TL as a function of terrestrial age, and Fig. 6b shows the abundance of two cosmogenic isotopes in relation to their natural TL levels (Sears and Durrani, 1980; Melcher, 1981a). In both cases there is a suggestion that the natural TL is falling to lower levels as the terrestrial ages of the meteorites increases.
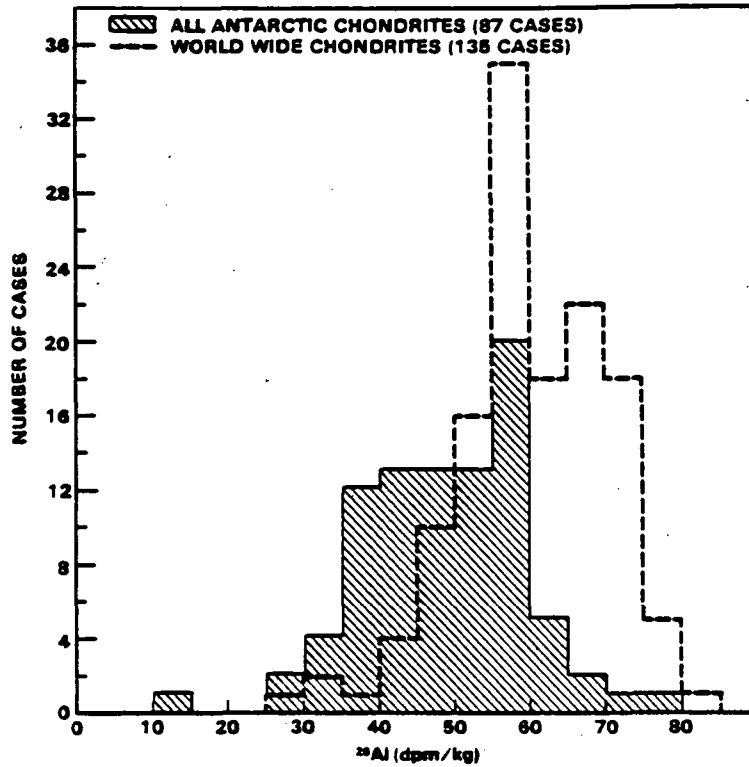
Figure 5: Histograms of the Al-26 content of non-Antarctic and Antarctic meteorites (from Evans et al., 1982).
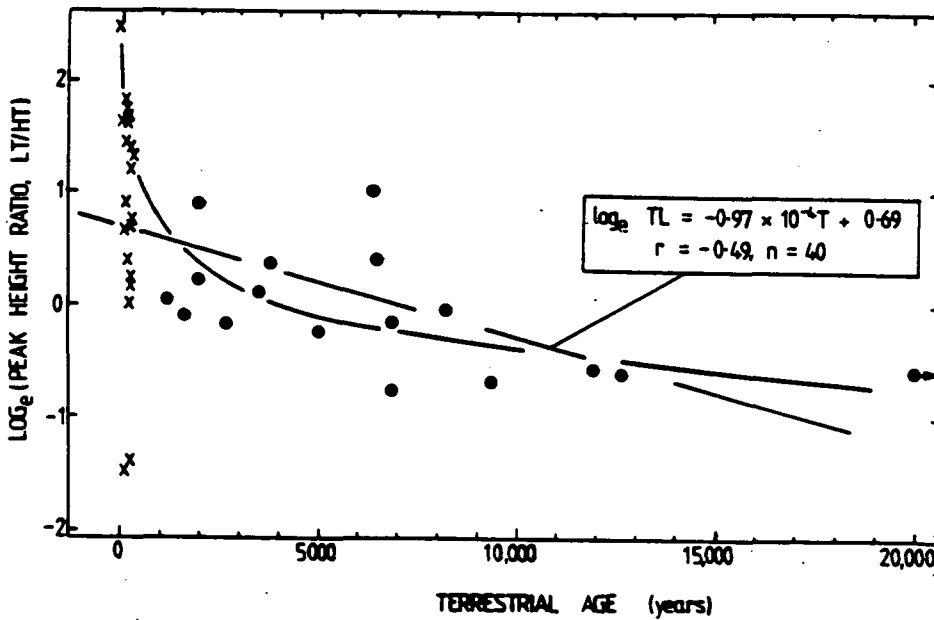

Figure 6a: Plot of natural TL against terrestrial age for observed falls (crosses) and finds whose terrestrial age has been determined from their C-14 contents (dots) (from Sears and Durrani, 1980). The straight line is a least squares fit, the regression equation and parameters are given in the box, assuming a first-order decay process equation (2), while the curve was drawn in by eye to suggest the form expected from second-order decay.
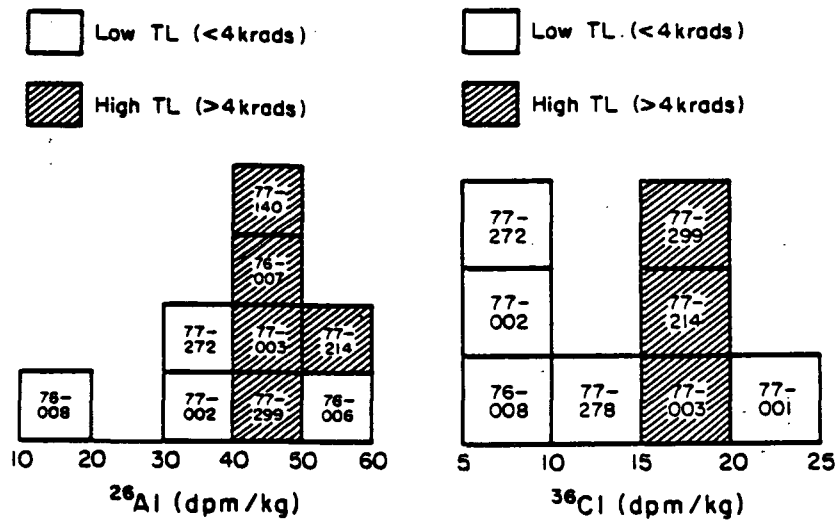
Figure 6b: Histograms of Al-26 and Cl-36 content of Antarctic meteorites of known natural TL levels (in equivalent dose in rad) (from Melcher, 1981a).

Prairie Network meteorites appear to have terrestrial ages within a few half-lives of carbon-14 (5220 y) (Boeckl, 1972), yet display a similar natural TL spread to the Antarctic meteorites which have terrestrial ages comparable with the half-life of Al-26 (750,000 y). The similarity in the TL despite different terrestrial ages presumably reflects the higher storage temperature for the Prairie Network meteorites.

A process other than large terrestrial age is involved in determining the natural TL levels in certain meteorites, since several meteorites observed to fall within the last 200 y have TL levels of ~0.1 (Fig. 6a). Such meteorites have experienced a thermal and/or radiation history very different to the others, for instance they may have been reheated recently so that their TL was drained and unable to return to the equilibrium value before fall to earth. The lack of low temperature TL, but apparently normal levels of high temperature TL, is most evident on a plot of equivalent dose against glow temperature (Fig. 7) (Melcher, 1981b). Solar heating during close passage to the Sun provides a reasonable explanation of these data. The temperature (T) of an object d astronomical units (a.u.) from the Sun is given by

$$T = \frac{CB}{d^2 S\delta} \gamma \qquad (5)$$

where C is the solar constant, B the cross section and S the surface area of the object, δ is Stefan's constant and γ the ratio of the absorbed and emitted radiation (typically ~0.5). Assuming plausible figures this becomes

$$T = 278 \ (\frac{\gamma}{d^2})^{1/4} \qquad (6)$$

The important orbital parameter as far as TL is concerned is the perihelion distance. For the Pribram and Lost City meteorites whose fireballs were photographed at several locations, the perihelia were 0.790 and 0.967 which correspond to temperatures of 255 and 236 K, respectively. One of the fireballs
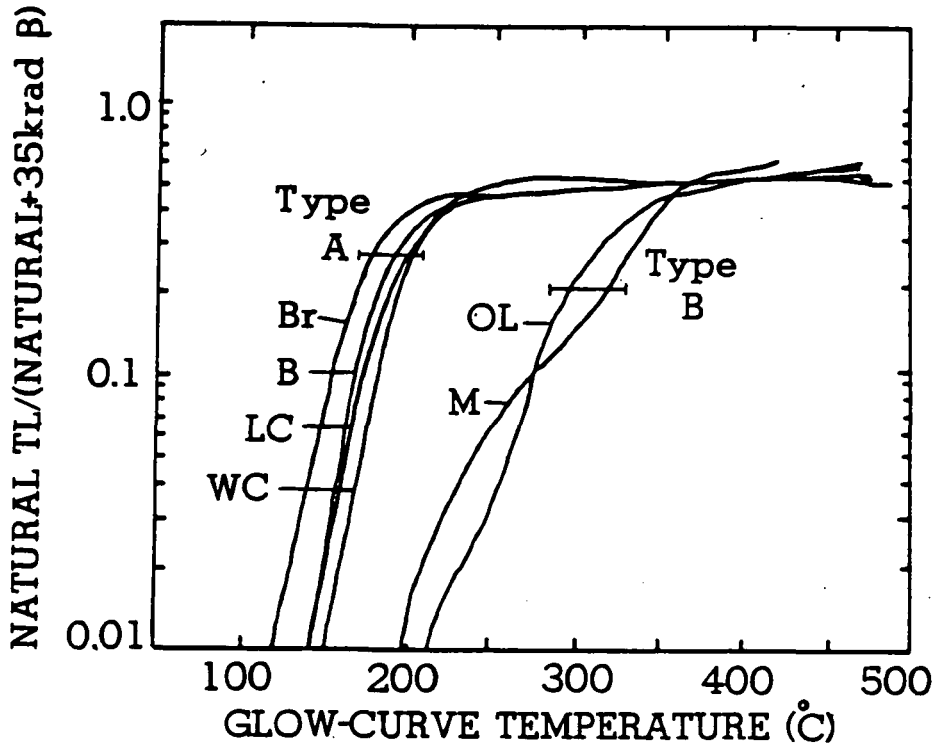
Figure 7: Plots of equivalent dose (natural TL/induced TL times test dose) against glow curve temperature for several observed falls. Most meteorites (type A) have no natural TL <200°C in the glow curve due to thermal drainage, probably under equilibrium conditions in space. However, a few (type B) have suffered unusually high drainage, perhaps due to close solar passage (from Melcher 1981a, McKeever and Sears, 1980).

observed by the Prairie Network, but which did not yield a meteorite, was Meteor 40503 with a perihelion of 0.722 and corresponding temperature of 275 K. On the basis of the above theory if we assume

$$n \propto \exp (E/kT) \tag{7}$$

then the ratio of trapped electrons for a meteorite with perihelion at 0.722 and 0.967 a.u. is very approximately given by

$$\frac{n_{0.722}}{n_{0.967}} = \exp \left(\frac{E}{k275} - \frac{E}{k236}\right) \tag{8}$$

$$= 0.01$$

for a trap depth of ~1 eV. A two-order of magnitude difference in natural TL is consistent with known variations in perihelia and plausible TL kinetic models. In an attempt to test this idea, McKeever and Sears (1980) and Melcher (1981b) compared the natural TL variations of falls with $^3He/^{21}Ne$ ratios, a ratio less than 0.3 is an indication of gas-loss due to solar heating. However, the

meteorites which had suffered gas-loss had normal TL suggesting that if heating was involved that it occurred long enough ago that the TL had recovered. A more reasonable test of the idea is to examine the natural TL of meteorites known to have small perihelia when they entered the atmosphere.

There are other instances in which dose-rate or temperature changes can occur which influence natural TL levels. Variation in the dose-rate may occur with the attenuation of primary cosmic radiation and build-up of secondary radiation. The natural TL level is 10-15% higher at the center of a 55 x 40 cm slab of the Estacado meteorite (Fig. 8a) (Sears, 1975) and a 50% variation in
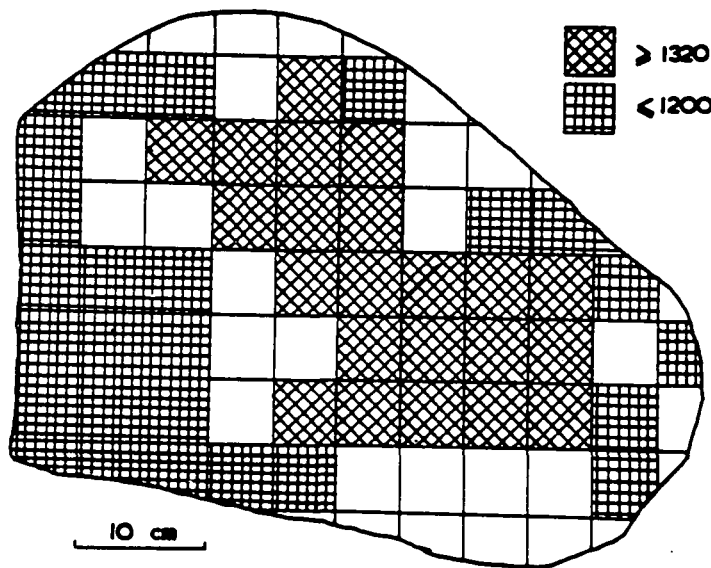

Figure 8a: Natural TL in a 40 x 55 cm slab of the Estacado meteorite (from Sears, 1975).

the TL of the Lost City meteorite was observed over a 10 cm distance (Fig. 8b) (Vaz, 1971), both most plausibly caused by cosmogenic dose rate variations. Factors of 2 change in natural TL also occur in two core samples taken from the St. Severin meteorite by Lalou et al. (1970) (Fig. 8c). As yet, however, there is no indication that shielding effects can result in order of magnitude natural TL variations, and, at most probably only contributes to the scatter in Fig. 4. The thermal pulse caused by atmospheric passage drains the TL over the outermost 5 mm or so (Fig. 8b), but this effect can easily be avoided by careful sampling.

A mechanism also exists in which natural TL decays in a poorly understood but extremely rapid means in certain materials. Hasan et al. (1985) found that certain shergottites and the Kapoeta howardite displayed such "anomalous fading" and suggested that it was only affecting samples in which the feldspar is present in the low temperature form. If this is the case, then anomalous fading will not generally be a problem since such meteorites are rare, and, in any event, seems to be readily detected by laboratory tests. McKeever and Durrani (1980) found no evidence for anomalous fading in two ordinary chondrites, Barwell and Saratov.
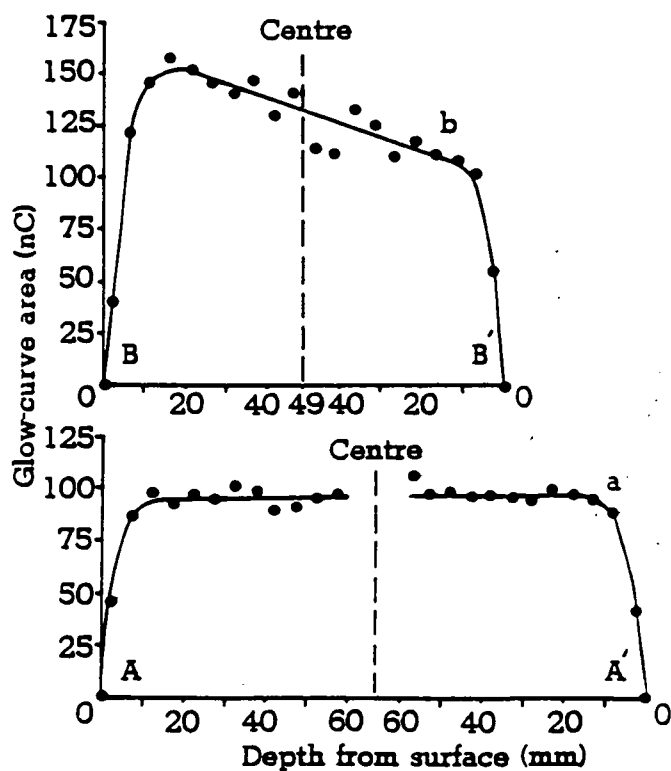
Figure 8b: Natural TL variations in two bars removed from the Ucera and Lost City meteorites. The outer 5 mm or so of each bar also shows draining of the TL due to the heat generated by atmospheric passage (from Vaz, 1971).
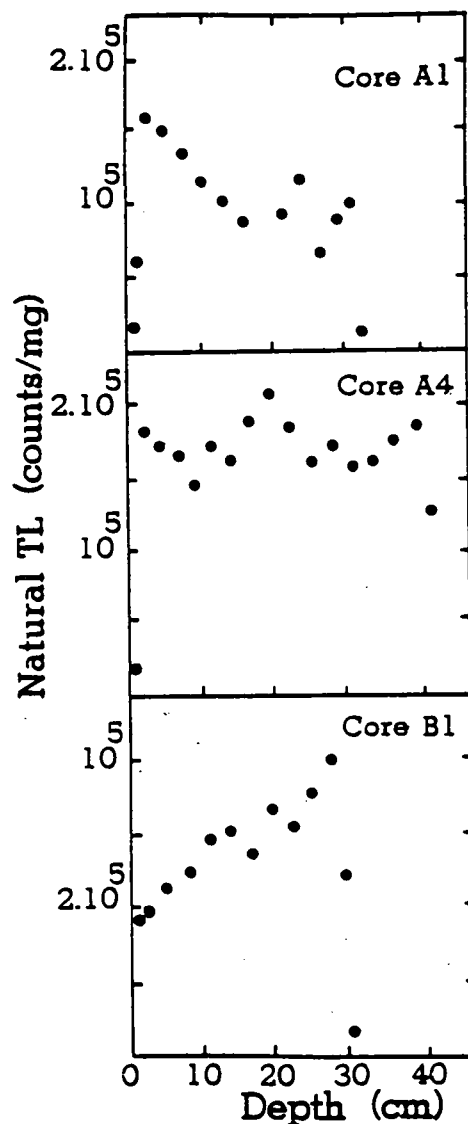
Figure 8c: Natural TL along three cores taken from two fragments (A and B) of the St. Severin chondrite. Cores A1 and A2 were approximately perpendicular (for the precise orientations, see Lalou et al., 1970, from which the data were taken).

6. The Induced TL Properties of Meteorites

The TL sensitivity of meteorites shows a 10^6-fold range, the ordinary chondrites alone show a 10^5-fold range and the shergottites have values below them (Sears et al., 1980; Hasan and Sears, 1985). With a few exceptions, the mineral responsible for the TL in meteorites is feldspar and the range in TL sensitivity reflects the amount of the phosphor present. Heavily shocked ordinary chondrites, in which the feldspar has been fused or partially converted to maskelynite, have TL sensitivities one to two orders of magnitude lower than unshocked equilibrated chondrites. Such low TL sensitivities can be reproduced by annealing an unshocked chondrite to ~1100°C, which is similar to the post-shock residual temperature for heavily shocked chondrites inferred from studies of the metal and sulfide (Fig. 9; Liener and Geiss, 1968; Sears et al., 1984).
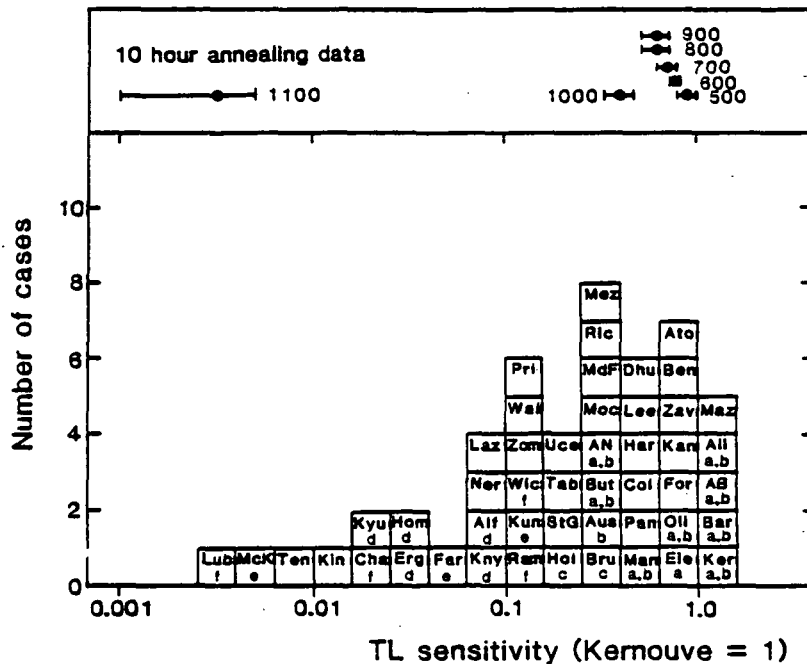

TL sensitivity (Kernouve = 1)

Figure 9: Histogram of TL sensitivity levels in equilibrated ordinary chondrites of a variety of shock histories. The meteorites are identified by the first three letters of their names (see Sears, 1980, for identification) and their shock classification is also indicated (a, unshocked; f, heavily shocked). The data across the top of the histogram indicate the TL sensitivity of Kernouve samples which have been annealed for 10 h at the temperatures indicated (in °C) (Sears et al., 1984).

Unshocked ordinary chondrites display a large range of TL sensitivity which is metamorphism-related (Fig. 10). The feldspathic constituent of unmetamorphosed ordinary chondrites is present as a glass which has little or no TL sensitivity. During relatively low-grade metamorphism the glass produces crystalline feldspar and the TL sensitivity increases accordingly. This has permitted a reliable subdivision of the type 3 chondrites into types 3.0 to 3.9 and many textural, compositional and isotopic variations are related to these types. The mechanism for metamorphism-related increase in TL was recently confirmed by
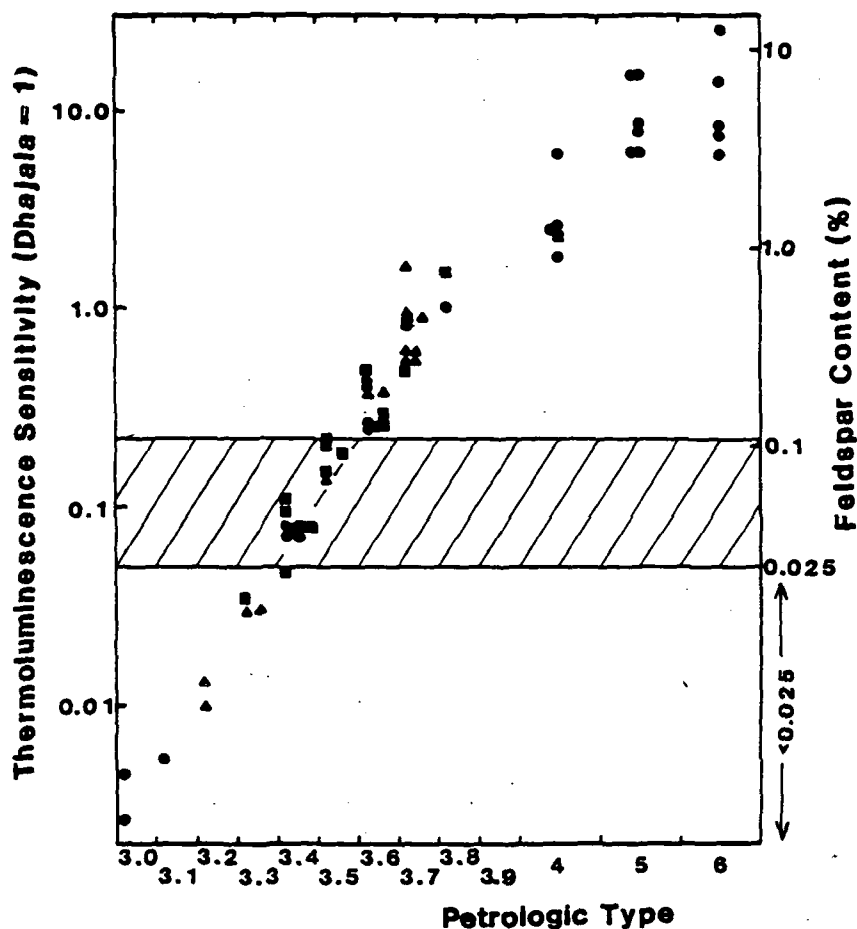
Figure 10: TL sensitivity variations in unshocked ordinary chondrites of a variety of petrologic types (from Guimon et al., 1985b). The cross-hatching refers to the TL sensitivity range in which the TL peak is narrow and at low glow-curve temperatures and probably indicates that the feldspar is in the low-temperature form. The right-hand axis is an estimate, based on the TL, of the feldspar content of the meteorites. The symbols refer to the literature sources for the data: circles, Sears et al. (1980); squares, Sears et al. (1982); triangles, Sears and Weeks (1983).

annealing a type 3.4 chondrite in a manner known to cause divitrification of synthetic glasses. A factor of 7 increase in the TL at 200°C in the glow curve resulted after only 200 h of annealing (Fig. 11). At metamorphic levels equiva-lent to a TL sensitivity of 0.025 (where Dhajala = 1) the induced TL curve con-sists of a narrow peak (100°C) at relatively low temperatures in the glow curve (~100°C), but at high levels of metamorphism the curve becomes broader (160°C) and moves to higher glow curve temperatures (200°C). This increase in TL peak temperature and peak width can be reproduced in the laboratory by annealing at >700°C for 100 h either a low petrologic type meteorite or a terrestrial feldspar in the low-temperature (ordered) form (Fig. 12). In the case of the terrestrial feldspar, the x-ray diffraction pattern indicated that the TL changes were associated with the onset of the conversion of the ordered to the disordered form (Guimon et al., 1984; 1985a).
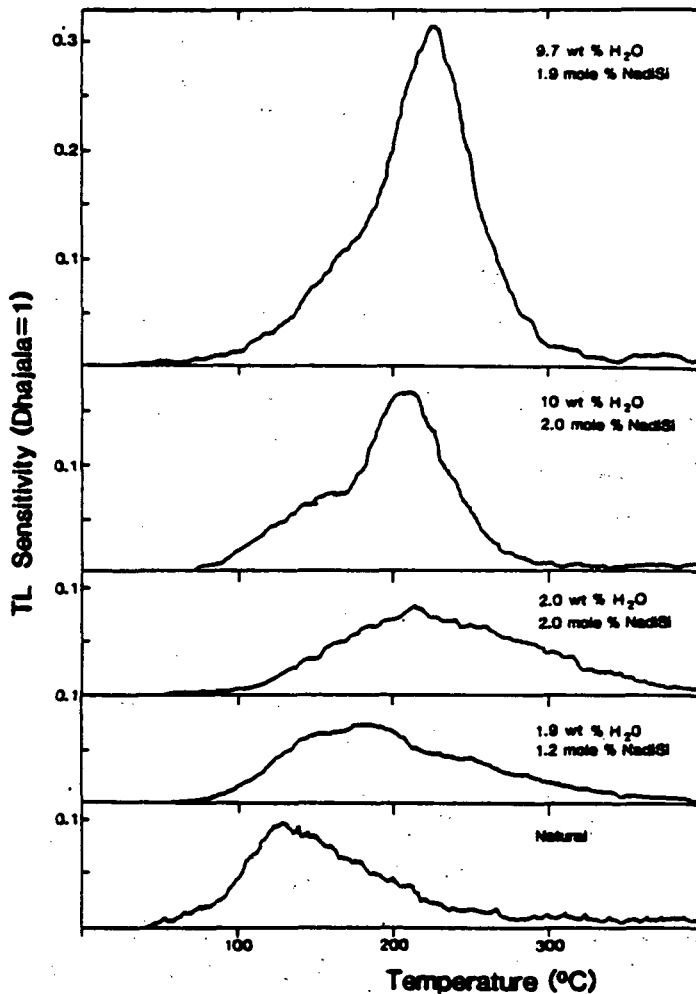
Figure 11: Glow curves for several samples of the Allan Hills A77011 chondrites which have been annealed at 755-850°C and 1 kbar for ~1 week with a variety of devitrification catalysts added (from Guimon et al., 1985b).

Although very different in origin, history, composition and petrology, the TL properties of the shergottites can be understood in very similar terms to those of the ordinary chondrites (Hasan and Sears, 1985). Mineral separation experiments indicate that the TL phosphor is also feldspar and the extensive maskelynization suffered by the class is consistent with their very low TL sensitivity values. The shergottites also show systematic variation in peak temperature and width which can be understood in terms of feldspar being present in the high and low temperature forms in varying relative amounts (Fig. 13). Annealing treatments under much milder conditions than those used for ordinary chondrites produce spectacular TL sensitivity increases which is consistent with the known relative instability of the glass in shergottites relative to the igneous glass in type 3 ordinary chondrites (Fig. 14). Again, the temperature of the TL peak is related to the annealing temperatures.
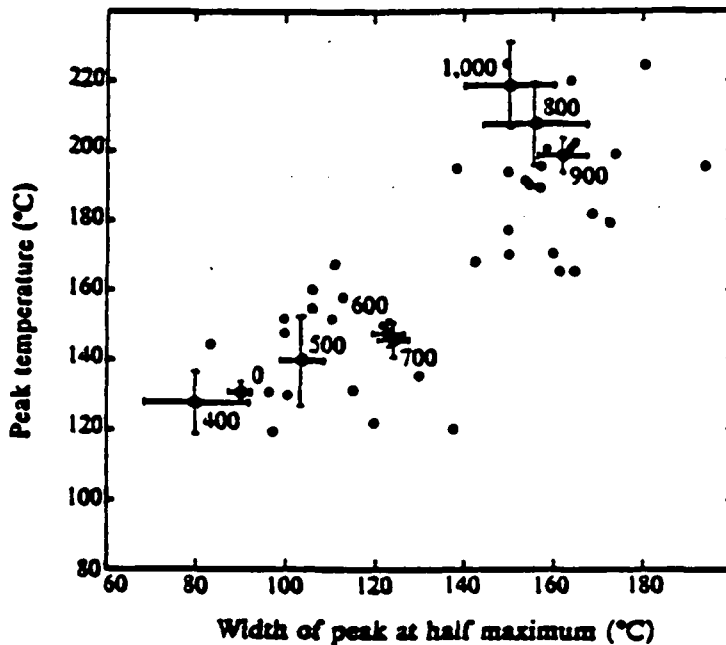
Figure 12: TL peak temperature against peak width for 39 type 3 ordinary chondrites (dots) and for a L3.4 chondrite (Allan Hills A77011) annealed for 200 h at the temperatures (°C) indicated (dots with error bars) (from Guimon et al., 1984).

7. TL as a Survey Technique for Antarctic Meteorites

The complexity and demands of surveying the Antarctic meteorites by TL are comparable with those of petrographic and electron microprobe surveys currently being performed. However, the nature of the available information is, by and large, very different. The following summarizes the above discussion with particular reference to the desirability of surveying recovered Antarctic meteorites with the technique and draws on the discussions published by Sutton and Walker (1985), Melcher (1981a) and McKeever (1982).

Natural TL

1) Meteorites with high TL. None of the Antarctic meteorites yet measured have natural TL levels comparable with those of brightest observed falls. It seems fairly clear that a high natural TL can only reflect a recent fall, since the peak height ratio in even the most highly irradiated samples decays to ~1.0 within a few thousand years (Fig. 6a).

2) Meteorites with low TL. Several processes can lead to a meteorite having abnormally low natural TL. The sample could have a particularly large terrestrial age, could have suffered reheating within the last 10^5 y or so, perhaps by having a small perihelion, or could be subject to anomalous fading. Anomalous fading can readily be identified by laboratory tests and seems to be relevant to relatively few meteorites.
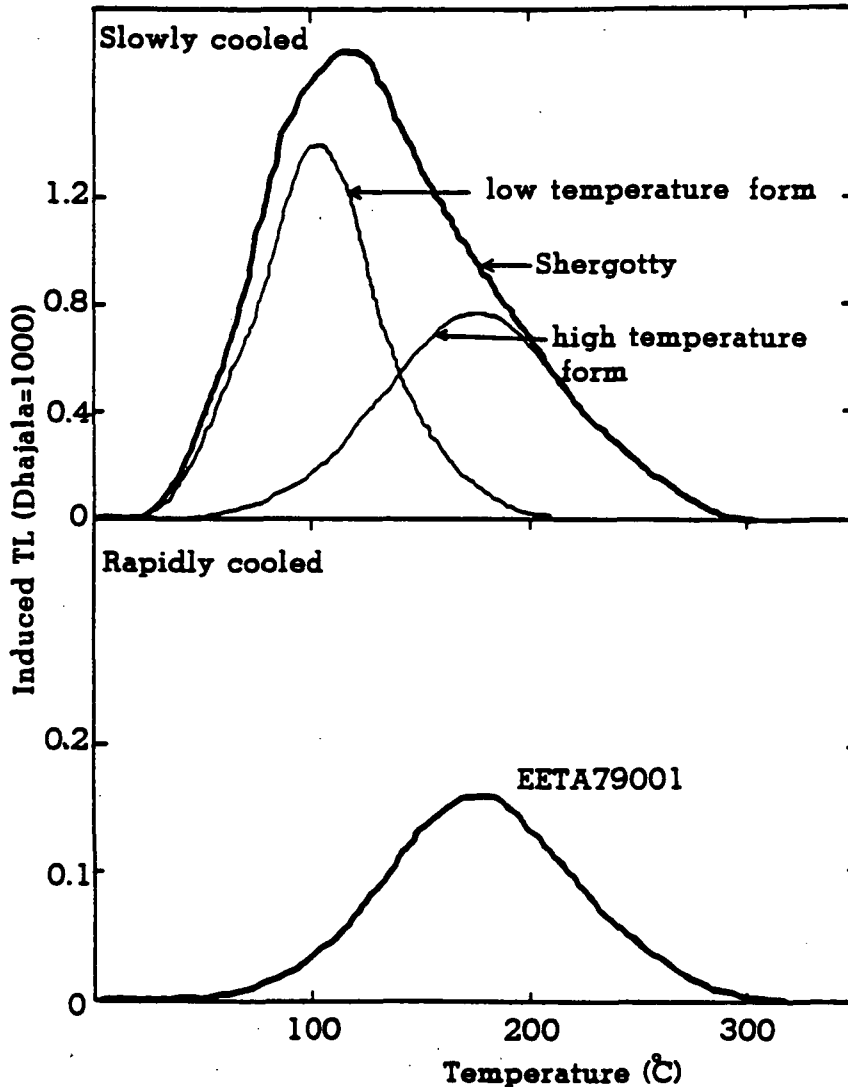
Figure 13: Glow curves for the Shergotty and Elephant Morraine A79001 shergottites with a suggested mechanism for explaining the peak temperature, peak width, and TL sensitivity. It is suggested that post-shock recrystallization of maskelynite in the meteorites produced feldspar in varying amounts and forms depending on cooling rate (Hasan et al., 1985).

3) Cosmogenic dose rate variations throughout the meteorite should cause variations in natural TL levels, but on the basis of existing data these seem to be relatively small. However, this point should be further tested by measurement of the natural TL variation throughout large meteorites.

4) Pairing is an important aspect of Antarctic meteorite curation and the problem could have serious implications for a variety of statistical studies. No single technique yet exists for unambiguous pairing of fragments of the same fall, but since natural TL levels span a range of over 100 and yet variations within a single meteorite seem to be less than ~50%, the natural TL may provide additional information on the question.
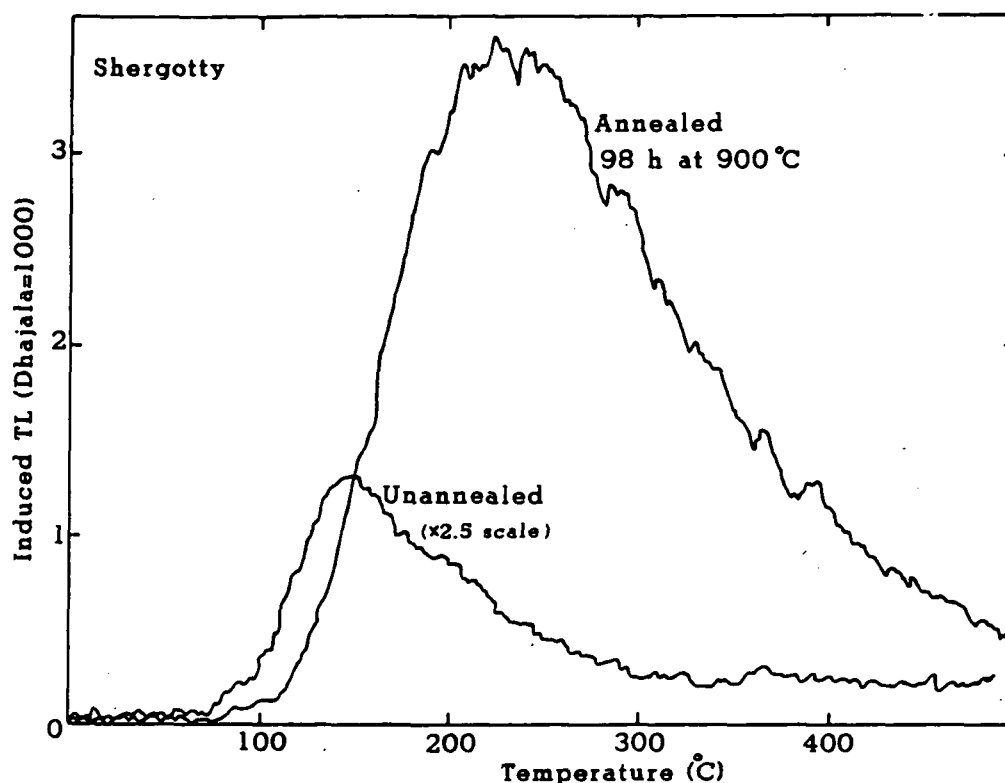
Figure 14: Glow curves for the Shergotty meteorite before and after an annealing treatment. The annealing produced considerable crystallization of the high temperature form of feldspar whose TL peak appears at 220°C in the glow curve (Hasan et al., 1985).

Induced TL

1) Heavily shocked ordinary chondrites have TL sensitivities 10^{-1} to 10^{-2} times those of equilibrated unshocked ordinary chondrites.

2) While types 5 and 6 ordinary chondrites have similar TL sensitivities, type 4 chondrites tend to have TL sensitivities an order of magnitude or so lower than type 5,6 levels. Type 3 ordinary chondrites have TL sensitivities 10^{-2} to 10^{-5} times type 5,6 levels, and TL sensitivity provides a means of subdividing the type 3 chondrites according to their metamorphic history. All type 3 ordinary chondrites from the US Antarctic collection have been assigned to petrologic types on the basis of TL sensitivity.

3) Pairing studies are also possible using TL sensitivity, but the method is really only useful for type 3 chondrites which show a very large intra-chondrite spread. The pairing of several Allan Hills A77011 samples was discussed by Sears et al. (1982) who pointed out that the fragments paired on a petrographic basis had a rather large TL sensitivity spread and suggested that there may be fragments from two discrete falls present.

Acknowledgements

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A PRELIMINARY REPORT ON A POSSIBLE STROMATOLITE FIND FROM THE ELEPHANT MORAINE, ANTARTICA: A POTENTIAL DIRECTIONAL INDICATOR FOR ICE MOVEMENT: P.P. Sipiera* and C.A. Landis, Department of Geology, University of Otago, New Zealand.

During the 1983-84 Antarctic Search for Meteorites field season, numerous specimens of a shiny black rock were collected from among the glacial debris at the Elephant Moraine. From a distance these black rocks gave the appearance of meteorites, but upon closer inspection, distinct layering and radial crystal growth patterns became clearly visible. In hand specimen these rocks exhibit a distinctive jet-black coloration, along with a "desert-glaze" that is the probable result of a sand-blasting effect by the wind-blown granular snow. Most specimens have the layered appearance, but a few resemble rounded "clumps" of material attached to a clastic sedimentary baserock (see Figure 1). Later laboratory investigations showed that these unusual specimens are primarily composed of carbonate minerals.

Petrographically, microscopic examination of twelve randomly collected specimens revealed a variety in the habits of the carbonates, but the overall trend tends to be one of radiating acicular crystals that have the appearance of a psuedo-cellular structure reminscent of stromatolites. A mean mineralogical composition of 99.53% $CaCO_3$, .10% $FeCO_3$, .10% $MgCO_3$, and .03% $MnCO_3$ was obtained from twelve electron microprobe spot analyses of the specimen shown in Figure 1. The coloration apparent in the zonation in Figure 2 is primarily attributed to the variability of the $FeCO_3$ and $MnCO_3$ content between core and rim.

On the question of a possible stromatolite nature to these rocks, it is open to debate and cannot be resolved at this time without further study. Comparisons have been made to various stromatolites from around the world, and some structural similarities exist, but are not conclusive. If these rocks are indeed representative of stromatolites, then they must be altered forms of the original material. In Walter, 1976, examples of similar materials of non-organic nature are cited. One possibility is a form of calcrete, and as reviewed by Read in Walter, 1976, it is easily confused with cryptalgal structures. It is then possible that the Elephant Moraine rocks may represent a mixture of algal material interlayered with either calcrete or cryptalgal sedimentation. A second possibility has been pointed out by Faure (pers. comm., 1985) in his suggestion that these carbonate rocks may be of hydrothermal origin. This is based on their $^{87}Sr/^{86}Sr$ ratios which exceed those of marine strontium, and the fact that the calcite he examined is associated with opaline chert.

Given the fact that these black carbonate rocks were found among glacial debris that was probably transported over a great distance, the determination of their source area could aid in the comprehensive understanding of ice movement in the area. A preliminary search of the literature has not found any other Antarctic location where similar material has been collected. One possible site was reported by Burgess and Lammerink, 1979, in which they briefly discussed black stromatolites in the Shackleton Limestone from the Byrd Glacier area. Comparison with this material in the collection at Victoria University in New Zealand proved negative, but does not rule it out since unclassified material remains to be studied. It is hoped that future research will be able to specifically identify this possible stromatolite material and that a source locality will be found. At present, we can only hope that this preliminary report will provide an awareness of this rather unique material.

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*Present Address: Meteorite Research Group, Harper College,
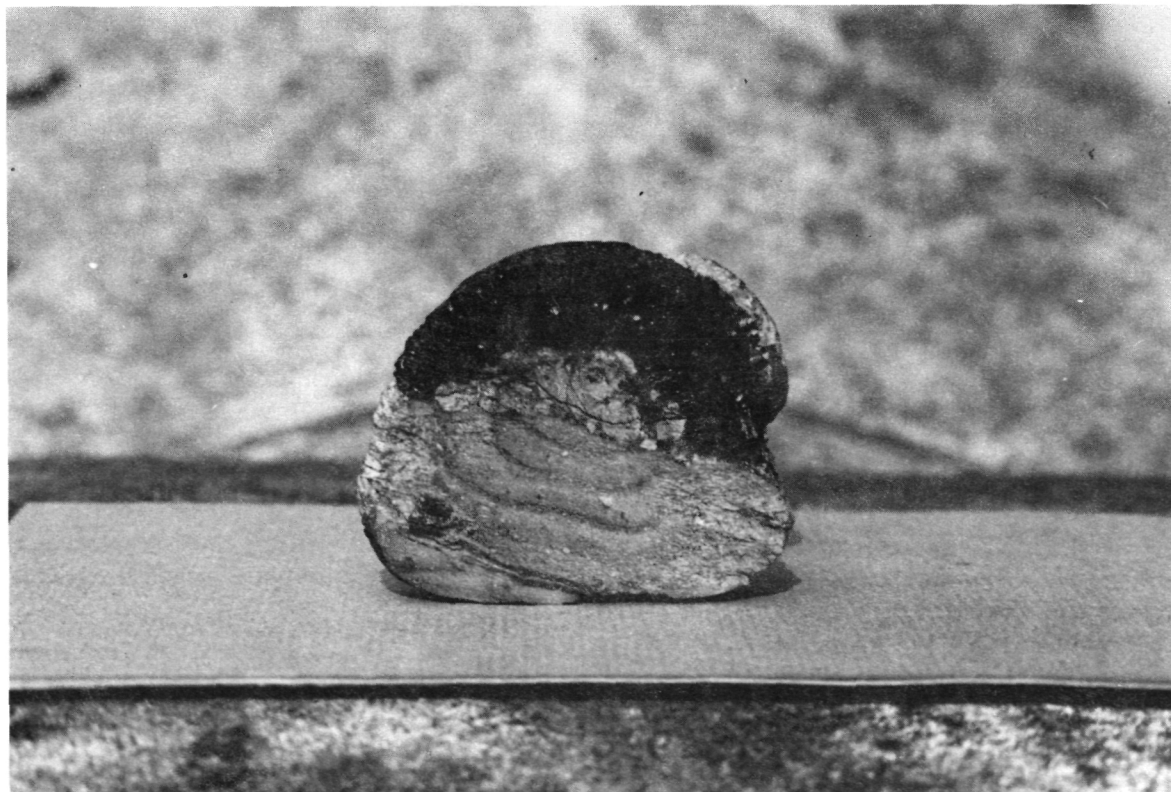   Palatine, IL 60067, USA.

Figure 1. Example of the black calcite in association with a shale. Note the acicular habit exhibited by the calcite. (Specimen is approximately actual size)
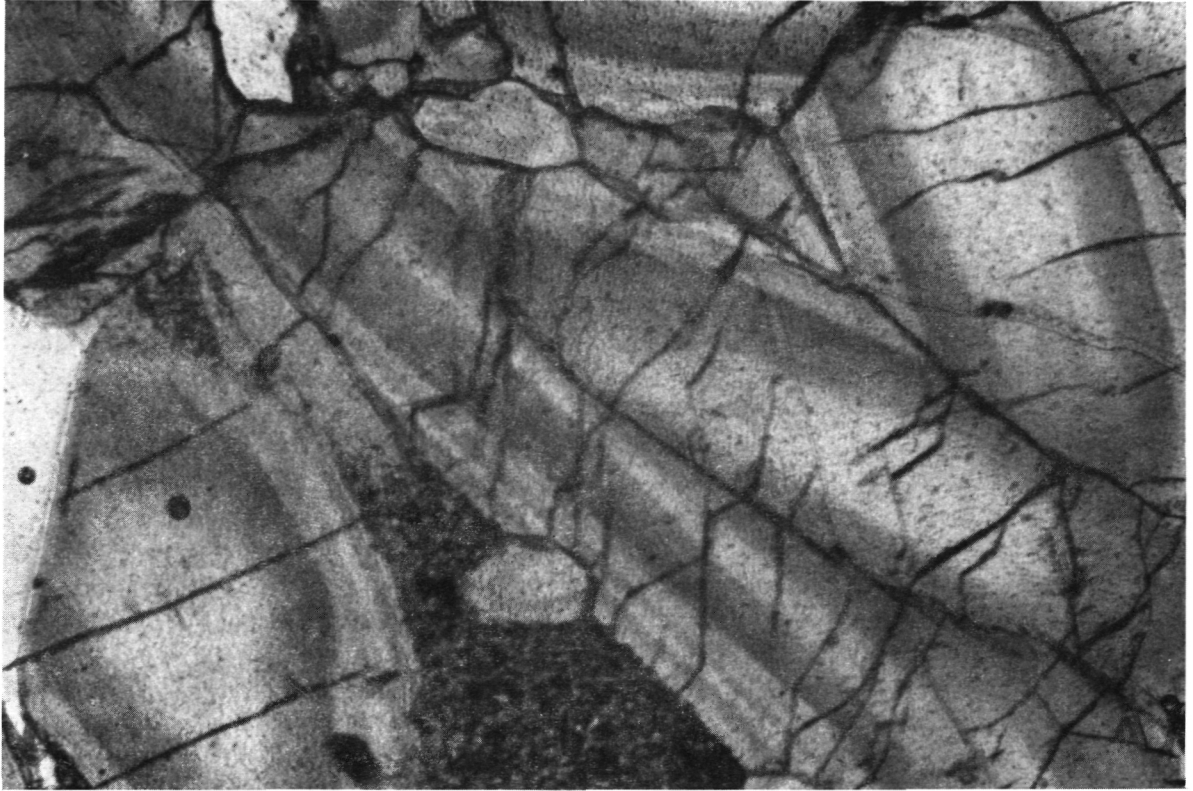
Figure 2.   Photomicrograph of the psuedo-cellular structure in the
possible stromatolites found at the Elephant Moraine.   (10x magnification)

N86-28830

THERMOLUMINESCENCE OF ANTARCTIC METEORITES: A RAPID SCREENING TECHNIQUE FOR TERRESTRIAL AGE ESTIMATION, PAIRING STUDIES, AND IDENTIFICATION OF SPECIMENS WITH UNUSUAL PRE-FALL HISTORIES.

S. R. Sutton and R. M. Walker, McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130.

ABSTRACT: Thermoluminescence (TL) is a promising technique for rapid screening of the large numbers of Antarctic meteorites, permitting identification of interesting specimens that can then be studied in detail by other, more definitive techniques. Specifically, TL permits determination of rough terrestrial age, identification of potential paired groups and location of specimens with unusual pre-fall histories. Meteorites with long terrestrial ages are particularly valuable for studying transport and weathering mechanisms. Pairing studies are possible because TL variations among meteorites are large compared to variations within individual objects, especially for natural TL. Available TL data for several L3 fragments, three of which have been paired by other techniques, are presented as an example of the use of TL parameters in pairing studies. Additional TL measurements, specifically a blind test, are recommended to satisfactorily establish the reliability of this pairing property. TL measurements also identify fragments with unusual pre-fall histories, such as near-sun orbits.

INTRODUCTION: Thermoluminescence is a relatively rapid analytical technique. Although the results may sometimes be ambiguous, permitting several interpretations, it is potentially useful as a method for rapidly identifying interesting specimens that can then be examined by other methods in a timely fashion. This paper discusses the use of TL in determination of terrestrial ages, pairing properties, and unusual pre-fall histories. Field observations raise immediate questions concerning certain specimens and it would be useful to have a rapid technique for giving first order answers to these questions. For example, in the 1984-85 field season, fragments of a distinctive meteorite were found scattered over a large area. The fact that some fragments were found on white ice, not blue ice (as is usually the case), suggests that the fragments were part of a shower that arrived on Earth quite recently. Corroboration of this hypothesis (or not) could influence plans for the study of these fragments as well as affect thinking about concentration mechanisms.

TL MEASUREMENT: The thermoluminescence measurement consists of heating the sample (typically 5 mg of powder) from room temperature to about 500°C and plotting the TL intensity versus sample temperature, the so-called "glow curve." Two types of glow curves, natural and artificial, are registered for each fragment. The natural glow curve is that measured for the "as-received" material while the artificial glow curve is that measured after draining the natural TL and irradiating the sample to some known dose (e.g., 10^5 rads with beta particles). In general, natural TL provides information on the thermal and irradiation history of the object while information on the phosphors and their abundance is derived from artificial TL. Two characteristics of the glow curves lend themselves to these analyses, shape and intensity.

TERRESTRIAL AGE: Upon arrival on Earth, meteorites are shielded from cosmic irradiation by the Earth's atmosphere and their natural TL decays. Attempts to use the extent of TL decay for accurate terrestrial age determination [1,2] have been hindered by a lack of accurate knowledge of (1) the TL levels present in individual fragments immediately after fall and (2) the Antarctic storage temperature. It has been shown, however, by comparison with radiometrically-determined terrestrial ages that TL measurements are capable of providing approximate terrestrial ages. That is, specimens with high natural TL *must* have short terrestrial ages while those with low natural TL are likely to have long terrestrial ages (a caveat in the latter case, however, is that rare near-sun orbits can also reduce natural TL; see below). Melcher [1] used the intensity of natural TL expressed as equivalent dose (ED) as a measure of terrestrial age. The ED at a given glow curve temperature, the laboratory dose required to match the natural

TL intensity, is given by

$$ED = \frac{Natural\ TL}{Artificial\ TL} \times Lab\ Dose$$

Eleven L and H chondrites from Antarctica gave ED values at 200°C in the glow curve ranging from 0.13 to 22.7 krads. Estimated terrestrial ages ranged from <100,000 to >400,000 years and were consistent with ^{36}Cl ages. An order of magnitude difference in ED corresponds to roughly an order of magnitude difference in age. In another terrestrial age study of Antarctic meteorites, McKeever [2] examined the shape of the natural glow curve expressed as the ratio of the low temperature intensity (LT) to the high temperature intensity (HT) for eight L and H chondrites. TL terrestrial ages again were consistent with radiometric estimates.

PAIRING STUDIES: The TL emitted by a meteorite is a complex combination of many factors including phosphor TL characteristics and abundance, thermal history, irradiation history and terrestrial age. Because these factors are likely to be unique for each meteorite, unpaired meteorites are expected to have significantly different TL properties. Pairing studies using TL are possible because observed meteorite-to-meteorite TL variations are generally large compared to variations within single objects. The similarity of TL response from two objects would be consistent with pairing while discrepancy would be evidence for non-pairing.

INTER-METEORITE TL VARIATIONS: (1) Natural TL - In Melcher's terrestrial age study [1], the eleven L and H chondrites from Antarctica gave ED (200°C) covering a dynamic range of about a factor of 200. A variation of about 200 was also found in LT/HT values in McKeever's work [2]. (2) Artificial TL - The shape of the artificial glow curve in equilibrated chondrites has been found to be very similar although significant variations are found for unequilibrated chondrites [1,3]. This characteristic is not expected to be a very sensitive indicator of pairing. The variation in intensity of artificial glow curves, TL sensitivity, depends on petrologic type. Sears et al. [3] have found a variation of >1,000 in TL sensitivity for type 3's while types 4-6 vary by only a factor of about 10.

INTRA-METEORITE TL VARIATIONS: (1) Natural TL - Two effects are expected to be most important in producing natural TL gradients within individual meteorites, attenuation of cosmic radiation and thermal gradients during atmospheric entry. Simulation experiments suggest that cosmic ray attenuation effects should be less than a factor of two over dimensions of several tens of centimeters [4]. Natural TL gradients observed in 3 meteorites are consistent with this value (Ucera- 30%/10cm [5]; Plainview- 60%/10cm [6]; St. Severin- 50%/30cm [4]. In most cases, thermal decay of natural TL produced during atmospheric entry is significant only within a few millimeters of the fusion crust [7,8] so that careful selection of samples for TL analysis can avoid this effect. An exception, however, is Farmville (H4) which shows a factor of 10 variation in ED (200°C) across a 20 cm slab possibly resulting from an oriented entry [9]. (2) Artificial TL - Artificial TL variations result principally from phosphor abundance heteorogeniety but variations in phosphor TL characteristics can also be significant for unequilibrated specimens. The range of TL sensitivity measurements on different fragments from the same meteorite is typically better than a factor of two [10]. For both artificial TL and natural TL measurements, the reproducibility of 5 mg aliquots from powdered small chips (~100 mg) is typically better than ± 20%, i.e., small compared to the effects described above [1].

TL PAIRING DATA FOR SELECT ANTARCTIC L3 CHONDRITES: Although the current TL data set for Antarctic meteorites is limited, data does exist for three L3 chondrites, ALHA-77015, 77140 and 77214, paired by other techniques (petrography, noble gases and radionuclides [11]). Table 1 summarizes the TL data on these fragments and other unpaired L3's. The small ED and TL sensitivity differences between 77140 and 77214 are consistent with the paired identification for these two fragments. However, the TL sensitivity for 77015 is a factor of 2 greater, a greater difference than the measured reproducibility of replicate measurements. TL sensitivity differences on this order led Sears et al. [12] to suggest that two separate falls are

represented, one containing three members including 77015 and another containing 5 members including 77140 and 77214. The LT/HT values (natural TL glow curve shape parameter), different by a factor of 3 for 77015 and 77214, are consistent with this interpretation. Table 1 also shows the clearly distinct TL data for two unpaired fragments, 77003 and 77278.

TABLE 1: TL Pairing Data for Several Antarctic L3 Chondrites

Specimen	ED (200°C)[a] (krads)	LT/HT[b]	TL Sensitivity[d]
Paired:			
ALHA-77015	nd	1.35	0.15[c]
ALHA-77140	4.95	nd	0.08[e]
ALHA-77214	6.5	3.90	0.078[c]
Unpaired:			
ALHA-77003	22.7	52.5	0.48[e]
ALHA-77278	3.2	nd	0.25[c]

[a]Melcher [1]; [b]McKeever [2]; [c]Sears, et al. [12]; [d]relative to Djahala; [e]Melcher [9]; nd=not determined

UNUSUAL PRE-FALL HISTORIES: An important asset of meteorite TL measurements is the ability to quickly identify meteorites with atypical thermal and/or irradiation histories. The classic example is Malakal (L5) which has extremely reduced low temperature ED although its high temperature ED is "normal" [1]. The extent of reduction suggests that the object suffered solar heating in an orbit with a perihelion of 0.5-0.6 AU, consistent with its unusually high [26]Al (79 ± 2 dpm/kg [13]). In another such example, the abnormally reduced low temperature ED's of two lunar meteorites, ALHA-81005 and Yamato-791197, were interpreted as resulting from heating during impact ejection and a subsequent space exposure which was sufficiently short to prohibited significant TL reaccumulation. A maximum Earth transit time of only ~2,000 years was indicated for both objects [14,15].

CONCLUSIONS: Natural and artificial thermoluminescence measurements on Antarctic meteorite fragments provide valuable information on the histories of these objects. Meteorites with short terrestrial ages can be easily identified as well as those likely to have very long terrestrial ages. Pairing studies are also feasible. Natural TL, probably the more sensitive pairing property, is observed to vary by a factor of 200 among individual Antarctic chondrite fragments while variations within fragments are expected to be less than a factor of 2. Inter-meteorite variation of artificial TL is less, only a factor of 10, but can be greater for particular meteorite classes (e.g., the >1,000-fold variation observed in type 3 unequilibrated chondrites). A systematic test program including a blind test is recommended to establish the reliability of TL pairing more definitively than is currently possible with the limited available data. TL can also pinpoint meteorites with unusual pre-fall histories, such as those with near-sun orbits or those such as lunar meteorites which have been exposed in space for only a short time. Such information would be useful in planning studies of particular meteorites by complementary (and more time consuming) techniques.

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PARENT SOURCES OF ANTARCTIC METEORITES AS INFERRED FROM PAIRING OF THE SPECIMENS.

Hiroshi Takeda, Mineralogical Institute, Faculty of Science, University of Tokyo, Hongo, Tokyo 113, Japan.

In the biginning of our Antarctic meteorite research, we thought that the Antarctic meteorites will provide us with good statistics on populations for different classes of meteorites. It is unclear, however, to estimate the number of different meteorites represented by the Antarctic collection, because some of them are paired. In addition, the number of Antarctic meteorites with unusual compostions or textures within a known class appears to be greater than what we expected from the non-Antarctic collections. It is natural to find rare, unique or unknown types, because the total number of specimen is large. We found, however, more anomalous ones in some classes of meteorite than the others. For example, all Yamato diogenites are different from the non-Antarctic diogenites in texture or chemical compositions (1) (2). Polymict eucrites are more abundant than howardites in the Antarctic achondrites (3) (4).

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 (4). Old terrestrial age of the Antarctic meteorites and differences betweeen the Yamato and Victoria Land collections are in favor of the hypothesis (5) (6). Even in more common meteorites, Antarctic and non-Antarctic meteorite may differ (7). They interpret these differences as reflecting derivation of Antarctic meteorites predominantly from parent sources or regions different than those from which contemporary falls derive.

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 body or mass for genetically related meteorites. To obtain a better understanding of the parent sources and their relation to asteroids, we reinvestigated several Antarctic achondrites 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.

(1) HED (Howardites, Eucrites, Diogenites) Parent Body. Discoveries of many polymict eucrites and the most diogenite-rich howardite, Y7308 from Antarctica, helped us to reconstruct their parent body (9). The polymict eucrites are regolith breccias produced by impacts of small bodies, which destructed, mixed and excavated only surface portions of the layered crust (9). The presence of unique clasts (4) and the same terrestrial age (6) suggested that Y74450, Y75011, Y75015, Y790007, Y790020 are paired. The basaltic clasts contain chemically zoned pyroxenes (4) and represent a extruded surface lava, framents of which were icorporated into cool regolith by a small impact.

Y7308 is a howardite rich in deep seated components such as Mg-rich orthopyroxene, and therefore it must be produced by a large scale impact, which may be comparable to lunar Mare Imbrium or Caloris Basin of Mercury.

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This model of the parent body promoted the discovery of a diogenitic spot in eucritic mare regions on 4Vesta by rotational observation of the reflectance spectra (10). The petrologic study of Y7308 by Ikeda and Takeda (11) favors the fractional crystallization model to produce the layered crust(9). Other paired Yamato howardites, Y790727, Y791208 and Y791492 differ from Y7308 because they contain less diogenitic components than Y7308.

The Y75032-type achondrites fill the compositional gap between dioge-nites and the cumulate eucrites, and show chemical and mineralogical charac-teristics intermediate between them in all respects (2). The Y75032-type achondrites sampled a transitional zone from diogenitic orthopyroxene and low-Ca inverted pigeonite and to cumulate eucrites in a trend of the frac-tional crystallization (12). Y791073, Y791200, and Y791201 contain more cumulate eucrite components. The unique mineralogy and texture suggested that this transitional achondrites are paired and came from a restricted region of the layered crust (9). Yamato 74013-type diogenites including 29 specimens show shock recrystallized textures indicating that they are pieces of a single fall (1). They may have been derived from beneath crater floor, where relatively slow cooling after shock heating produced such texture. All Yamato diogenites are different from the non-Antarctic ones.

Our recent study of rare Antarctic monomict eucrites, Y791186 and Y792510 and a crystalline clast in Y790266, indicates that they are similar to the non-Antarctic ordinary eucrites, but they differ texturally and chemically. Y790266 is a shocked clast-rich eucrite with a special chemical zoning of pyroxene with almost constant Mg concentration. Because non-An-tarctic monomict eucrites are products of thermal annealing at or near the crater floor or wall by an impact according to cratering mechanics (12), we interpret that the trend of Y790266 is an intermediate in the course of homogenization. Remnants of the Mg-rich core of the originally zoned pyroxene found both in Y790266 and Y791186 support the above hypothesis. The fact that Y791186 and Y792510 were almost completely homogenized but still the original chemical zoning can be traced, may suggest pairing, but other data are required to be sure of this suggestion. In the old layered crust model of parent body of the HED achondrites, the ordinary eucrites were placed between the lava eucrite and cumulate eucrite layer (19). The present model prefers that many ordinary eucrites with clouding of pyroxene and plagioclase may be placed at a crater floor and wall (12), and that thickness of this layer may be thinner than that proposed previously.

(2) Ureilite Parent Body. Discoveries of Antarctic ureilites have almost doubled the numbers of meteorite samples in the ureilite group. Each of them showed some characteristic features, and are believed to be all differ-ent falls. This situation is in real contrast with the Antarctic HED achondrites, in which many of them are pieces of the same fall (1) (4). 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 %. A similar trend was found in single pigeonite crystal showing clouding from Y790981 and ALH81101, which show strong shock textures.

The wider range of the Fe/(Mg + Fe) ratios in pyroxene now available from the Antarctic ureilites enabled us to test systematic variations of other elements with respect to the Fe/(Mg + Fe) ratios. Our plot of MnO/FeO ratio revealed weak anti-corelation as was found for chondrites (13). This anti-corelation is the result of reequilibration in the solid state with little melt when the metal-silicate equilibrium is involved. The oxidation

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-reduction is an important process to produce a suite of ureilites. Little evidence of the presence of a planetary crust or layered structure for the ureilite parent body has been found.

(3) LL Chondrite Parent Body. Among the chondrite classes, the LL chondrites preserve records of surface processes taken place on a planetary body. Chondritic vesicular melt breccias (e.g. Y790964) revealed shock partial melting and rapid cooling at near surface condition (14). Much slower cooling of a similar partially molten breccias may produce achondritic LL chondrites such as Y74160 (13). Mineralogical study of Y791067, which is similar to Y74160, indicates that it contains more olivine and more homogeneous plagioclase than those of Y74160. Removal of shock produced partial melt from LL chondrites and much slower cooling may produce Y791067.

In summary, the above difference may suggest that the Antarctic meteorites may have been derived from regions different than those from which contemporary falls derive. If so, they are useful in reconstruction of their parent bodies or masses. However we have to admit that the difference may be an artifact produced by inadequate sampling. The discovery of a Vesta-like surface materials on near earth asteroid, 1915 Quetzalcoatl (15) suggests that fragments from different portions of it may be delivered to earth in different time sequence.

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METEORITIC ABLATION AND FUSION SPHERULES
IN ANTARCTIC ICE

K.Thiel, J.Peters, G.M.Raisbeck[*], and F.Yiou[*]
Nuclear Chemistry Dept., University of Köln
* Laboratoire René Bernas, C.N.R.S., Orsay

In the course of two Antarctic expeditions in 1980/81 and 1982/83 approx. 4 metric tons of documented ice samples were collected from the Atka Bay Ice Shelf ($70^{\circ}37'S/8^{\circ}22'W$), Antarctica, and subsequently shipped to Köln for cosmic dust studies. After filtration of the melt water using $0.8\mu m$ pore size acetate filters ∿700 Antarctic spherules (AAS) in the size range 5...500µm were handpicked from the filter residue under optical microscopes. From their physical properties ∿600 black metallic, mostly magnetic spherules (mean diameter $41\pm24\mu m$, mean density $5.2\pm2.3gcm^{-3}$) and ∿100 glassy transparent spherules ($95\pm25\mu m$; $2,0\pm1.2gcm^{-3}$) can be distinguished.

For the chemical investigation of single dust grains the following techniques were applied: Scanning electron microscopy (SEM), X-ray analysis (EDAX), instrumental neutron activation analysis (INAA), laser microprobe mass analysis (LAMMA), and accelerator mass spectroscopy (AMS). For more than 95% of the total mass (>100 spherules) the bulk and trace elements were determined in single grain analyses using EDAX, INAA, and LAMMA. The largest sphere (306µg) was additionally analysed for Be-10 applying AMS at the Laboratoire René Bernas, Paris Sud.

The element pattern of the dust particles was compared with that of typical terrestrial material (crustal rock, volcanic fly ash, steel) as well as meteoritic matter (C1-chondrites, iron meteorites, mesosiderites, pallasites).

The majority of the spherules exhibit elemental compositions compatible with meteoritic element patterns (cf. fig 1). One sphere representing approx. 40% of the total mass of all spherules was shown to be definitely extraterrestrial by accelerator mass spectrometry yielding $(1.9\pm0.7)\cdot10^9$ atoms/g Be-10.

The analytical results lead to the conclusion that 93wt-% (spherule size 0.2...20µg) to 99wt-% (spherule size 0.2...300µg) of all AAS show element patterns similar to meteoritic material the percentage depending on the size range of the spherules.

From their outer appearance (roughness and texture of the surface) in the scanning electron microscope five different groups (A...E) of metallic spherules may be distinguished, containing also different fractions of the bulk elements Fe, Si, and Mg (see table).

Type	Fe_2O_3	SiO_2	MgO
A	ca 94%	ca 3%	n.d.
B	" 90%	" 5%	ca 5%
C	" 74%	" 19%	" 2%
D	" 81%	" 3%	" 8%
E	" 64%	" 19%	n.d.

Table 1. Main types of metallic opaque spherules from Atka Bay/Antarctica.
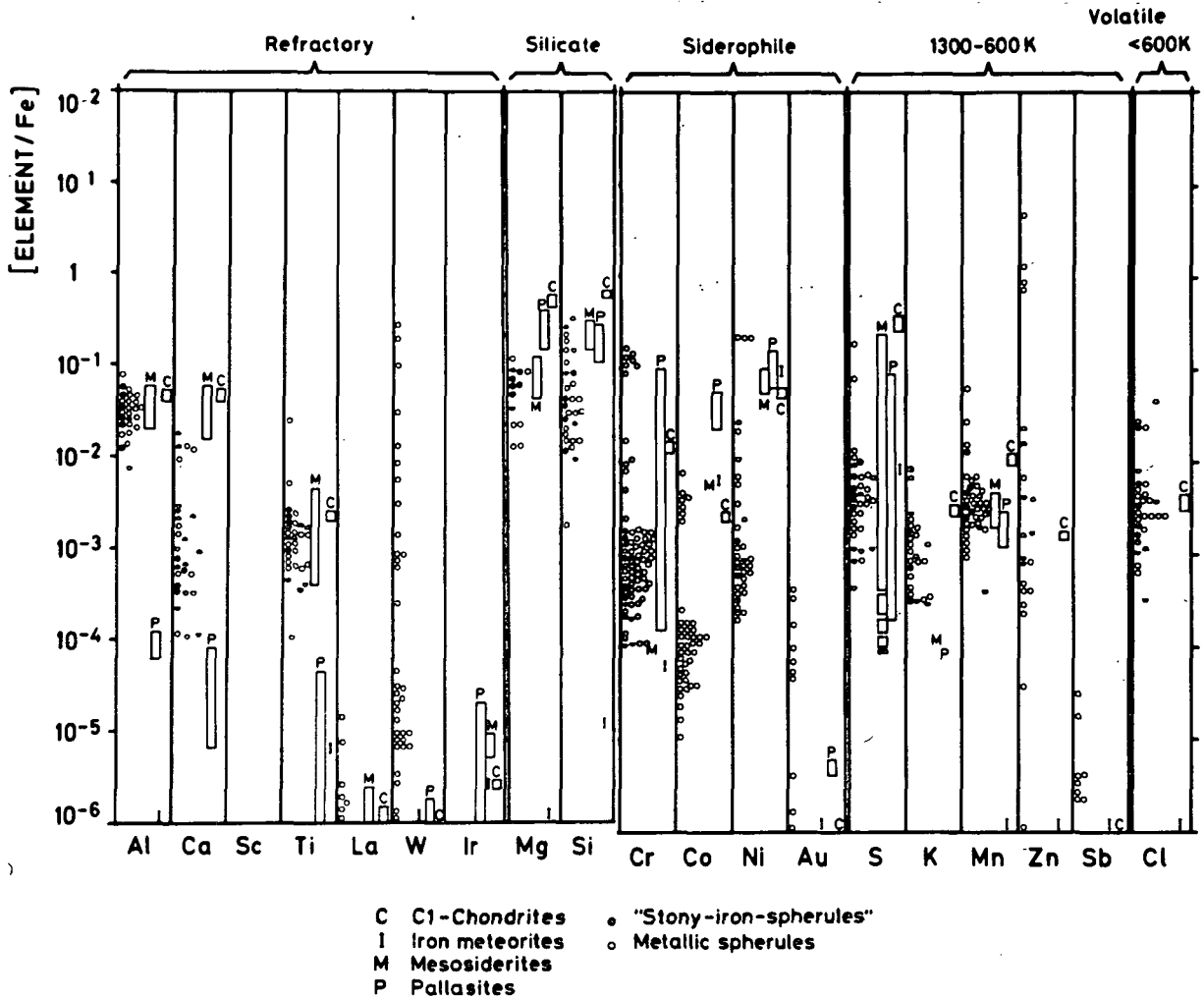
(n.d. not detected)

Fig 1. Element pattern of some of the AAS compared with the mean composition of meteorites

Most of the glassy transparent type of spherules turned out to be of terrestrial origin.

From the mass frequency distribution of the AAS in the mass range $>10^{-6}$g the cumulative particle flux N of spherules having masses m exceeding a given particle mass m_p can be derived to be

$$N(>m_p) = 5.87 \times 10^{-14} m_p^{-1.143} \{m^{-2}s^{-1}\}$$

This flux is higher than the (extrapolated) interplanetary meteoroid flux in the mass range $<10^{-6}$g by a factor of 2...3 (fig 2).

The discrepancy is discussed in terms of a contribution to the AAS objects due to atmospheric ablation and/or fusion of micrometeorites in the mass range $>10^{-6}$g.
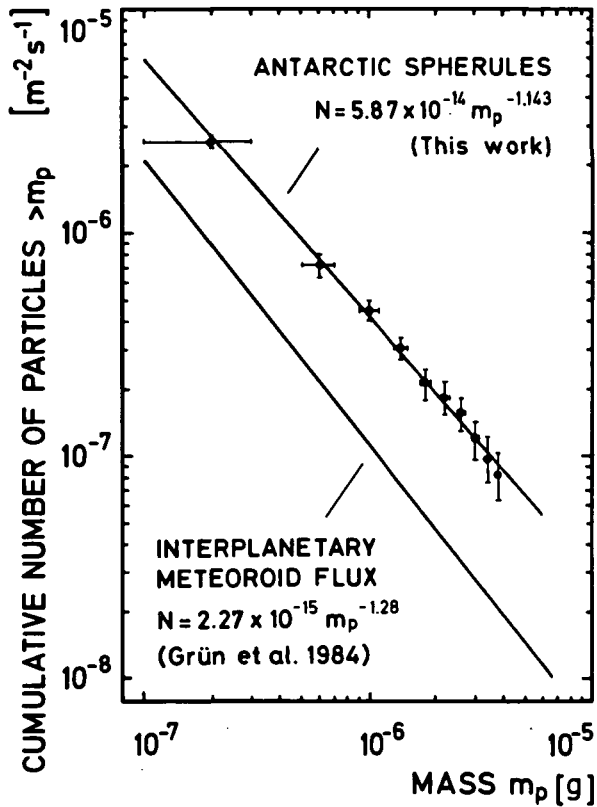
Fig 2. Cumulative particle
flux of AAS and inter-
planetary meteoroids
according to Grün et
al. (1984)[1]

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OVER 5,600 JAPANESE COLLECTION OF ANTARCTIC METEORITES: RECOVERIES, CURATION AND DISTRIBUTION; K. Yanai, and H. Kojima, National Institute of Polar Research (NIPR), 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173, Japan

Recoveries of Yamato Meteorites

Until 1969, only six meteorite fragments had been recovered from the Antarctic continent. In December 1969, the Japanese Antarctic Research Expedition (JARE) collected nine meteorite pieces from a bare ice field south of the Yamato Mountains in east Antarctica(1). The nine specimens have been classified into four types of meteorites indicating they did not derive from a common fall. The types include an enstatite chondrite (EH3), a diogenite (granoblastic), a carbonaceous chondrite (C4) and six ordinary chondrites.

In December 1973, another 12 specimens, including a howardite, were found on the bare ice near the Yamato Mountains(2). Eight specimens were collected from the same ice field as those of the 1969 collection while the others were found on a bare ice field located 30-40 km to the north and north-west. This find indicated that meteorites could be found on other bare ice fields.

The 1974 field season was very successful when a JARE search party collected 663 meteorite pieces from the Yamato Mountains bare ice fields during November and December. About 200 of these specimens were found in the same vicinity of the 1969 and 1973 finds. Over 400 specimens were found in previously unsearched areas of the ice field between Massif A and Motoi Nunatak, near Massif A, near JARE-IV Nunataks, and south of Massif B. The 1974 collection included many meteorite types including a lodranite, a pallasite, numbers of achondrites, and six ungrouped meteorites, but no irons(3,4).

In 1975 the systematic search techniques initiated in 1974 resulted in a find of 308 new fragments. Included within these finds were two irons and a unique diogenite. Most of these meteorites were collected from the area of bare ice located east of Massif D and Massif G(5).

The first theory on a concentration mechanism of Antarctic meteorites was proposed as a result of the dense concentation of Yamato specimens found on the bare ice surface(4). It was suggested that meteorites which fell into the snow accumulation zone were trapped by the gradually thickening ice sheet and were transported to an ablation zone by the moving ice. Ablation zones are found near mountains or nunataks where the ice sheet has stagnated. Meteorites that had been trapped within the ice for a long time appeared on the bare ice surface after the ablation of snow and ice.

The search for meteorites during the 1979 field season was the most systematic up to that time and it was based on the dense concentration mechanism theory. The JARE party mainly searched the area of stagnant ice adjacent to the Yamato Mountains and several nunataks located near these mountains. Over 3,600 meteorite fragments were recovered from the bare ice in this field season. Included within these finds was a most peculiar specimen, a lunar meteorite (anorthositic regolith breccia). The 1979 collection also contains many irons, lodranites, achondrites and carbonaceous chondrites(6).

In the 1980, 1981, 1982, 1983, and 1984 field seasons, 13, 133, 211, 42, and 58 specimens were collected, respectively. In particular, the 1982 collection included two lunar meteorites and a C1 chondrite which was classified as preliminary.

The total area of exposed bare ice around the Yamato Mountains is on the order of 4,000 square km. Ten JARE parties have searched for meteorites there in the face of a great deal of danger, however, much of it still remains to be searched. The Yamato Mountains are the one place in Antarctica with the greatest possibility for many more meteorites.

Recoveries of Victoria Land Meteorites:

A Japan-U.S. program titled "Antarctic Search for Meteorites" (ANSMET) was initiated as a result of the discoveries of meteorites in the Yamato Mountains. This joint program continued for three years (1976-1979) in the area of the bare ice fields of Victoria Land.

The first two meteorites found in Victoria Land were collected from the bare ice surface of the polar plateau adjacent to the Wright Valley in December 1976. They were chondrites and were named Mt. Baldr Meteorites after the name of the nearest mountain. Nine other specimens were collected that same season from the bare ice on the plateau side of Allan Nunatak (renamed Allan Hills), 230 km north of McMurdo Station, in January 1977. These were named Allan Hills Meteorites and they consisted of one iron, one eucrite and seven ordinary chondrites, one of which weighed over 400 kg.(7).

In the second year the joint party collected about 300 specimens from the bare ice around Allan Hills during December 1977 and January 1978. This collection consists of many ordinary chondrites, several irons, a few carbonaceous chondrites and achondrites including a shergottite(8).

In the last year (1978-79) of the cooperative effort the joint party searched several areas and collected nine irons from the detritus of Derrick Peak, and over 300 specimens from the bare ice abound Bates Nunatak, Meteorite Hills, Reckling Peak and the Allan Hills(9,10).

Curation of Yamato and Victoria Land Meteorites:

The present Japanese collection of Antarctic meteorites with the exception of Victoria Land specimens is estimated to total 5,618 fragments. The Department of Antarctic Meteorites, NIPR, Tokyo has been processing the Japanese collection since 1975. All collected specimens have been numbered, weighed, photographed, identified, and classified as preliminary. The specimens are stored in an air conditioned clean room.

The Yamato collection includes 7 stony-irons (six lodranites), 60 carbonaceous chondrites including the largest mass over 25 kg, many achondrites including aubrites, ureilites, diogenites, howardites, eucrites and anorthositic breccias (lunar meteorites), 4 enstatite chondrites and many ordinary chondrites. The collection may also contain more new and as of yet unidentified specimens.

Japanese Antarctic Meteorite Sample Distribution:

Since 1975, the meteorite curator of the NIPR has received 410 research proposals from scientists representing fifteen countries. Those proposals also include several consortium studies such as the lunar meteorite(s) and the Y-691 enstatite chondrite. All research proposals are judged for scientific merit by the Committee on Antarctic Meteorite Reseach of Japan. To date, over 2,100 samples have been allocated to scientists throughout the world.

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Table   Types of Meteorite of the Yamato Collection

	Y-69	Y-73	Y-74	Y-75	Y-79	Y-80	Y-81	Y-82	Y-83	Y-84
E chondrite	1		2		205					
H3			9	5	15			1		
L3			5	0	1			1		
LL3			2	1	1					
L-LL3				2						
H4	1	3	52	11	213					
L4			9	11	4					
LL4			3	1						
H5	3	2	236	11	68			1		
L5			7	5	6					
LL5			1	3						
H6	2	2	218	14	33					
L6		3	71	216	71			2		
LL6		1	5	5	2					
C.chondrite	1		4	3	31		7	15		
Shocked ch.			2		179					
Ungrouped ch.			6	5						
Iron				2	9					
Pallasite			1							
Mesosiderite										
Lodranite			1	1	3	1				
Aubrite					1					
Ureilite			4		3			1		
Diogenite	1		22	7	30	1	2	5		
Howardite		1			15			3		
Eucrite			3	5	39			10		
Anorth.Br.					1			2		
Unclassified	0	0	0	0	2746	11	124	170	42	58
Total	9	12	663	308	3676	13	133	211	42	58

Participants

Annexstad J. O.
Code SN2, NASA Johnson Space Center,
Houston, TX 77058 U.S.A.

Arnold J. R.
Dept. of Chemistry, B-017, University of California at
San Diego, La Jolla, CA 92093 U.S.A.

Bartoschewitz R.
Alter Postweg 13,
3170 Gifhorn, F. R. Germany

Begemann F.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Braun O.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Brückner J.
Max-Planck Institute für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Cassidy W. A.
University of Pittsburgh,
321 Old Engineering Hall, Pittsburgh, PA 12560 U.S.A.

Clarke R. S.
Smithsonian Institution,
Washington, DC 20560, U.S.A.

Delisle G.
Bundesanstalt für Geowissenschaften and Rohstoffe,
Postfach 510153, 3000 Hannover 51, F. R. Germany

Dreibus G.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Drewry D. J.
Scott Polar Research Institute,
University of Cambridge, Cambridge, England

Englert P.
Universität Köln,
Zülpicherstrasse 47, 500 Köln 1, F. R. Germany

Fegley B.
Dept. Earth, Atm. and Planet Sci.,
MIT, Cambridge, MA 02139, U.S.A.

Fink D.
Racan Inst. of Physics, Hebrew Univ.,
Jerusalem, Israel

J. L. Gooding
SN2 NASA Johnson Space Center
Houston, TX 77058 USA

Herpers U.
Universität Köln,
Zülpicherstrasse 47, 500 Köln 1, F. R. Germany

Herzog G.
Dept. of Chemistry, Rutgers University
New Brunswick, NJ 08903 U.S.A.

Heumann K. G.
Universität Regensburg,
Postfach 379 8400, Regensburg F. R. Germany

Heydegger H. R.
SN3 NASA Johnson Space Center
Houston, TX 77058 U.S.A.

Ikeda Y.
Ibaraki University, Dept. Earth Sciences,
Bunkyo 2-chome, Mito 310, Japan

Jentsch O.
Max Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Jull T.
Dept. of Physics, University of Arizona,
Tucson, AZ 85721 U.S.A.

Kaiser T.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Kallas K.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Keil K.
Institute of Meteoritics, University of New Mexico,
Albuquerque, NM 87131 U.S.A.

Kigoshi K.
Dept. of Chemistry, Gakushin University,
Mejiro, Toshima-ku, Tokyo 171, Japan

King E. A.
Dept. Geosciences, University of Houston,
Houston, TX 77004 U.S.A.

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Klas W.
Universitat Köln Zülpicherstrasse,
5000 Köln 1, F. R. Germany

Klöck W.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Koeberl C.
Institut für Analytische Chemie,
Abteilung Geochemie, Postfach 73, 1094 Wien, Austria

Krähenbühl U.
Anorganisch-chemisches Institut, Universität Bern,
Freie Strassse 3, 3000 Bern, Switzerland

Kruse H.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Lang B.
Warsaw University, Department of Chemistry,
Zwirki i Wiguri 101, 02-089 Warsaw, Poland

Lee T.
Institute of Earth Sciences, Academia Sinica,
P.O. Box 23-59, Taipei, Taiwan 107, Republic of China

Lindner L.
NIKHEF-K, P.O.B. 4395,
1000 AJ Amsterdam, Netherlands

Lipschutz M.
Dept. Chemistry, Purdue University,
W. Lafayette, IN 47907 U.S.A.

Lugmair G. W.
Scripps Institution of Oceanography,
Mail Code A-012, La Jolla, CA 92093 U.S.A.

Luzius-Lange D.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Marvin U.
Smithsonian Astrophysical Observatory,
60 Garden St., Cambridge, MA 02138 U.S.A.

McKay G. A.
Code SN4, NASA/Johnson Space Center,
Houston, TX 77058 U.S.A.

Müller N.
Max-Planck-Institut für Kernphysik,
6900 Heidelberg, F. R. Germany

Newsom H. E.
Institute of Meteoritics, University of New Mexico,
Albuquerque, NM 87131 U.S.A.

Nishiizumi K.
Dept. Chemistry, B-017, University of California at
San Diego, La Jolla, CA 92093 U.S.A.

Oehm I.,
Max-Planck-Institut für Kernphysik,
69 Heidelberg, F. R. Germany

Oeschger H.
Physikalisches Institut, Universitat Bern,
Sidlerstrasse 5, 3012 Bern, Switzerland

Ostertag R.
Institut für Mineralogie, Corrensstrasse 24,
4400 Munster, F. R. Germany

Ott U.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Palme H.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Pepin R. O.
School of Physics and Astronomy,
University of Minnesota,
Minneapolis, MN 55455 U.S.A.

Quiizano M.
Federacion Nacional de Cafeteros,
Avenida Jumenes No. 7-65,
Apdo. Aereo 3938, Bogota, D.E. 1, Colombia

Rao M. N.
Goecosmophysics Division, Physical Research Laboratory,
Navrangpura, Ahmedabad 380009, India

Reedy R. C.
Group INC-11, Mail Stop J514,
Los Alamos National Laboratory,
Los Alamos, NM 87545 U.S.A.

Rowe M. W.
Dept. Chemistry, University of Antwerpen,
2610 Wilrijk, Belgium

Rutherford M. J.
Dept. Geological Sciences, Brown University,
Providence, RI 02912 U.S.A.

Sarafin R.
University of Köln,
Zülpicherstrasse 47, 5000 Köln, F. R. Germany

Schmitt-Strecker S.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Schmutzler J.
Goethestrasse 30,
2000 Hamburg 50, F. R. Germany

Scholten B.
Universität Köln,
Zülpicherstrasse 47, 5000 Köln, F. R. Germany

Schultz L.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Schwade J.
969 So. Chicago Ave.,
Kankakee, IL 60910 U.S.A.

Sears D.
Dept. Chemistry, University of Arkansas,
Fayetteville, AR 72701 U.S.A.

Signer P.
ETH Zürich, N O C 61,
8092 Zürich, Switzerland

Sipiera P. P.
Harper College,
Palatine, IL 60067 U.S.A.

Specht S.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Spettel B.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Takeda H.
Mineralogical Institute, University of Tokyo,
Hongo, Bunkyo-ku, Tokyo 113 Japan

Thiel K.
Universität Köln,
Zülpicherstrasse 47, 5000 Köln, F. R. Germany

Vogt S.
Universität Köln,
Zülpicherstrasse 47, 5000 Köln, F. R. Germany

Wänke H.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Weber H.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Weckwerth G.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Weinke H. H.
Universität Wein, Institut für Analyt. Chemie,
Postfach 73, 1094 Wien, Austria

Wetherill G. W.
Dept. Terrestrial Magnetism,
5241 Broad Branch Road, N.W.,
Washington, DC 20015 U.S.A.

Wieler R.
ETH Zürich,
N O C 61, 8092 Zürich, Switzerland

Yanai K.
National Institute of Polar Research,
9fi10, Kaga 1-Chome, Itabashi-ku, Tokyo 173, Japan

Zadnik M.
Enrico Fermi Institute,
5640 S. Ellis Ave., Chicago IL 60637 U.S.A.

Zimmermann T.
Max-Planck-Institut für Chemie,
Saarstrasse 23, 6500 Mainz, F. R. Germany

Zolensky M. E.
Code SN4, NASA/Johnson Space Center,
Houston, TX 77058 U.S.A.