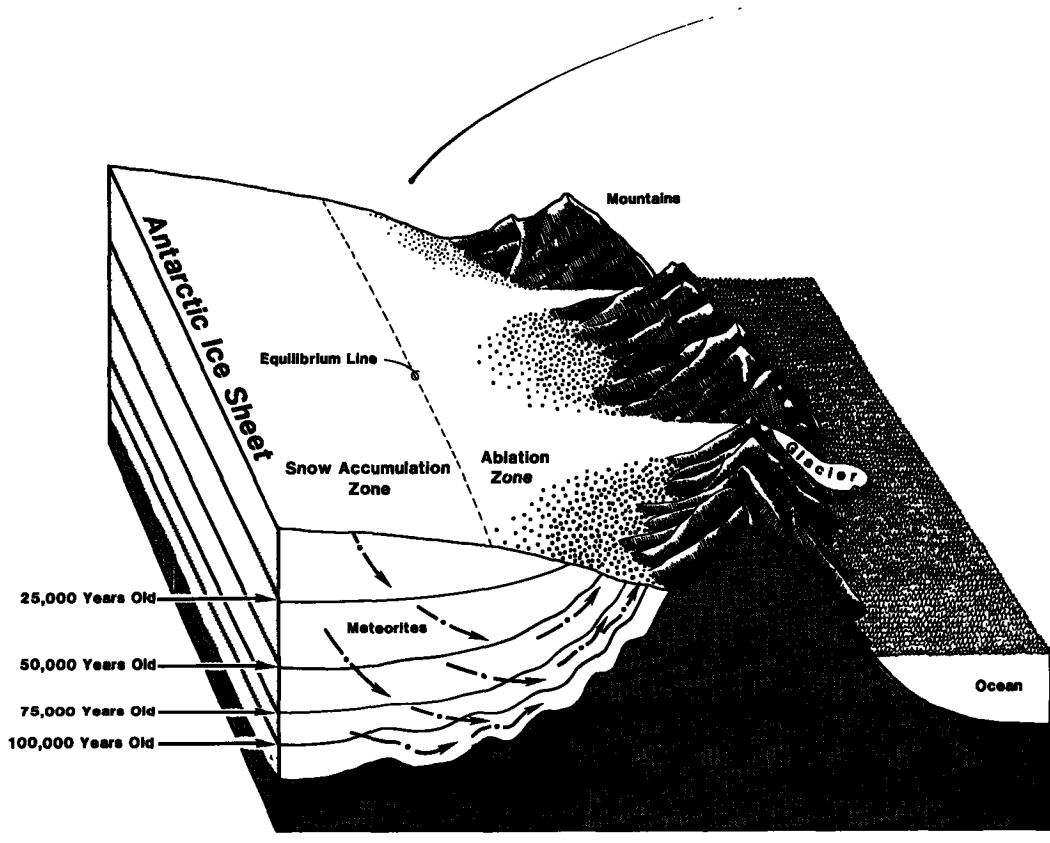


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# WORKSHOP ON ANTARCTIC METEORITE STRANDING SURFACES



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**WORKSHOP ON**  
**ANTARCTIC METEORITE STRANDING SURFACES**

**Edited by**  
**W. A. Cassidy and I. M. Whillans**

**Held at**  
**University of Pittsburgh**  
**July 13-15, 1988**

**Sponsored by**  
**Division of Polar Programs, National Science Foundation**  
**Lunar and Planetary Institute**

**Lunar and Planetary Institute    3303 NASA Road 1    Houston, Texas 77058-4399**

**LPI Technical Report Number 90-03**

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**With warm memories of**  
**Edward L. Fireman**  
**who died suddenly on**  
**March 29, 1990**

**Ed was a generous collaborator**  
**and a constant source of**  
**creative research ideas**

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## **Executive Summary**

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The discovery of large numbers of meteorites on the Antarctic Ice Sheet is one of the most exciting developments in polar science in recent years. The meteorites are found on areas of ice called stranding surfaces (Fig. 1, in Summary of Technical Sessions).

Because of the sudden availability of hundreds, and then thousands, of new meteorite specimens at these sites, the significance of the discovery of meteorite stranding surfaces in Antarctica had an immediate and profound impact on planetary science, but there is also in this discovery an enormous, largely unrealized potential to glaciology for records of climatic and ice sheet changes.

The glaciological interest derives from the antiquity of the ice in meteorite stranding surfaces. This exposed ice covers a range of ages, probably between zero and more than 500,000 years. Field reconnaissance suggests that some sequences are not severely disturbed by ice flow and should contain continuous records.

Because of this the Workshop on Antarctic Meteorite Stranding Surfaces was convened to explore this potential and, if needed, to devise a course of action that could be recommended to granting agencies. The event was held at the University of Pittsburgh from July 13-15, 1988, and was sponsored by the Lunar and Planetary Institute. Funding was provided by the National Science Foundation (Grant DPP88-03394).

The workshop recognized three prime functions of meteorite stranding surfaces. They provide:

- 1: A proxy record of climatic change. A long record of climatic change is probably preserved in the exposed ice



stratigraphy. This record has potential advantages over those obtained by deep ice core drilling (Fig. 4, in Summary of Technical Sessions), mainly because of the nearly unlimited amount of old ice available, but also because of the low cost in recovery and the length of the record. Moreover, there are helpful dating techniques from meteoritics that are not available to ice core studies. Among these are the use of meteorite concentrations and their terrestrial ages and cosmic ray exposure ages of associated terrestrial rocks to test advance/retreat models for the ice.

2. A proxy record of ice volume change. One of the key questions for the Quaternary Era is the role of East Antarctica in sea-level variation. The consensus is that the East Antarctic Ice Sheet near the Allan Hills stranding surfaces has not varied dramatically during the time interval represented by the ice exposed there. It probably has varied in minor ways, however, and it is likely that records of small- to medium-scale ice flow fluctuations can be obtained from studies of total gas content, fuller studies of the meteorite terrestrial and exposure ages and meteorite concentrations, and studies of strain and retrograde metamorphic effects in the ice. Such a record of ice sheet changes would be important to the understanding of Quaternary sea-level variations (Fig. 7, in Summary of Technical Sessions).

3. A source of unique nonterrestrial material. New, previously undescribed types of meteorites continue to be discovered. Other finds extend the known compositional variety of already discovered types. The Antarctic meteorites represent Earth's collection of interplanetary debris over a much longer period of time than other collections. Glaciological studies in areas where these remarkable

concentrations occur would help our understanding of how these concentrations came to be.

While all three topics are important, the workshop focused on the first two, with presentations by meteoriticists, glaciologists, geologists, meteorologists, and geophysicists. Agreement was unanimous that the potential exists in meteorite stranding surfaces for clear proxy records of climate and ice change. This is confirmed by recent meteoritical studies, which support the predictions of the ice flow model that the ice is old, and by studies of the ice itself that suggest the presence of stratigraphic sequences. This interplay of meteoritical and glaciological techniques is one of the attractive features of scientific work on the stranding surfaces.

Specific recommendations, written by three different authors at the request of the coconveners to convey the views of the group, are included as separate sections of this report. They are *Deducing Past Climate* by G. Crozaz, *Origin of Stranding Surfaces* by G. Faure, and *Strategies for the Future* by M. Lipschutz. Most of their recommendations fall into the following categories: (1) Further tests should be carried out on the structure and stratigraphy of the ice to determine if the flow and stratigraphy are as simple, or nearly as simple, as first results indicate; (2) an expanded capability should be developed in cosmogenic nuclide age determination and its application to ice sheet studies; (3) new applications of cosmogenic isotopes should be fostered to measure exposure ages of terrestrial rocks as ablating ice sheets retreat; and (4) further synergism between the glaciological and meteoritical techniques should be encouraged.

The workshop participants are enthusiastic over the scientific potential of the meteorite stranding surfaces. The stranding

surfaces are a scientific wellspring that remains to be tapped, and it is desirable that the scientific community and the funding agencies develop a coherent strategy for realizing the full potential of this first-order scientific resource.

# Summary of Technical Sessions

## SUMMARY

### Introduction

Emphasis in the workshop was placed on discussions directed toward understanding the potential in Antarctic meteorite stranding surfaces for supplying data on earlier climates and ice sheet size. A need had been perceived for such a workshop because, while the potential value of the recovered meteorites had been recognized early and rich dividends are currently being realized from their study, it seemed that their importance to glaciology was being underemphasized.

### The Meteorite Stranding Surfaces

Meteorite stranding surfaces are places where there are concentrations of meteorites on the ice surface (Fig. 1 and Table 1). Of the major stranding surfaces listed in Table 1, seven had been previously known in detail, but the Lewis Cliff Ice tongue (Fig. 2), discovered in 1985, was described specifically for the first time at the workshop.

*There is no reason to believe that all major meteorite stranding surfaces have been discovered and every reason to expect that many more will be found.*

### Age Determination of Ice in Stranding Surfaces

High concentrations of meteorites, such as found on the stranding surfaces listed in Table 1, require 10,000 to 100,000 years to build up; therefore, the ice upon

TABLE 1. The Eight Major Known Meteorite Stranding Surfaces in Antarctica.  
All discovered between 1969 and 1985.

Stranding Surface	Location
Allan Hills (4 ice patches)	76°43'S; 159°40'E
Belgica Mountains	72°35'S; 31°15'E
Elephant Moraine	76°11'S; 157°10'E
Lewis Cliff Ice Tongue	84°17'S; 161°05'E
Pecora Escarpment	85°38'S; 68°42'W
Reckling Moraine	76°15'S; 158°40'E
Sør Rondane Mountains	72°00'S; 25°00'E
Yamato Meteorite Field	71°30'S; 35°40'E

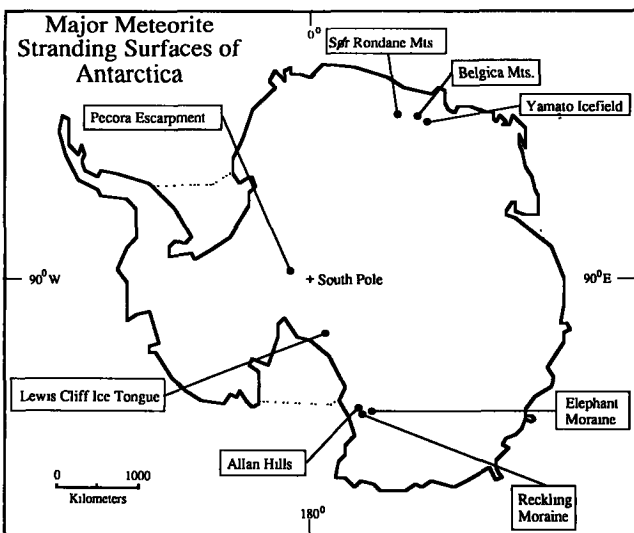


Fig. 1. Map of Antarctica showing approximate locations of the major known meteorite stranding surfaces. Meteorites have been recovered at a number of other sites, but only singly or in small numbers.

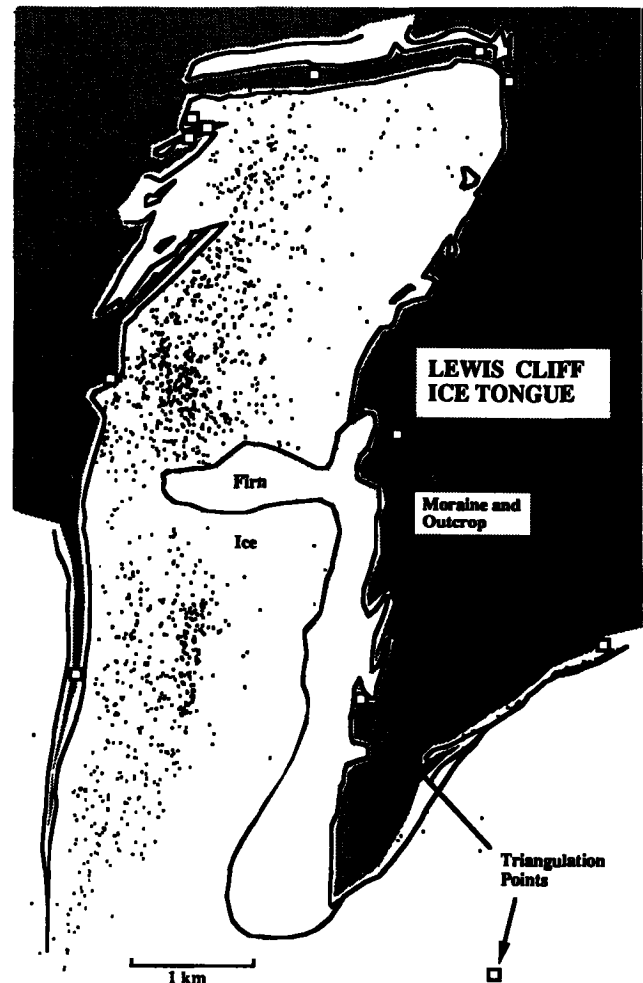


Fig. 2. Map showing locations of meteorites or meteorite fragments recovered on the Lewis Cliff Ice Tongue. North is toward the top; ice flow is from the south. The notable clustering of specimens along the western side of this northward-flowing ice body is not entirely explained.



Fig. 3. Part of a fault or fold in a section through Lewis Cliff Ice Tongue. Direction of ice flow is right to left.

which the meteorites are found must be ancient. Ancient Antarctic ice is available in virtually unlimited quantity; the problem is finding the means to determine its age.

The most straightforward method for estimating the age of the ice is the use of ice-flow models. These models have already been applied and suggest ages for the ice of up to 500,000 years. The validity of the models is supported by the successful prediction of meteorite concentration densities and their terrestrial age distributions.

Thorough tests of model predictions have not been undertaken. Although these models probably are accurate to a first approximation, it is believed that the actual age distribution of the ice could be distorted with respect to the simple theoretical predictions. In particular, glaciologic flow models do not account for folding and thrusting in the basal 100 m or 200 m of the ice (Fig. 3). Other variables affecting the models are stratigraphic disconformities and past variations in snow accumulation rate or ice thickness. Independent methods therefore are necessary to calibrate, or act as fiducial points for, the age scale.

Several possibilities have been suggested for dating the ice. These include (1) the use of  $^{10}\text{Be}$  (as used to date the Vostok core); (2) the use of radionuclides in tephra layers to obtain ages; (3) correlation of specific features such as tephra or  $^{10}\text{Be}$  spikes with otherwise-dated sections; (4) dating of embedded meteorites; and (5) stratigraphic correlation with deep ocean cores using the stable isotopic ratio of the ice and enclosed air (Fig. 4). These techniques include those used to date conventional deep ice cores. The principal difference between their use on ice cores and stranding surface ice samples is that the available sample volumes are much larger at meteorite stranding surfaces, and techniques otherwise limited by small sample sizes can be applied.

*There are thus a number of possible techniques for dating the ice; these avenues should be explored.*

#### **Structure and Ice Dynamics of Stranding Surfaces**

A major source of stratigraphic information is the numerous dust bands. These extend across the stranding surfaces in directions roughly perpendicular to flow directions of the ice and can be mapped. In some cases they are outcrops of volcanic ash that dip up-

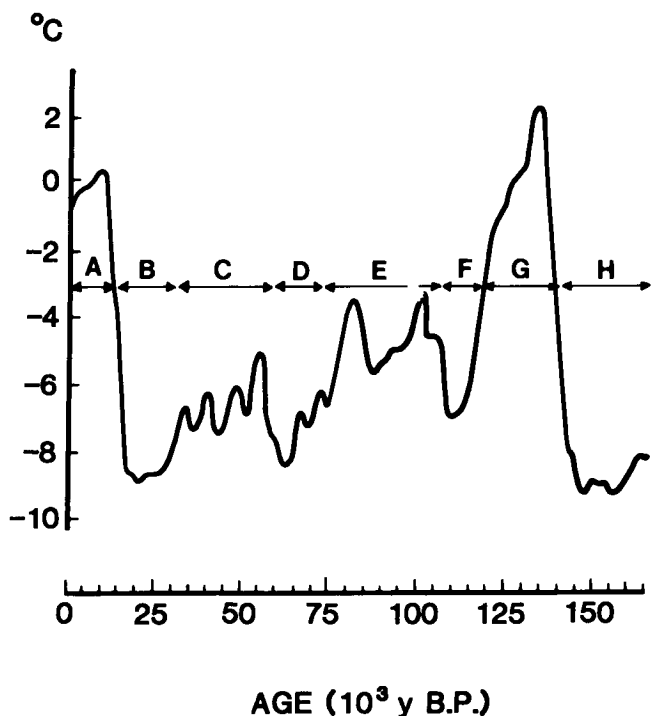


Fig. 4. Past temperatures inferred from the stable isotopic ratios in ice from the Vostok core. Climate stages A through H are those indicated by the ice-core data.

glacier at various angles. These thin layers represent time horizons and are valuable stratigraphic markers (Fig. 5).

Many of the dust bands are curved, indicating differential movement of the ice. There may also be faulted offsets associated with basal ice. Mapping of these dust bands can provide important information on the relative simplicity or complexity of flow.

In addition to the dust bands, apparent regelation ice (ice formed under wet-based glaciers) has been noted in the Lewis Cliff Ice Tongue, Reckling Moraine, and Elephant Moraine stranding surfaces. In some cases, this ice carries entrained rocks from the bed of the glacier and in other cases is clear except for the presence of bubble trains.

The ice structure has been examined at two sites where meteorites were found embedded in the ice. Glaciologists agree that the fabric, texture, and air bubble distribution indicate retrograde metamorphism of deep, highly deformed ice. Beyond that, interpretation is limited by the small number of samples studied; the two sites differ from one another in terms of texture.

*Systematic structural studies could greatly enhance our understanding of the origin and age sequences of the ice in the stranding surfaces.*

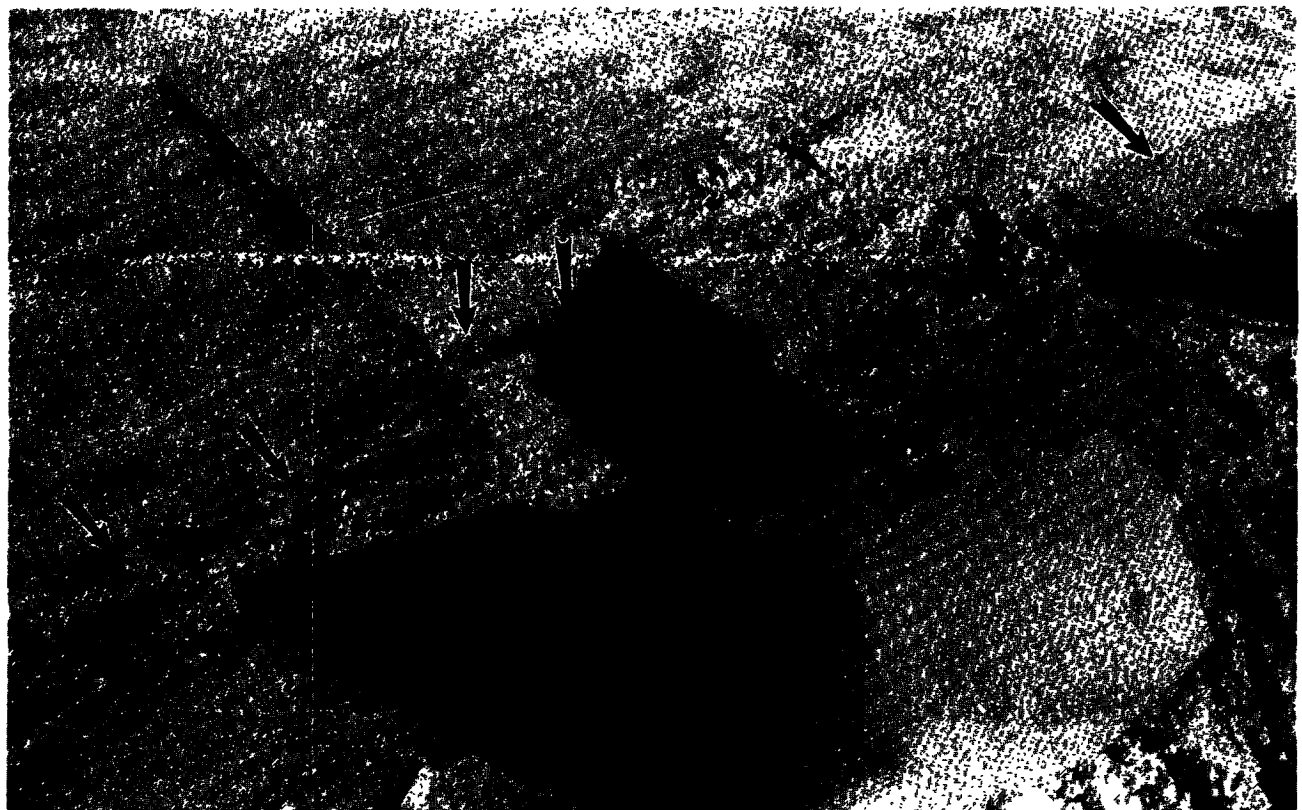


Fig. 5. A dust band at Lewis Cliff Ice Tongue, dipping toward the upstream direction. The band is about 3 cm thick.

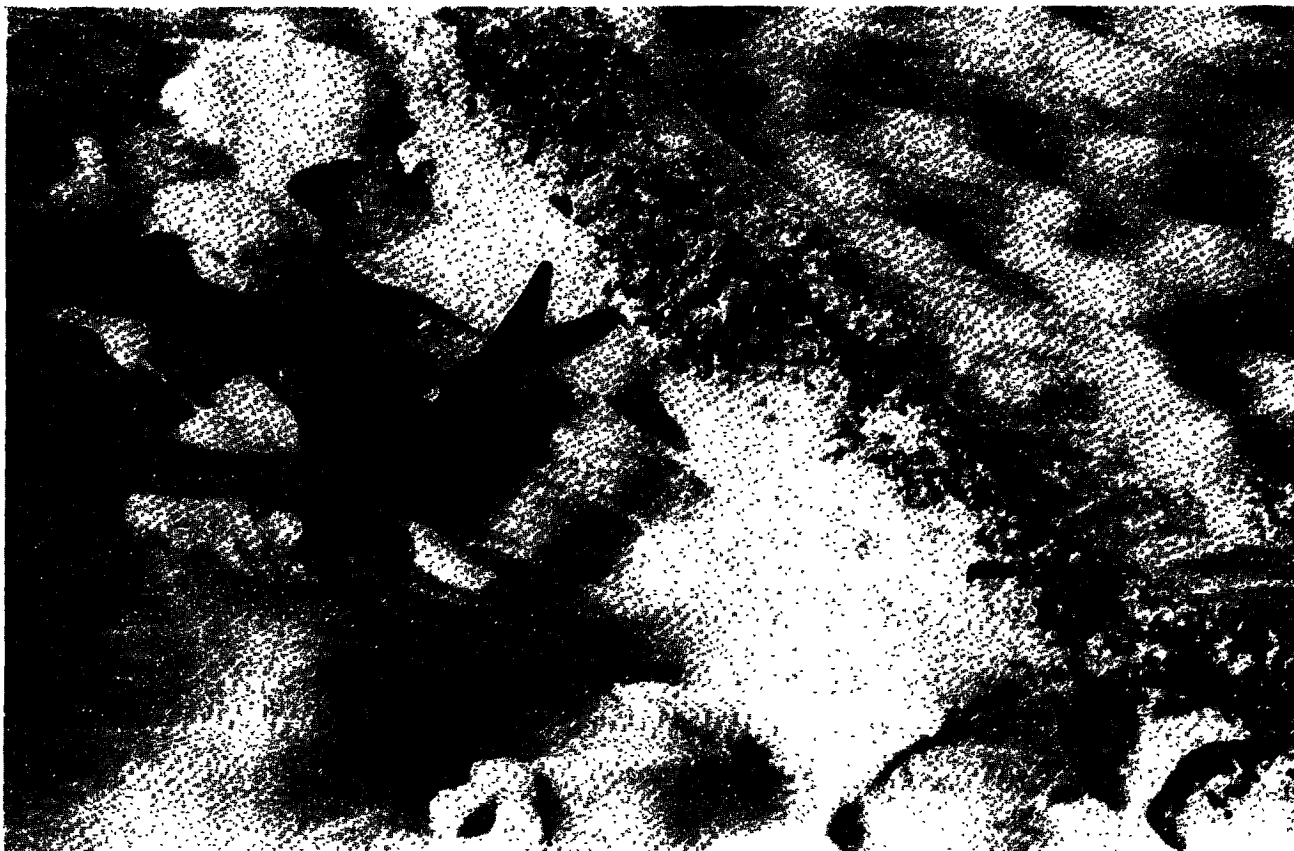


Fig. 6. Nahcolite ( $\text{NaHCO}_3$ ) crystals at Lewis Cliff Ice Tongue.

#### Other Observations

Evaporitic deposits are prominently represented at the Lewis Cliff Ice Tongue. Borates occur massively on the crests and sides of some ice-cored moraines and bicarbonates weather out along cracks parallel to boundaries that are interpreted as basal thrust surfaces. These mineral deposits (Fig. 6) are close to, or part of, the meteorite stranding surface. The question of their origin is germane to our overall understanding of the history of the stranding surface, but its answer lies in the province of glaciological studies.

*Our understanding of meteorite stranding surfaces would benefit from structural and mineralogical studies similar to those of field geology, as well as from greater involvement by glaciologists.*

## PLAN OF THE WORKSHOP

The workshop topics were chosen to induce dialogues between meteoriticists and glaciologists, suggest areas of common interest, and provide a convenient opportunity to plan coordinated research; the sequence of papers generally was planned to give background information before introducing new data or interpretations.

Introductory sessions included a summary of past work on meteorite stranding surfaces, physical descriptions of the major known examples, and a summary of genetic models that have been proposed to explain them (Abstracts 1 through 5).

The geometry of stranding surfaces was considered from the standpoints of (1) bedrock topography inferred from gravity measurements and ice-sounding radar and (2) inversion of the surface topography near supraglacial moraines using glaciological theory (Abstracts 6 through 9).

A section on cosmogenic nuclides began with a basic treatment of radionuclide production in space by cosmic-ray bombardment and continued with their use in studying meteorite concentration mechanisms, their potential in dating meteorite stranding surfaces, terrestrial age determinations of Antarctic meteorites, and exposure ages of present-day bedrock surfaces near meteorite stranding surfaces. Several contributors discussed the mechanism of meteorite concentration based on these age determinations (Abstracts 10 through 15).

The potential use of major and trace atmospheric gases and of oxygen isotopic measurements to deduce climate change were explored. Preliminary studies suggest that the ice near Elephant Moraine, Reckling

Moraine, and Allan Hills is in depositional-stratigraphic order and records at least one cycle of global interglacial-glacial-interglacial climate change. Reservations are necessary because the sampling of ice is limited, but it does appear that those areas may qualify as "horizontal ice cores" (Abstracts 16 and 17).

The volcanic ash layers that occur in the ice were explored in a series of talks on their mineralogical characteristics, their possible source volcanoes, their relation to the meteorite stranding surfaces, and age determination methods in use or as a prospect for these features (Abstracts 18 through 21).

The evaporites at Lewis Cliff Ice Tongue were described chemically and mineralogically (Abstract 22).

The evidence leading to the interpretation that the two *in situ* meteorites are contemporaneous with the ice surrounding them was outlined (Abstract 23).

The Antarctic meteorite collection can be compared with modern meteorite falls to test whether or not the Antarctic meteorites are different, especially considering that the meteorite stranding surfaces contain meteorite specimens that fell over time periods of hundreds of thousands of years. Based on orbital dynamics and cosmic-ray exposure ages, a finding that the two collections are different would be unexpected, but for that reason also would be quite exciting! The three presentations that explored this possibility provoked vigorous discussions (Abstracts 24 through 26).

The regional setting of Antarctic meteorite stranding surfaces was described by two participants, who pointed out the value of data from such sites in contributing to a study of the Antarctic surface wind regime and in helping to constrain the timing of a period of climatic warming about 1 to 2 m.y. ago (Abstracts 27 and 28).

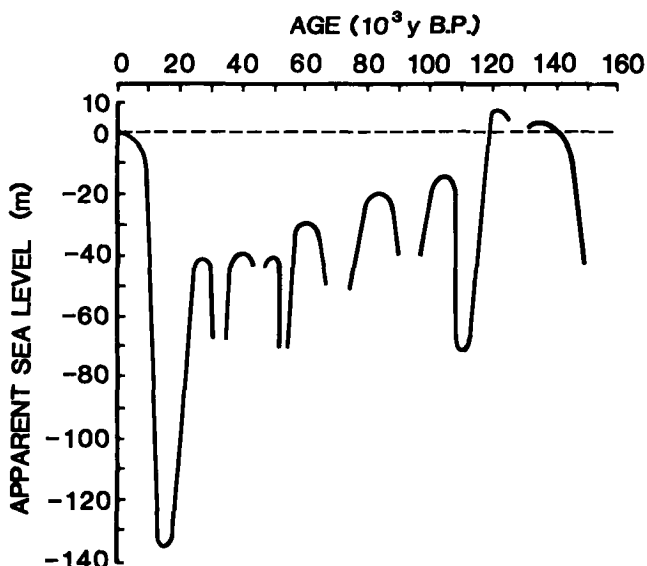


Fig. 7. Past sea-level variations due mainly to changes in the volume of ice sheets.

One unexpected development resulting from close examination of stranding surface ice has been the discovery of interplanetary dust particles (IDPs). One paper described such an occurrence in Allan Hills ice (Abstract 29).

## PROGRESS AND RECOMMENDATIONS

New material presented at the workshop included:

- Supraglacial moraines. These indicate the existence of subsurface barriers that lie close to the surface and cause topographic steps in the ice surface. Similar, but deeper, barriers cause steps but do not produce supraglacial moraines. The existence of such barriers now has been verified by radio echo-sounding.
- Measurements of temperature variations within a meteorite. On sunny days with no wind, meteorites can reach temperatures several degrees above the freezing temperature of water. This indicates that chemical weathering of meteorites can be much accelerated once they have been exposed on the ice surface.
- Measurements of the "unshielded ages" of surface rocks bordering stranding surfaces. Rocks exposed at the Earth's surface receive a finite cosmic-ray dose that is proportional to altitude. If the rocks are shielded by mantling ice, they do not receive this irradiation. A knowledge of cosmogenic isotope concentrations in surface rocks near edges of the ice sheet, as well as near the edges of stranding surfaces, can indicate recent fluctuations in thickness and the area covered by ice. Such data may be correlatable with changes in sea level (Fig. 7).
- Discussions of *in situ* meteorites and tephra layers. The terrestrial age of an *in situ* meteorite infers the absolute age of its enclosing ice; mappable tephra layers mark time horizons and are also potentially datable.
- Warnings about structural complications at stranding surfaces. Complex folding, faulting, and flow distortion would make stratigraphic interpretations more difficult.
- The concept of horizontal ice cores (Fig. 8). A channel sample of ice at a stranding surface may contain a stratigraphic sequence. Samples are easily and cheaply obtained, and sample sizes can be much larger than in an ice core. Future resampling is equally easy at any point in the sequence.



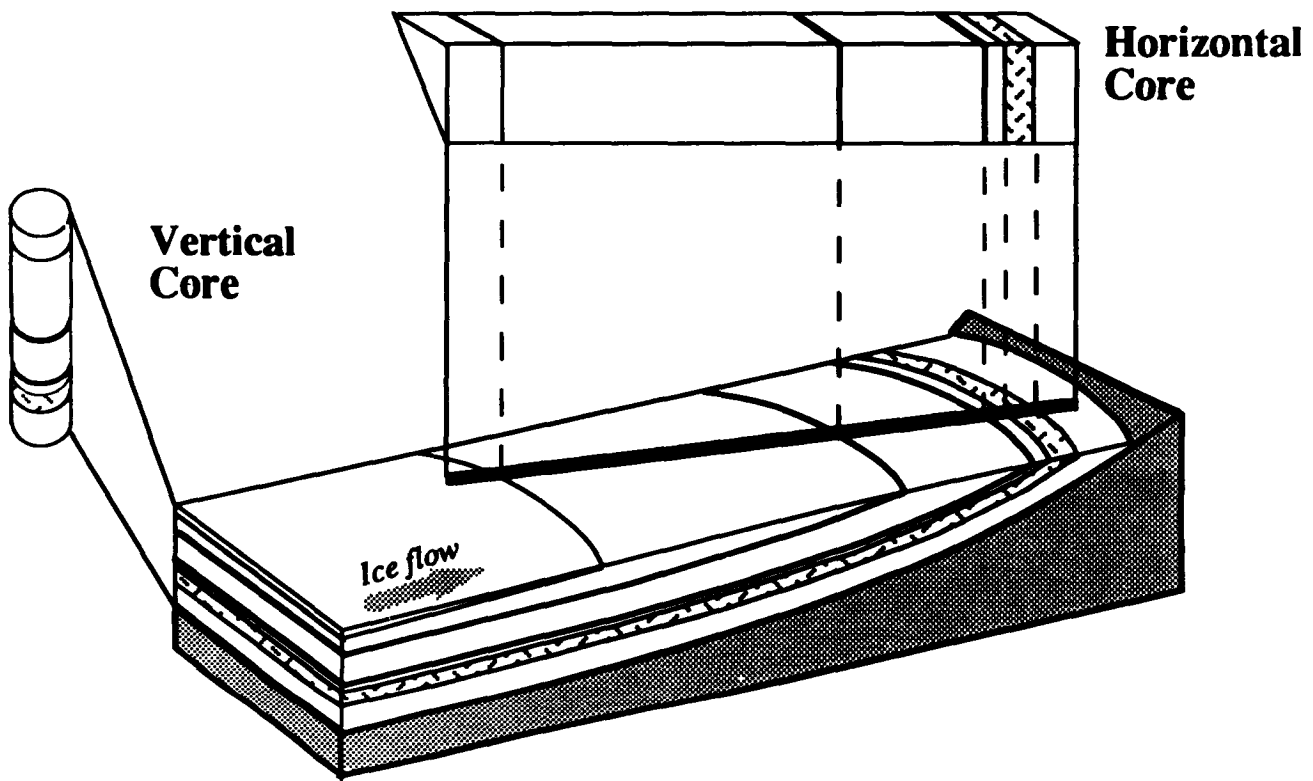


Fig. 8. The relationship between a horizontal core and a vertical core on a stranding surface. The horizontal core is obtained by cutting with a chain saw along a line perpendicular to the time horizons.

- $\delta^{18}\text{O}$  measurements on stranding surface ice. Such measurements may have already detected evidence of climatic changes.
- Microclimates. Very little is known about the microclimates of stranding surfaces. If more were known, we might better understand the stranding surface phenomenon, be better able to predict their locations, and better understand the entire ice sheet.

We recommend a program of research on meteorite stranding surfaces and their associated materials.

*Recommended for support are projects directed toward understanding the nature of meteorite stranding surfaces, understanding the nature of meteorite concentration processes, and learning the range of meteorite terrestrial ages represented on each stranding surface. We identify the following research activities as being important to these topics:*

- ice thickness measurements and bedrock configuration determinations
- ice stratigraphic determinations involving mapping of tephra bands and tectonic reconstructions

- ice dynamics studies such as horizontal and vertical velocity vector and ablation rate measurements
- age determination of tephra bands and terrestrial residence time of meteorites
- regional studies such as determination of upstream gathering areas in the accumulation zone, surface wind regimes, and topographic trends
- surface sampling for indications of ice sources, climate change, and air chemistry
- expanded reconnaissance activities designed to identify new meteorite stranding surfaces and understand their distribution on a continent-wide basis

*Participants found general agreement in the following: While in the past the primary thrust of the program has been recovery of large numbers of meteorites, and while this continues to be a scientific imperative, meteorite stranding surfaces themselves deserve study. The situation appears to present a classic opportunity, in which one unexpected discovery -- Antarctic meteorites -- leads not only to fundamental insights in its own field but also opens exciting directions in another.*

## Specific Summaries and Recommendations

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### DEDUCING PAST CLIMATE

*G. Crozaz*  
*Washington University*

Deep concern exists today about the future of the Earth's climate, and in particular the question of how global climate dynamics are influenced by changes in atmospheric chemistry. Because, at least in the general sense, the past is the key to the future, it is of great value to find new sources of information on past climates and atmospheres. The records are locked in the Antarctic ice sheet, retrievable but with great difficulty.

It has long been recognized that deep ice coring can provide samples of ice that trapped old air and contain records of past climatic changes. A more recent development, emphasized in this workshop, is the realization that meteorite stranding surfaces represent old ice now exposed at the surface that can be easily sampled in large quantities. Study of these stranding surfaces thus provides a new way to explore past variations in climate and atmospheric chemistry. While stranding surfaces are not an alternative source for all the data that can be derived from deep ice core studies, there is an interesting double analogy that can be made between the U.S. ice coring program and the U.S. space program, on the one hand, and the study of stranding surfaces and meteoritics, on the other: The first two are very expensive and currently greatly delayed due to technical problems; the second two are much cheaper and simpler to exploit. Just as meteorites are often called "the poor man's space probe," meteorite stranding surfaces may become known as "the poor man's probe into our past climate."

Stranding surface ice studies should be planned, taking into consideration the measurements already made in deep ice cores. The most recent, and highly successful, deep ice coring operation was made at Vostok Station, Antarctica. Studies included O and H isotopic measurements,  $^{10}\text{Be}$  determinations, and analyses of a number of trapped gases and chemicals. As in deep ice cores, it would be interesting to measure components such as Na, whose concentrations drastically change at glacial/interglacial transitions, or to look for changes in crystal size and orientation that also occur at such transitions. Studies of microparticles such as volcanic tephra, that may vary in concentration over time, should also be included.

Stranding surface ice has the potential advantage over deep ice cores of supplying information about a more distant past. Moreover, the sampling size can be very large. When using these surfaces, it will be essential, but not trivial, to determine the age of the ice and to make a variety of measurements on the same sample. Sampling guidelines need to be formulated that will optimize the significance of the results. In particular, spot samples will have little value; cores or horizontal channel samples should be used instead to study the "continuous record." It will also be important to guard against all kinds of sample contamination, either associated with exposure of these samples on the surface or with the sampling itself. Interaction and collaboration between glaciologists and meteoriticists are critical to this project.

### ORIGIN OF STRANDING SURFACES

*G. Faure*  
*The Ohio State University*

Stranding surfaces are exposures of ice near the margin of the East Antarctic ice sheet where specimens of meteorites and other objects embedded in the ice can accumulate. Stranding surfaces are not randomly distributed but are located where the flow of the ice sheet is obstructed by topographic features of the subglacial bedrock. As a result, the flow direction is deflected upward and the upwelling ice is ablated primarily by sublimation, which is enhanced by katabatic winds.

This explanation for the existence of stranding surfaces arises from the ice-flow model of Whillans and Cassidy and appears to be a good working hypothesis. An alternative model by Nishio and Annexstad explains the accumulation of meteorites as a consequence of the lowering of the ice surface by rapid ablation following a postulated change in climate. This mechanism can be superimposed on the Whillans-Cassidy model and would provide additional meteorite specimens on the stranding surface.

A third possibility, that stranding surfaces may be buried by snow or firn and are later uncovered by ablation, has been proposed by Cassidy. This process appears to be taking place on a local scale by the movement of snow patches that temporarily cover the stranding surface and the meteorites that reside on its

surface. Although the alternative models of Nishio-Annexstad and Cassidy have merit, the principal mechanism responsible for the formation of stranding surfaces is the ice-flow scenario of Whillans and Cassidy.

The insight this model provides permits us to ask specific questions about the glaciological processes and their effect on the transportation and accumulation of meteorites. The presentations at this workshop have demonstrated that the information provided by meteoriticists and glaciologist-geologists is complementary and leads to enhanced understanding of the origin of stranding surfaces. In addition, the results illuminate broader questions about the history of the meteorite flux, the response of the East Antarctic ice sheet to climate change, and the record of climate change contained within the ice sheet.

### Summary of Results

The results presented at the workshop support several significant conclusions about stranding surfaces:

1. The stranding surfaces west of the Allan Hills are located over and slightly down-ice of subglacial bedrock ridges or peaks. The bedrock ridges obstruct the flow of the ice and cause the formation of ice ramps (also called monoclines or steps), which are located over the obstructions. Most of the known stranding surfaces are associated with these ice ramps, and meteorites are commonly concentrated on the stranding surfaces in the lee of ice ramps. The supraglacial moraines known as the Reckling and Elephant Moraines are also located on the lee side of ice ramps, which form horseshoe-shaped depressions in the surface of the ice sheet. The thickness of the ice over the bedrock ridge at the Reckling Moraine is less than 100 m. The ridge appears to be part of a cirque that opens to the northeast. Other cirque basins in this area have already emerged from the ice in the Griffin Nunataks, Rieker Hills, and elsewhere in the drainage basin of the David Glacier. The development of ramps and depressions in the surface of the ice sheet due to the presence of bedrock ridges is predictable from ice-flow theory and is therefore consistent with the Whillans-Cassidy model.

2. Terrestrial residence ages of meteorites based on the decay of cosmogenic radionuclides vary from near zero to almost one million years. Age determinations based on the decay of cosmogenic  $^{36}\text{Cl}$  are most reliable because its distribution does not vary significantly with depth in the meteoroid and does not depend on its shape. Meteorite specimens from the Main Ice

Field of the Allan Hills have a greater range of residence ages than those at the Far Western Icefield and at the Yamato Mountains. The frequency of terrestrial residence ages of meteorites from the Main Ice Field of the Allan Hills decreases exponentially with increasing magnitude of the age. The terrestrial ages also increase from west to east toward the Allan Hills, which is consistent with the Whillans-Cassidy model. The relative scarcity of meteorites with old terrestrial residence ages may be attributed to the effects of weathering. The interiors of meteorites lying on a stranding surface may reach temperatures above  $0^{\circ}\text{C}$  during the summer when the wind velocity is low.

3. Oxygen isotope profiles of ice collected from shallow pits along traverse lines across the Reckling Moraine and the adjacent stranding surfaces indicate the presence of ice that formed under glacial and interglacial climatic conditions. One-meter ice cores taken within the moraine are isotopically homogeneous, whereas ice south of the moraine exhibits fluctuations of the  $\delta^{18}\text{O}$  parameter of about 2‰ with a wavelength of about 20 cm. Surface ice may be contaminated by melting and refreezing of recently deposited snow, but samples taken more than 10 cm below the surface of the ice are not detectably contaminated. The presence of isotopically homogeneous ice under the Reckling Moraine is consistent with the Whillans-Cassidy model and confirms that the moraines are forming by ablation of basal ice. The repetition of the glacial-interglacial  $\delta^{18}\text{O}$  signature may be caused by folding or low-angle thrust faulting of the ice.

4. Simple ice-flow considerations suggest that the Elephant Moraine began to form less than 100,000 years ago based on an inferred horizontal ice-flow velocity of 6 cm/yr and a length of 5600 m parallel to the ice flow direction. This result was confirmed by age determinations of quartz sandstone boulders from the Elephant Moraine based on *in situ* production of  $^{10}\text{Be}$  and  $^{26}\text{Al}$ . The actual dates of four boulders range from 280 years to 59,200 years, which indicates that the Elephant Moraine is probably more than 60,000 years old. It was suggested that both the Elephant and the Reckling Moraines began to form as a consequence of a *decrease* of the thickness of the ice in this area. The decrease in ice thickness may have been caused by a change in climate or by increased draw-down of ice by the David and Mawson Glaciers.

5. Tephra layers are a common feature of stranding surfaces and represent horizons of equal age within the ice sheet. The tephra from different ash layers have been traced by means of their chemical compositions to volcanic centers in northern Victoria Land (Pleiades)

and to the alkali basalts of Ross Island and southern Victoria Land. The tephra layers provide reference horizons for chemical or isotopic studies of the ice in stranding surfaces, reveal the internal structure of the ice sheet, and may permit stratigraphic correlation of ice in different areas. Dating of the tephra by isotopic means is very desirable but is technically difficult.

6. The stranding surfaces expose ice that contains cosmic dust particles, micrometeorites, and meteorite-ablation spherules. Several exotic particles have been found as well as large numbers of spherical particles of chondritic composition. New measurements of the meteorite flux have been made and may permit more quantitative interpretations of the abundance of meteorites on stranding surfaces.

#### Problems to be Resolved

Although much has been learned about meteorite stranding surfaces, more work is required before firm conclusions can be drawn, and some aspects of the phenomenon are not yet understood:

1. *The source of the ice in the Main Ice Field of the Allan Hills and therefore the size of the "catchment" area for the meteorites.*

The available  $\delta^{18}\text{O}$  values indicate that the ice did not originate from Dome C or another site in the interior of the continent. However, if the ice formed in a local accumulation area near the Transantarctic Mountains, the catchment area of meteorites may be too small to provide the more than 900 meteorite specimens that have been collected on the Main Ice Field.

2. *The topography of the subglacial bedrock beneath stranding surfaces.*

Since bedrock topography appears to affect the development of stranding surfaces and hence the accumulation of meteorites, much more information is needed about the topography of the subglacial flank of the Transantarctic Mountains near the Allan Hills and elsewhere. Current methods of measuring ice thickness by radar reflection and gravimetry are largely uncalibrated and are not designed to provide the detailed regional coverage that is needed.

3. *Terrestrial residence ages of meteorites.*

The residence ages of meteorites convey important information about the variation of the meteorite flux with time, about the rate of weathering of meteorites,

and about the age of the ice in which the meteorites are embedded during transport. However, only a small fraction of the total collection has been dated and some of the dates are questionable on technical grounds. The lack of an adequate number of terrestrial residence ages is hindering the effort to interpret them for studies of stranding surfaces.

4. *Improvements in the measurements of residence ages.*

The radionuclides that are currently used to measure residence ages ( $^{14}\text{C}$ ,  $^{36}\text{Cl}$ ,  $^{81}\text{Kr}$ ,  $^{53}\text{Mn}$ ,  $^{26}\text{Al}$ ,  $^{10}\text{Be}$ ) are not well suited to measure ages between 35,000 years and 200,000 years. Consequently, an apparent gap may be created in the distribution of measured terrestrial ages of meteorites, which may cause inappropriate interpretations. The difficulty may be overcome by using  $^{41}\text{Ca}$ , which has a half-life of about 100,000 years.

5. *Apparent discrepancy between residence ages of meteorites and the history of glaciation of Antarctica.*

The spectrum of terrestrial residence ages of meteorites in the Main Icefield of the Allan Hills and from other stranding surfaces (Elephant Moraine, Pecora Escarpment) extends to nearly 1 m.y. However, the presence of ice of comparable ages between  $2 \times 10^5$  yr and  $7 \times 10^5$  yr has not yet been recognized in ice cores or in surface exposures. Methods for dating ice by their content of cosmogenic radionuclides and U-series nuclides should be compared to evaluate their reliability.

6. *Use of tephra layers for correlation and dating.*

The presence of tephra layers in the ice is of great potential value for glaciological studies. However, they appear to be multicomponent mixtures of particles of different origins and compositions, causing the chemical composition of bulk samples to vary erratically over short distances. Moreover, dating of glass particles and mineral grains has not yet been attempted, although several methods may be applicable.

7. *Inaccessibility of stranding surfaces in Antarctica.*

Some of the stranding surfaces are situated in very remote locations and can be reached only by experienced persons via snowmobile traverses. The inaccessibility of potential study sites is a major obstacle to progress in understanding the origin of stranding surfaces. The Main Ice Field of the Allan Hills area is more accessible than any of the other ice fields, but it may be unique in some respects.

8. *Climatic and glaciological factors in the localization of stranding surfaces.*

Katabatic winds play an important role in ablating stranding surfaces. However, the role of ice movement, differences in albedo of snow and ice surfaces, seasonality of ablation rates, and the ages of stranding surfaces are not understood. In addition, no information is available to indicate whether stranding surfaces are expanding or shrinking and whether the margin of the ice sheet is advancing or retreating at the present time.

9. *Formation of subglacial brines by refreezing of basal meltwater.*

Melting of ice and refreezing of water at the base of the ice sheet may form brines that can precipitate a suite of characteristic minerals that may be exposed in terminal moraines. The presence of brines with low freezing temperatures may also affect the rate of flow of the ice sheet.

#### Directions for Future Research

In order to understand the occurrence of stranding surfaces and the processes that cause meteorites to accumulate on them, progress is needed toward solutions to several problems. *The ultimate justification for these research proposals is that the results may lead to the discovery of additional stranding surfaces, both in Antarctica and in Greenland, on which meteorites and rock samples of lunar and planetary origin may be recovered.* In addition, the proposed research will enhance our understanding of the properties of terrestrial ice sheets, particularly their response to climate change, and the record they contain of past climatic events.

1. It is clear that a major obstacle to progress is the *inaccessibility* of the research sites and the absence of suitable *topographic maps* or photographic images of known stranding surfaces. Over-snow travel could be greatly facilitated by the purchase of suitable vehicles that could be used to move researchers from landing strips on the polar plateau to research sites. Topographic maps contoured at 50-m intervals or less would help in mapping the stranding surfaces and in relating them to other topographic features of the ice surface.

2. The surface configuration of the bedrock under stranding surfaces should be mapped systematically by means of continuously recording radar-echo sounders

with precise location control. The results should be checked by drilling to bedrock, preferably using techniques that result in the recovery of continuous ice cores.

3. Samples for specific geochemical and isotopic studies should be collected systematically in places *where the glaciological conditions are understood.* The sampling interval should be adjusted to detect both short-range and long-range changes in the parameters to be studied. Whenever possible, several parameters should be determined on the same samples to permit correlations and comparisons of results. Interpretations should be based on large datasets.

4. Tephra layers in the ice deserve much more attention than they have received to date. They should be mapped to reveal the local structure of the ice, and the tephra should be studied to determine grain-size variation to detect graded bedding and multiple depositional events. The chemical composition of the tephra should be determined in closely-spaced samples to establish their continuity for use in correlation. Dating of tephra should be attempted.

5. Terrestrial ages of meteorites should be determined by the most reliable method on most of the available specimens. The terrestrial ages of the dated meteorites should be evaluated with regard to regional ice-flow patterns, type of meteorites, existence of meteorite showers, and frequency distribution.

6. Further work is needed to study the weathering of meteorites in the ice and on stranding surfaces in order to permit a reliable evaluation of differences in chemical compositions of meteorites in Antarctica with those that fell elsewhere in the world.

7. Particles of extraterrestrial origin embedded in the ice and in glacial sediment may include interplanetary dust grains, micrometeorites, cometary particles, and meteorite-ablation spherules, as well as particles derived from the Moon and from Mars. The studies of such particles should include cosmic-ray exposure ages, terrestrial residence ages, chemical compositions, and other relevant physical and chemical properties. The abundance of extraterrestrial particles in the ice and firn should be determined to evaluate their flux and to determine ice volumes from populations of particles.

8. The meteorite-collecting program should be continued because it has greatly enlarged meteorite collections available for study, because additional rock samples from the Moon and Mars may be found, and

because it has given direction to glaciological studies that contribute to a better understanding of the terrestrial environment.

## STRATEGIES FOR THE FUTURE

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The Antarctic ice sheet and its associated meteorites have the potential to profoundly influence the thinking of scientific communities working on them. For example, the recovery of lunar samples and possible martian samples has forced a rethinking of widely-held beliefs about planetary ejection/collection processes. Similarly, the distribution and terrestrial ages of Antarctic meteorites on the ice sheet will almost certainly influence the conventional wisdom of polar-ice-sheet dynamics and global climate change.

The Antarctic ice sheet and the meteorites stranded on its surface yield very different sorts of information. However, their recent histories are interdependent to such an extent that studies of them are synergetic: An understanding of the recent history of one gives feedback to better understand the other. Antarctic meteorites are important -- quite possibly unique -- sources of information on the origin and history of extraterrestrial objects: These meteorites constitute equally significant sources of information on Antarctic ice-sheet history and dynamics. The ice sheet is simultaneously a unique driver for and recorder of planetwide, geophysical events. In addition, a better understanding of its history and dynamics should enable additional meteorite source regions to be identified.

At this point, there are a number of unresolved questions that, if answered, should tap the unique potential of the ice sheet and meteorites as information sources to advance planetary science in its broadest sense -- terrestrial and extraterrestrial.

Three first-order questions are listed below together with associated, subsidiary ones.

1. *How is a meteorite-rich stranding surface to be identified so that meteorites can be garnered most efficiently?*

What are the hallmarks of and differences between stranding surfaces? Currently, the presence of blue ice and a surface-step topography seems essential. Are these totally controlled by subice basement topography and to what extent can this vary before meteorite con-

centrations no longer occur? Is there some sort of connection between nearby meteorite-rich areas (e.g., Allan Hills Main Icefield vs. Western Ice Fields) or are these totally separated, tapping different meteorite reservoirs? By what mechanism(s) do meteorite concentrations occur? If more than one mechanism is effective, do they operate separately or can they work in parallel?

2. *What information on ice sheet history and dynamic flow pattern(s) can be deduced from properties of meteorites and terrestrial rocks?*

To gain local, detailed information on ice sheet history and motion, can even a semiquantitative chronometer be developed that would be capable of differentiating a meteorite's terrestrial age into its interior transport/surface residence components? What ice sheet dynamic difference is responsible for the very different terrestrial age and mass distributions of meteorite populations from the widely separated Allan Hills and Yamato Mountains regions of Antarctica? How do these properties compare in meteorite populations from other major Antarctic regions? Are these differences reflective of different ice sheet transport velocities or drainage area sizes, for example, or an as yet unidentified cause? Within the relatively small area of the Allan Hills Main Icefield, terrestrial ages of meteorites vary with the sample's distance from the barrier, implying something like a simple Whillans-Cassidy ice flow model. Does such a relationship hold in every stranding area and what does the relationship in a given area tell us about ice sheet motion? Firn-cover near blue ice areas may be incidental or may reflect some fundamental difference in subsurface ice sheet motion. Do properties of meteorites from firn-covered areas differ (e.g., in terrestrial age or in other ways) from samples recovered from nearby blue ice areas? Since the age of the ice at a stranding surface is at least the age of the oldest meteorite on it, can meteorites be found with ages > 1 Ma? Are the surfaces on which they are found distinctive in some way from those yielding much younger meteorites? What are the exposure ages of terrestrial rocks at ice sheet margins? Can quantitative differential ice sheet motion be deduced from those data? Can a technique be developed sufficiently sensitive to determine the age of an individual dust particle and hence the age of its associated ice?

3. *How different are the meteorite populations of contemporary falls and those recovered from Antarctica and what information do these populations convey about*

*the formation and evolution of solar system bodies and processes?*

Since some of the very numerous differences between meteorite populations could conceivably reflect terrestrial weathering, what chemical and physical changes in meteorites are wrought by this process? When these are subtracted from the list of differences, which of the remaining properties are critical to establishing the preterrestrial genetic differences between the populations? How do these critical properties vary in Antarctic meteorite populations defined by terrestrial age, sample mass, or preterrestrial orbit? What parent-body genetic processes are revealed by the properties of Antarctic meteorites? To what extent is our current picture of the meteorite delivery process to Earth correct?

In answer to the above questions, certain needs for the future exist:

*It is necessary that essential studies of stranding surfaces and the meteorites on them continue to be carried out.* Determination of terrestrial ages of meteorites has the highest priority by far but rock exposure ages, subice basement topography, ice flow and dynamic studies, and investigations of meteorite properties are of very high priority.

*It is important to develop and employ new techniques to discover additional meteorites, especially in firm-covered areas.* These techniques -- an outgrowth of the discovery of new meteorite-rich areas and a more complete understanding of the meteorite collection/transport/concentration process(es) -- will provide samples to test the latter, as well as to probe solar system objects and processes.

*In connection with the immediately preceding need, it is essential to continue to identify new meteorite-rich surfaces and to collect meteorites from old and new areas.*

*It is necessary to be able to identify especially significant samples as expeditiously as possible.* Hence, new techniques must be developed and employed to survey important meteorite properties (e.g., weathering, terrestrial age) rapidly.

*It is very important that results obtained by Antarctic geologic, glaciologic, and meteorite communities continue to be mutually communicated among and between these groups.* The samples under study and a complete understanding of results from them require an interdisciplinary approach to maximize their potential as planetary and polar probes.

*Finally, it is necessary to expand the links currently existing between countries collecting or likely to collect Antarctic meteorites, so as to maximize the number of samples and their utility as planetary and polar probes.*

To satisfy these needs, certain facilitating steps need to be taken:

*Foremost among these steps should be the establishment of substantial additional Accelerator Mass Spectrometry (AMS) capability.* Answers to many of the questions raised earlier can be determined only if the cosmic-ray exposure history and/or terrestrial age of specific samples are known. The current AMS capacity is totally inadequate to provide this information on cosmogenic radionuclides in the requisite number of samples. Without a markedly enhanced AMS capability, it will be impossible to provide answers to any but a very few of the questions listed earlier.

*Steps should be taken to continue to encourage additional consortium studies of Antarctic rock and ice and meteorite samples.* Each of these materials is the result of a complex set of processes -- some simultaneous, some sequential -- that must be understood if the information contained within the samples is to maximally benefit planetary sciences, and especially its polar component. Experience has shown that if such complex samples or processes are examined by a single approach, disciplinary bias may give less than optimum results: A multidisciplinary approach is clearly called for.

*Steps should be taken to continue to expand communication between those communities involved with the study of stranding surfaces and the meteorites on them, by workshops and as part of normal professional meetings.* Communication with outside groups can be fostered and/or carried out by the Meteorite Working Group, professional societies, and granting agencies. In fact, it would probably be beneficial to initiate communication with new groups through the Meteorite Working Group, professional societies, and granting agencies.

The research opportunity presented by Antarctic ice sheet stranding surfaces and meteorites on them is of enormous potential value to planetary sciences, in general, and its polar component, in particular. Realization of this potential may benefit other scientific areas directly and indirectly, but it will be these two areas that should reap the primary reward.

# ABSTRACTS



**IDENTIFICATION OF MAJOR ANTARCTIC METEORITE STRANDING SURFACES  
AND PROGRESS IN MAPPING THEM**

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In this presentation I first review the significant meteorite stranding sites that have been discovered and studied along the Transantarctic Mountains by U.S. scientists: not enough data are available currently on the sites developed by the Japanese to be able to discuss those sites in detail. In the second part of this presentation I give the status of the Antarctic Meteorite Location and Mapping Project (AMLAMP). Table 1 lists the known meteorite findsites in Antarctica. Some are individual findsites; others are sites where only a few specimens have been found, and a few have yielded thousands of specimens. Following are brief descriptions of some of these sites.

The Pecora Escarpment was visited briefly on a reconnaissance traverse in 1982-83. A total of 32 meteorites was collected from among the 80 to 100 specimens observed. From limited data, it appears that the highest density of meteorites occurs at the southwest end of the escarpment. A number of meteorites were found on ice in the lee of the barrier. This was surprising because we had come to expect meteorites on the upstream sides of barriers and not on the downstream sides.

In the Thiel Mountains there are two meteorite stranding surfaces; in addition, the Thiel Mountains pallasite was found not on a stranding surface, but in a moraine below Mt. Wrather, as a single individual. Based again upon reconnaissance studies only, the Davies Escarpment appears to harbor a minor concentration: small outcrops of country rock emerge from the face of the ice escarpment in a couple of places, indicating that the ice is thin over a subsurface ridge extending southward from the Thiel Mountains. There are wide areas of exposed, whitish ice. This ice has abundant trapped air in the form of bubbles, and is assumed not to have been deeply buried; therefore young. One meteorite was found near the south end of the escarpment and six were found on the more extensive blue ice areas at the north end. At the Moulton Escarpment the blue ice upstream of the bedrock barrier was thought to have good potential for meteorites, but proved to be barren. Downstream, in the lee of the nunatak, 11 specimens were discovered and collected. Several large, discrete ice-cored moraines occur here in a parallel sequence, and most of the meteorites were found between the bedrock and these moraines; thus this may be another lee-type concentration.

So far, the Lewis Cliff stranding site has produced 1018 meteorite specimens, therefore the Beardmore region may become as important as the Allan Hills-David Glacier region. The nearby areas at the southwest end of the Queen Alexandra Range in the vicinity of the Goodwin Nunataks and the upper Walcott Neve have been visited only on a reconnaissance basis, but a significant number of specimens was discovered. Systematic searching of the area will be quite productive. The MacAlpine

Hills, at the head of the Law Glacier, 24 km west of Lewis Cliff, is the site of a small but densely populated meteorite concentration: in 1987-88, during reconnaissance searches, 21 meteorites were collected and another 25-30 were located but not collected. Reconnaissance in the Dominion Range, somewhat to the east of the Walcott Neve, also suggests that significant finds may be made there.

To date, the Allan Hills-David Glacier region has been the most prolific source of meteorites along the Transantarctic Mountains, with approximately 2150 specimens recovered through 12 field seasons. Additional reconnaissance searches during the 1987-88 season proved that large numbers of specimens will continue to be found. The area has eight major stranding sites: the Allan Hills Main Icefield, the Allan Hills Near Western, Middle Western and Far Western Icefields, Reckling Moraine Icefield, Elephant Moraine Icefield, and two large ice areas to the west and northwest of Elephant Moraine.

The Frontier Mountains in North Victoria Land is the site of another small meteorite concentration. Discovered during a German expedition in 1984-85, 42 specimens were recovered from heavy surficial moraine in an ice embayment at the southeast end of this nunatak. The site is in the lee of an ice-flow barrier, and appears to be another lee-type concentration.

The distributions of meteorites at stranding sites hold clues to the concentration mechanisms. Maps can be valuable tools in distribution studies, as well as in pairing attempts; therefore the locations of recovered meteorites have been determined by field survey methods. Computer mapping capabilities and a computer data base of meteorite locations have been developed at the Lunar and Planetary Institute, Houston. Meteorite location maps of the following icefields currently are available from the LPI:

- Allan Hills Main Icefield
- Allan Hills Near Western Icefield
- Allan Hills Middle Western Icefield
- Allan Hills Far Western Icefield
- Elephant Moraine Icefield

These maps give the locations of meteorites found over the period from the 1979-80 through the 1986-87 seasons. Meteorite location maps of the Lewis Cliff area are under development.

The database also contains meteorite classification data and mass data and there are plans to add terrestrial ages. The database can be searched and selectively sorted to generate thematic maps, using the meteorite location maps as a base. Currently thematic maps can be provided on a custom basis by contacting the Computing Facility at the LPI. Explanatory texts to accompany these maps will be published through the LPI Technical Reports system later this year.

PROGRESS IN MAPPING: J. Schutt

Table 1. Abbreviation, Number of Specimens through 1987-88, and Coordinates\* of Antarctic Meteorite Find Localities (modified after Annexstad, et al. 1986)

<u>Abbreviation</u>	<u>Specimens</u>	<u>Locality</u>	<u>Coordinates*</u>	
A	3	Asuka	72°00'S	26°00'E
ALH	1561	Allan Hills region	76°43'S	159°40'E
	1111	Main Icefield		
	145	Near Western Icefield		
	85	Middle Western Icefield		
	317	Far Western Icefield		
B	5	Belgica Mountains	72°35'S	31°15'E
BTN	6	Bates Nunatak	80°15'S	153°30'E
BOW	1	Bowden Neve	83°30'S	165°00'E
DRP	15	Derrick Peak	80°04'S	156°23'E
DOM	11	Dominion Range	85°20'S	166°30'E
EET	590	Elephant Moraine	76°11'S	157°10'E
FRO	42	Frontier Mountains	72°59'S	160°20'E
GEO	2	Geologists Range	82°30'S	155°30'E
GRO	21	Grosvenor Mountains	85°40'S	175°00'E
ILD	1	Inland Forts	77°38'S	161°00'E
LEW	1018	Lewis Cliff	84°17'S	161°05'E
MAC	21	MacAlpine Hills	84°13'S	160°30'E
MBR	2	Mount Baldr	77°35'S	160°34'E
MET	28	Meteorite Hills	79°41'S	155°45'E
MIL	1	Miller Range	83°15'S	157°00'E
OTT	1	Outpost Nunatak	75°50'S	158°12'E
PCA	32	Pecora Escarpment	85°38'S	68°42'W
PGP	1	Purgatory Peak	77°20'S	162°18'E
QUE	3	Queen Alexandra Range	84°00'S	168°00'E
RKP	87	Reckling Moraine	76°16'S	159°15'E
TYR	1	Taylor Glacier	77°44'S	162°10'E
TIL**	19	Thiel Mountains	85°15'S	91°00'W
Y	5940***	Yamato Mountains	71°30'S	35°40'E

\*The geographic coordinates of the localities are those named features given in "Geographic Names of the Antarctic" (1981) ed. F.B. Alberts, NSF pub. 81-85, U.S. Govt. Printing Office, Washington, D.C. 20305, therefore they are not necessarily the exact coordinates of the meteorite concentration that bears the same name. An exception is Elephant Moraine, which is not an officially named feature: its coordinates are exact.

\*\*TIL represents the current usage abbreviation for later finds in the Thiel Mountains region. (The earlier Thiel Mountains (1961) find is not included.)

\*\*\*Through the 1986-87 season

**THE ALLAN HILLS METEORITE STRANDING SURFACE**

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The main Allan Hills Icefield is located 230 kilometers northwest of McMurdo Station on the plateau side of the Convoy Range. The icefield is composed of a lower basin feature where most meteorites are found and an upper section on the west side about 150 meters higher than the basin. Blue ice which feeds into the basin from the west decreases in velocity from about 1 m per year to zero as the Allan Hills are approached [1]. A complete physical description of the blue ice field and the geology of the Allan Hills has been reported [2].

Glacier ice is formed in Antarctica at a depth of 60-100 m when the pressure of successive snow layers causes the closure of air spaces between grains (density =  $830 \text{ kg/m}^3$ ). This ice reaches the surface when its forward movement is blocked by mountains, nunataks or sub-glacial obstructions and the overlying snow and firn is ablated off. The exposed ice appears blue on sunny days, and so these areas are called "blue ice fields". If the blockage is nearly complete as in the Allan Hills Icefield a mature stranding surface for meteorites is created with very old ice on the surface.

A Landsat view of the general region surrounding the Allan Hills shows a large number of blue ice fields in the general vicinity of the Mawson and David Glaciers. To the west of the hills are found three separate units labeled the Near, Middle and Far Western Icefields. To the north are located the Reckling Peak and Elephant Moraine fields. Although these regions and others in the area rival the Allan Hills Main Icefield in size, they are different because the ice is only partially blocked by sub-glacial obstructions. The main ice field has yielded the largest number of meteorites found in this part of Antarctica; some are of great terrestrial age, which qualifies this as a mature stranding surface.

Blue ice, similar to that at the Allan Hills Main Field, has been described by various authors [3], [4], [5]. These surfaces are composed of whaleback or rippled ridges about 5-10 cm high and over 20 cm long. In smoother areas, tensional cracks aligned along and perpendicular to the flow direction are seen. The ice fields are highly ablative (4-10 cm/yr with an average about 5 cm), which is primarily caused by sublimation enhanced by frequent katabatic wind flow. Dust bands cross the ice fields and are deformed by differential flow to form vaguely parabolic forms in outcrop. In a mature stranding surface a step-like feature forms, producing the lower basin region where large meteorite concentrations are located. The lip of the step feature contains pinnacles and surface crevasses which are normally snow bridged. Similar type features are also found farther away from the ridge on the up-glacier side of the ice field where faster moving ice is moving into the field. Radial and terminal moraines are common in the lower parts of the ice field where sub-ice material reaches the surface. The composition of the rocks and their origins for the Elephant Moraine ice field has been presented

elsewhere [6].

Although the processes involved in the generation of a stranding surface are seemingly understood the origin of the surface ice is not. Two competing theories [7], [8] differ in their estimate of the path length of the ice from origination to the stranding surface. Recent work [9] on the delta Oxygen 18 values from the Elephant Moraine and Allan Hills regions suggest differing path lengths for the ice in each region. As more information about stranding surfaces becomes available it may be possible to resolve the differences between the competing models of stranding surface generation.

Blue ice is generally accepted as quite old and so may present an opportunity for the scientific investigation of deep ice that is easily sampled. Unfortunately the flow blockage mechanism results in serious overthrusting of the ice and complicated fold features. Tracing dust bands to their origins, sampling ice for known horizons using trapped gases and mapping the features surficially, englacially and subglacially may yield meaningful data. Until a coordinated scientific investigation of blue ice stranding surfaces is conducted we can only speculate on their origins and significance.

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**PHYSICAL DESCRIPTION OF THE ELEPHANT AND RECKLING MORAINES**  
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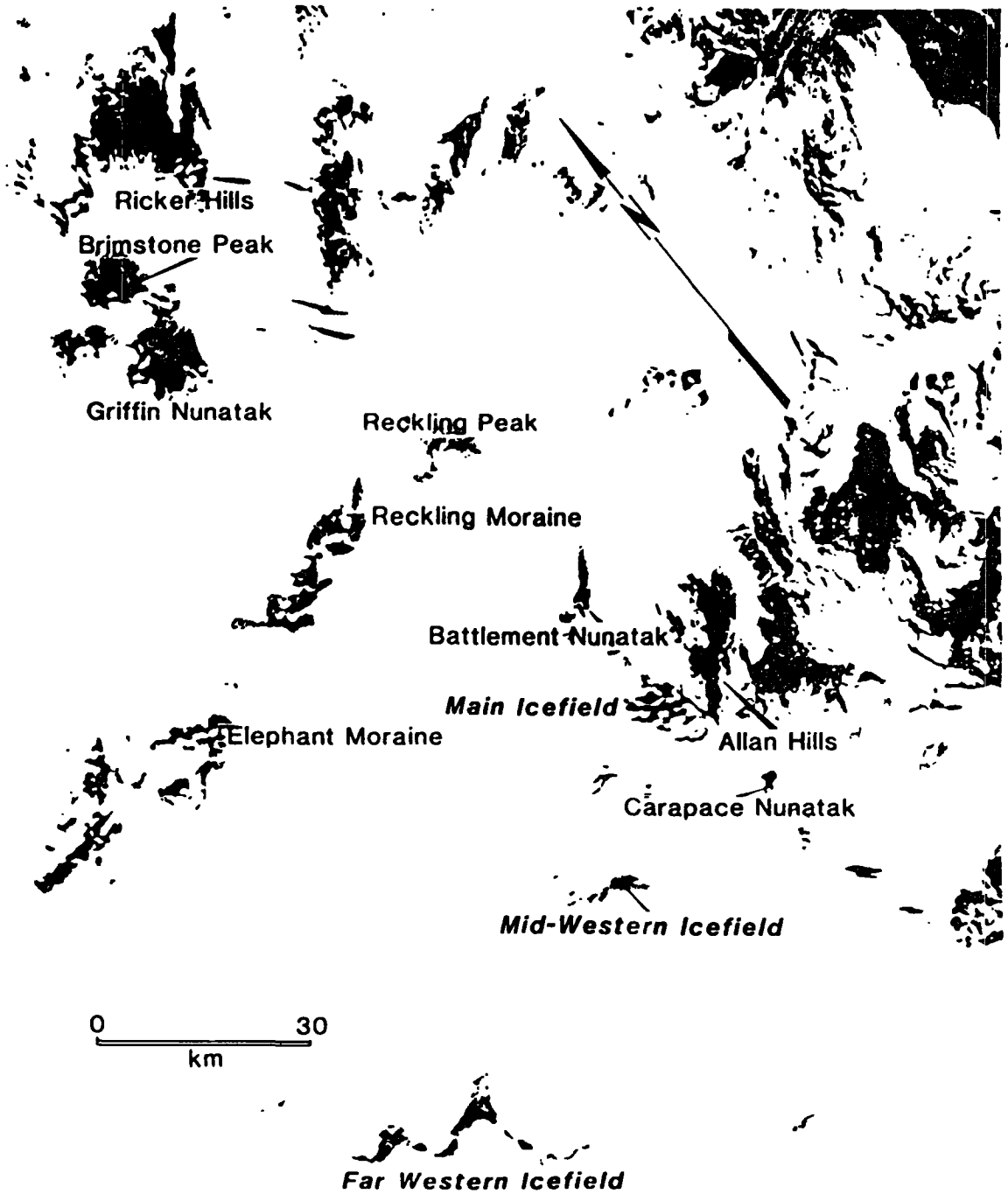
The so-called Reckling and Elephant Moraines are located on the large system of ice fields that extends west of Reckling Peak (76°16'S, 159°15'E) in southern Victoria Land for a distance of more than 100 km (see Figure). Both moraines are composed of clasts of sandstone, shale, dolerite and basalt with minor occurrences of coal, diamicton, and limestone. Clasts composed of granitic igneous rocks or high-grade metamorphic rocks are absent. Numerous meteorite specimens have been collected on the ice fields (stranding surfaces) adjacent to the moraines, but very few have been found in the moraines and at least some of those may have been wind-borne.

Both moraines are roughly horse-shoe shaped and are located in a "down-stream" position relative to major topographic ice ramps (also called steps or monoclines) involving differences in elevation of up to 100 m. The ice at the tops of the ramps is heavily crevassed and features "ice-pinnacles." Exposures of glacier ice extend from the basins below up to the top of the ice ramps at both locations.

Both moraines are 5.6 km in length and the clasts and fine-grained sediment that compose them occur in bands. These sediment bands are underlain by "dirty" ice which contains embedded clasts of the same lithologies as those which occur in the sediment above the ice. Some bands of dirty ice contain rounded clasts of clay-rich till in which marine diatoms of Miocene to Pliocene age have been found by D.M. Harwood. About 10% of the clasts in both moraines are faceted, striated and polished.

These observations permit the conclusion that the moraines are forming at the present time by ablation of basal ice of the East Antarctic ice sheet.

ELEPHANT AND RECKLING MORAINES: G. Faure



Regional distribution of stranding surfaces on the East Antarctic Ice Sheet west of the Allan Hills in southern Victoria Land, Antarctica.

**A GENERAL DESCRIPTION OF THE LEWIS CLIFF ICE TONGUE**

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The Lewis Cliff Ice Tongue appears to be an enclave of ice with meteorites on its surface, surrounded by ice that is barren of meteorites. It is an area of active ice ablation, fed by ice flowing northward off the East Antarctic Ice Plateau. This ice migrates along the face of the Lewis Cliff until its northward progress is halted by masses of ice from the Law Glacier. The Law Glacier flows toward the east and crosses the natural outlet of the Lewis Cliff Ice Tongue at right angles. Normally the flow of the ice tongue would be contributory to the flow of the Law Glacier, but in this area the Law Glacier seems to be mainly expanding laterally, possibly accompanied by diminished forward flow. Its lateral expansion opposes the drainage of the Lewis Cliff Ice Tongue. Because its further flow is blocked, ice of the Lewis Cliff Ice Tongue can leave only by ablation. New ice continues to flow in, bringing the occasional meteorite that remains behind, stranded on the surface. Ice is exposed in a roughly rectangular central area measuring about 10 km in length and 2 km in width, and is covered outside of this central area by a thin morainal veneer along its west, north, and east ridges (see Figure 2 of Summary section).

There is evidence in the form of faults or shear zones that resistance to flow occurs around the edges of this meteorite stranding surface, as well as in the form of ice core moraines that wrap around the exposed ice at its northern (farthest downstream) end. An ice core moraine is a ridge of ice mantled by unsorted glacially worn and striated rocks mixed with fine-grained debris, from the bed of the glacier. The source of the rocks and fine sediments in the ice-core moraine is a debris band that crops out at the crest of the moraine. The debris band is embedded in clear ice that is similar to, and perhaps identical with, regelated basal glacier ice. The presence of this glacially worked debris embedded in what appears to be regelated basal ice suggested that basal material of the glacier has been sheared or folded upward. The presence of the ice-cored moraines therefore supports the concept that flow at the north end of the ice tongue is mainly thwarted (see Figure 1 of this Abstract).

Apparent tephra bands cross the ice tongue along a general E-W strike, i.e. perpendicular to the flow direction, and dip upstream at various angles. Tephra layers should be time horizons, and this suggest that a relative chronological stratigraphy can be determined. An achondrite specimen was discovered in situ in the ice, only partly exposed above the ice by ablation. The terrestrial age of this sample should be identical to the depositional age of the ice around it, and this should allow absolute age determination of the ice at one point in the stratigraphic column.

The Lewis Cliff Ice Tongue is similar to many other meteorite stranding surfaces in being upstream of a physical barrier to flow, having exposed ice that is ablating actively,



## LEWIS CLIFF ICE TONGUE: W. A. Cassidy

having a step down in surface topography part way along its length, and probably having a stratigraphic sequence exposed horizontally. One atypical feature is the presence of evaporite-type mineralization that seems to occur in proximity to the boundary between clear (possibly regelated) ice and normal blue ice, but within the normal blue ice (ref. Fitzpatrick, this volume). The reasons for this mode of occurrence and, in fact, the mechanism of emplacement of these evaporite bands currently are not understood; they may have something to do with the presence here of a meteorite stranding surface, or they may be only incidental to it. What is clear is that to date, more than 1000 meteorites and meteorite fragments have been recovered from this relatively small stranding surface.



Fig. 1. A debris band exposed in a wind-eroded section through an ice-cored moraine at Lewis Cliff Ice Tongue.

**SUMMARY OF GENETIC MODELS FOR CONCENTRATION OF METEORITES**  
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The mechanisms by which the meteorites are concentrated need to be understood in order to properly deduce the age of the underlying ice, the fall history of meteorites, and the past stability of the east antarctic ice sheet. Three models have been published:

1. Nishio and others (1982). According to this model the ice was formerly substantially thicker. The meteorites were concentrated largely as a lag from the ablation of the ice as it thinned to its present shape. The ice thus travelled a short horizontal distance, was buried to a depth of only 500 m, and is about 20,000 years old. To account for the observed concentrations of meteorites there must have been larger fluxes of meteorites than at present. The ice has been little strained and features such as depositional tephra should show little thinning.
2. Whillans and Cassidy (1983). The ice flow and meteorite flux are taken as constant in time. Meteorites are concentrated by:
  - (i) Infall into the accumulation zone and transport to the ablation zone. About half of the collected meteorites arrive in this way and the mechanism is more effective where the snow accumulation rate is small.
  - (ii) Direct falls onto the ablation zone.
  - (iii) Transport with progressively decreasing speed toward the glacial edge. This crowds the meteorites near the edge. Strong lateral spreading with ice being diverted into neighboring outlet glaciers is critical to this mechanism.

The model predicts the age of the oldest ice and oldest meteorites to be about 0.5 M years. Young meteorites may be found everywhere, but old meteorites only near the edge. The observed concentration conforms with the usual influx rate and, as predicted, more meteorites occur near the edge. Meteorites should emerge at a rate about equal to the meteorite influx rate and old ice should be strongly strained.

3. Cassidy (1983). This model is an additional consideration to be super-imposed on the other models. It concerns the effects of climatic change on time-scales much shorter than that of the overall mechanism for concentration. The areal distribution of blue ice is:
  - (i) fixed with respect to the bed, and, or

- (ii) variable with time, so that flowing ice is alternately exposed or buried. While exposed, meteorites collect as a lag. Later net accumulation buries this concentration which is substantially exhumed by further ablation. The contact between low-grade and high-grade metamorphic ice zones is a likely surface for these buried stranding surfaces.

All the models have merit and could be combined.

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**BEDROCK TOPOGRAPHY BENEATH ANTARCTIC METEORITE STRANDING SURFACES**

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Gravity data are used herein to infer the bedrock topography under some of the meteorite-bearing, blue icefields searched to date by the U.S. ANSMET program. Twenty-four gravity stations have been emplaced in the Allan Hills region along a 55 kilometer, east-west traverse from the Far Western Icefield to a point between the Near Western and Main Icefields. And seventy-one gravity stations have been emplaced along several traverses on, and in the vicinity of, the Lewis Cliff Ice Tongue.

Along the Allan Hills traverse, gravity values (after corrections for instrument drift and differences in station latitudes and elevations) rise sharply from W to E over all three icefields traversed. It would be a coincidence of exceptional proportions if this were due to anything but rises in the bedrock under the icefields, and if there were not a cause and effect relationship between the occurrence of bedrock highs and the exposed ice surfaces.

These rises in bedrock are substantial: a 400 meter, minimum, rise under the Far Western Icefield; an 800 meter rise under the Mid-Western Icefield; and a 500 meter rise under the Near Western Icefield. Presumably these bedrock rises deflect the northward-moving ice sheet upward, converting much of its horizontal velocity to a vertical component, thus bringing both old ice and meteorites to the surface as ablation and sublimation of the rising ice proceed. Earlier suppositions that the ice sheet was generally moving from west to east and that the Far, Mid and Near Western Icefields, plus the Main Icefield, comprise a single, large system, with transported meteorites also lying between these icefields (under the firn) appear to be incorrect. Rather, the bedrock obstructions to ice movement are separate and each icefield is a separate stranding surface with ice flowing unimpeded between them.

The situation is more complex in the Lewis Cliff area, where there are a number of blue icefields, some of which contain numerous meteorites and some of which are barren. At the Lewis Cliff Ice Tongue itself, where several hundred meteorites have already been found while 30% of the ice tongue still remains to be searched, almost all the meteorites have been found west of a north-south line bisecting the tongue. Thus far, gravity surveys have failed to reveal any anomalies that could reasonably be interpreted as bedrock impediments to ice movement. There is also no apparent subsurface explanation for the asymmetrical meteorite distribution on the ice tongue. East-west gravity traverses across the ice tongue are readily interpreted in terms of a simple, almost symmetrical, U-shaped bedrock valley containing the ice tongue.

It is obvious from studies of the enormous "terminal" moraine, at the northern end of the Lewis Cliff Icefields, that there is an absolute barrier to northward ice flow. The apparent lack of any bedrock barrier gives credence to the suggestion of W.A. Cassidy (this volume) that the Law Glacier, which lies across the northward path of the Lewis Cliff Icefields, is that barrier. A great deal of additional data are needed to confirm and extend this preliminary conclusion, preferably by airborne, ice-penetrating radar systems.

**SUBICE TOPOGRAPHY AND THE FORMATION OF SUPRAGLACIAL MORAINES**  
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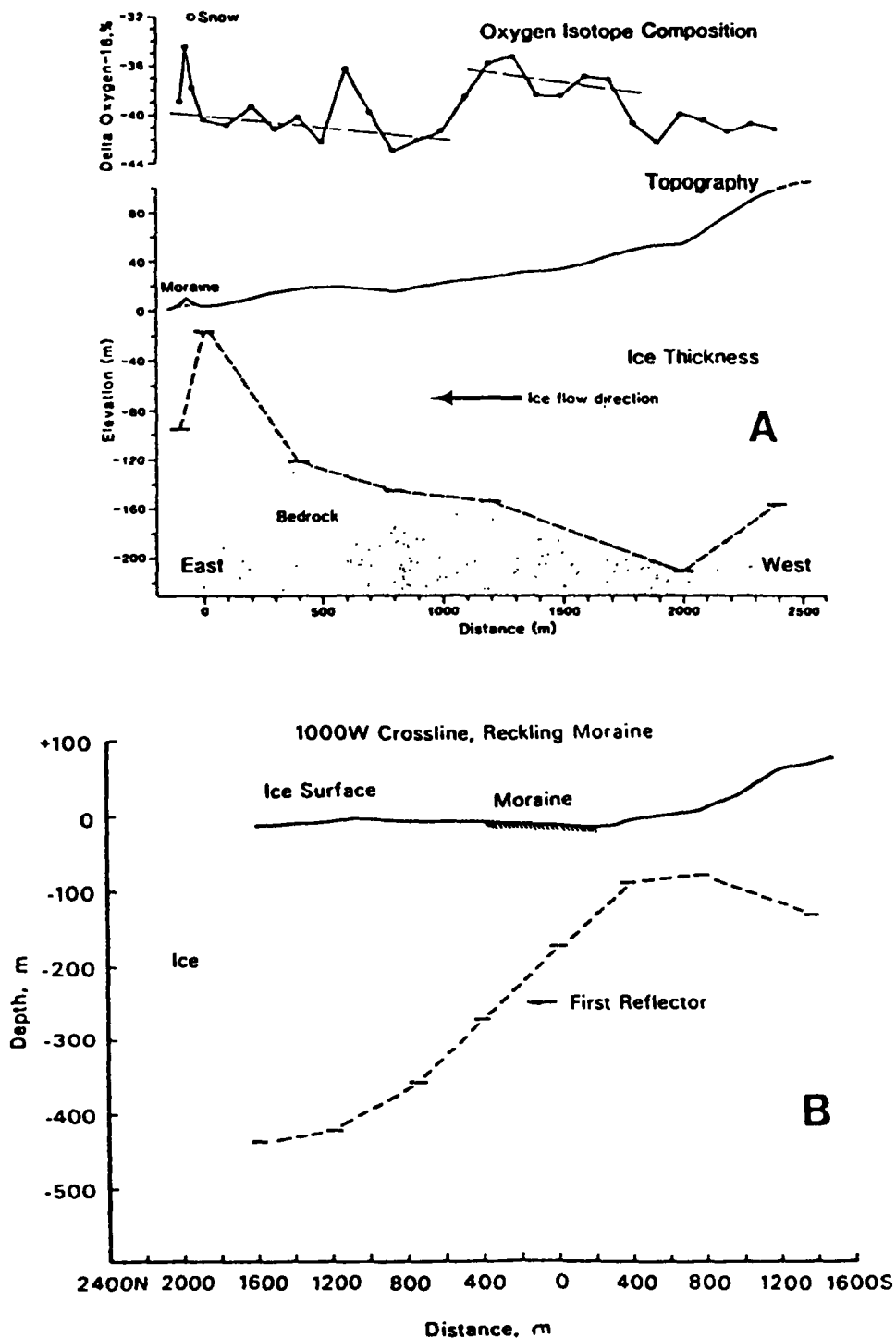
The so-called mono-pulse radar transmitter combined with an oscilloscope was used during the 1986-87 field season to measure the thickness of the ice at known locations along surveyed traverse lines across the Reckling Moraine and in the Main Icefield of the Allan Hills. The results indicate that subglacial bedrock ridges occur at both localities and that the ice thins to 50 m or less over them.

A profile across part of the Main Ice Field in the Allan Hills in Figure A shows that the ice-cored moraine is located in the lee of a subglacial bedrock ridge which actually crops out a few hundred meters south of the traverse line. The moraine itself is underlain by ice containing a high concentration of embedded sediment. A profile of  $\delta^{18}\text{O}$  values of the ice suggests the presence of ice representing relatively cold ( $\delta^{18}\text{O} = -40\text{‰}$ , SMOW) and warm ( $\delta^{18}\text{O} = -34\text{‰}$ , SMOW) climatic conditions. Snow deposited in January of 1987 along the traverse has  $\delta^{18}\text{O} = -32\text{‰}$  (SMOW).

Systematic measurements of ice thickness across the Reckling Moraine indicate that the ice ramp is located above a flat-topped bedrock ridge, shown in part B of the Figure, that appears to delineate a bedrock basin opening toward the north. The Reckling Moraine is located in the lee of the ridge at the base of the ice ramp. The thickness of the ice above the bedrock ridge is less than 100 m but thickens to more than 500 m on either side of it.

These results indicate that the ice ramps are associated with bedrock ridges which deflect the flow of the ice sheet upward and thereby force basal ice to become exposed at the surface. The basal ice ablates leaving a residue of clasts and fine-grained sediment which form the moraines. Since most of the known ice fields on the margin of the East Antarctic Ice Sheet are associated with ice ramps, their distribution is probably also controlled by the topography of the local bedrock.

## SUBICE TOPOGRAPHY AND SUPRAGLACIAL MORAINES: G. Faure



- A. Profile of subice bedrock topography, ice thickness and oxygen isotope composition of ice along a traverse extending west from a supraglacial moraine toward the polar plateau in the Main Icefield, Allan Hills, Antarctica
- B. Profile of ice thickness adjacent to the Reckling Moraine based on data obtained by altimeter and a radar-echo sounder used also in part A of this figure.

**SUPRAGLACIAL MORAINES, ASSOCIATED METEORITES  
AND CLIMATE CHANGE**

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The Elephant and Reckling Moraines are forming at the present time by ablation of basal ice brought to the surface over subglacial bedrock ridges that impede the flow of the ice sheet. The time elapsed since the Elephant Moraine began to form can be estimated from its length of 5.6 km and from the horizontal ice-flow velocity. Observations in the Elephant Moraine indicate that flow lines have a dip of about  $40^\circ$  and that the average annual ablation rate is about 5 cm/yr. If the ablation rate is equal to the vertical velocity component, the horizontal velocity vector  $h = 5/\tan 40^\circ$  or about 6 cm/y. Therefore, if all clasts that currently make up the Elephant Moraine had emerged from a single point source, the age of the moraine would be  $5.6 \times 1000 \times 100/6 = 93,000$  y. Because clasts are actually emerging at many sites along the Elephant Moraine, its age is probably less than that value.

The formation of supraglacial moraines may have been initiated by thinning of the ice sheet which brought subglacial bedrock ridges close enough to the surface of the ice sheet to cause basal ice to become exposed at the present sites of the Elephant and Reckling Moraines. The Figure indicates that farther south only ice ramps with associated ice fields developed because the ice over the bedrock ridges remained thick enough to prevent basal ice from reaching the surface. "Downstream" from the moraines the ice thinned enough to expose nunataks including the Griffin Nunataks, Brimstone Peak, Ricker Hills, etc.

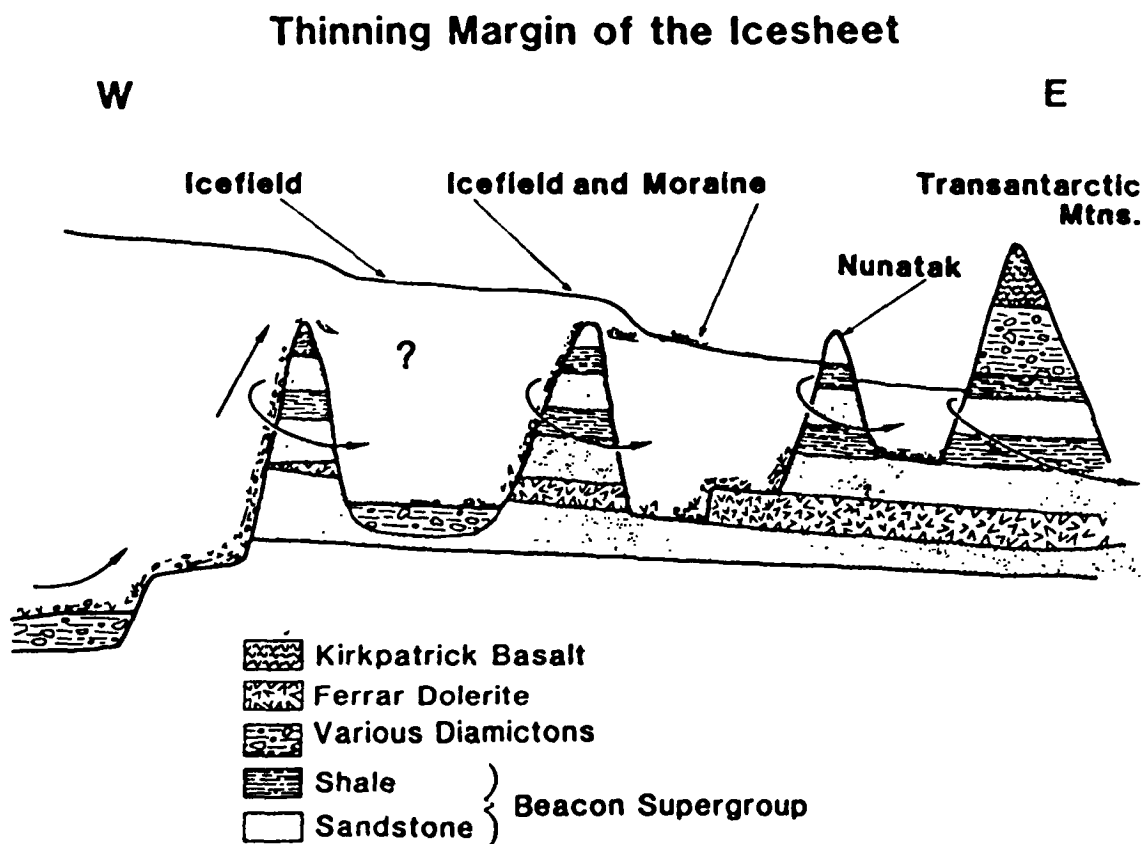
The postulated thinning of the ice sheet may have been caused by a change in climatic conditions that caused ablation rates to increase in this region. Alternatively, structural changes in the valleys of the David, Mawson or McKay Glaciers may also have resulted in increased drawdown of the ice sheet and a reduction in ice thickness.

The formation of the Elephant and Reckling Moraines by ablation of basal ice implies that the adjacent ice fields expose a stratigraphic section through the ice sheet. Therefore, meteorite specimens and other solid objects that have accumulated on the ice surface were transported englacially after they were deposited on the surface of the ice sheet. The reason why meteorites occur only rarely within the moraines is that they are transported englacially and not at the base of the ice sheet.



## SUPRAGLACIAL MORAINES AND CLIMATE CHANGE: G. Faure

Schematic cross-section of the margin of the East Antarctic Ice Sheet in the drainage basin of the David Glacier showing the inferred relationship between subice bedrock topography and the occurrence of stranding surfaces, supraglacial moraines, and nunataks.



### PRIMER ON ICE FLOW

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Some of the features of glacial flow and their relevance to the meteorite fields are reviewed.

The driving force per unit area for glacial flow is called the driving stress and it is the product of surface slope, ice thickness, ice density, and acceleration due to gravity. The ice is thus driven in the direction of the slope of the top surface. The direction of surface slope is usually very variable and the net flow is in the direction of the slope averaged over distances of 10 or 20 km.

The flow is resisted by friction at the bed. (Only rarely are horizontal pushes, pulls, and drags important). This friction is usually concentrated around subglacial hills. The glacier adjusts quickly so that its driving stress is larger where basal friction is largest. This means that surface slope is steep where the ice is shallow and the surface is composed of steps or undulations. In two dimensions, the surface is bowl-shaped just down-glacier from basal peaks.

Often surface accumulation and ablation are closely correlated with surface slope, with more ablation or less accumulation on steep slopes where katabatic winds are stronger.

The flow of ice is non-turbulent and most deformation occurs near the bed because temperature is higher and stresses larger there. There is abundant evidence for folding and overthrusting in near-basal ice. As in other rocks, the fabric, texture and relationship between constituents (air bubbles and ice) are very indicative of deformational style and history. Thin sections are easy to make.

A number of theoretical studies have addressed the stability of glaciers like the East Antarctic Ice Sheet. These indicate that response times to climatic change are in the range of 5,000 to 40,000 years and that the most dramatic changes should occur in ablation areas.

**COSMIC-RAY INTERACTIONS AND DATING OF  
METEORITE STRANDING SURFACES WITH COSMOGENIC NUCLIDES**

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A wide variety of products from cosmic-ray interactions have been measured in terrestrial or extraterrestrial samples. These "cosmogenic" products include radiation damage tracks and rare nuclides that are made by nuclear reactions.<sup>1,2</sup> They often have been used to determine the fluxes and composition of cosmic-ray particles in the past, but they are usually used to study the history of the "target" (such as the time period that it was exposed to cosmic-ray particles".<sup>1,2</sup>) Products made by both the high-energy galactic cosmic rays and energetic particles emitted irregularly from the Sun have been extensively studied.<sup>1,2</sup> Some of these cosmogenic products, especially nuclides, have been or can be applied to studies of antarctic meteorite stranding surfaces, the ice surfaces in Antarctica where meteorites have been found. Cosmogenic nuclide studies in samples from Antarctica and reported by others elsewhere in this volume include those in meteorites, especially radionuclides used to determine terrestrial ages, and those made in situ in terrestrial rocks. Cosmogenic nuclides made in the Earth's atmosphere or brought in with cosmic dust have also been studied in polar ice, and it should also be possible to measure nuclides made in situ in ice. As an introduction to cosmogenic nuclides and their applications, cosmic rays and their interactions will be presented below and production systematics of cosmogenic nuclides in these various media will be discussed later.

Cosmic-Ray Particles and Their Interactions. The main particles in space that produce cosmogenic products are the high-energy galactic cosmic rays (GCR) and the energetic (>10 MeV) particles from the Sun (often called solar cosmic rays, SCR). Both GCR and SCR include some electrons but are mainly nuclei of relatively light elements. About 99% of the nuclei in the cosmic rays are protons (<sup>1</sup>H) and alpha particles (<sup>4</sup>He), with protons dominating.<sup>1</sup> The GCR are fairly constant over time,<sup>3</sup> have fairly low fluxes, but have high energies. In contrast, the particles emitted irregularly (on average, once every few months) by big solar flares can have high fluxes (up to ~ 10<sup>6</sup> protons cm<sup>-2</sup>s<sup>-1</sup> at the peak of an event) but usually have fairly low energies.<sup>1-6</sup> Observations of event-integrated solar particle fluxes since 1954 have been summarized.<sup>5,6</sup> Average fluxes of solar protons with E<sub>p</sub> ≥ 10 MeV over periods of ~10<sup>4</sup> to 5x10<sup>6</sup> years have been determined from measurements of radionuclides of lunar samples and are ~100 protons cm<sup>-2</sup>s<sup>-1</sup>. A summary of the energies, mean fluxes, and interaction depths of these particles is given in Table 1.

As they pass through matter, cosmic-ray particles interact by two mechanisms: ionization energy losses or nuclear reactions.<sup>1,4</sup> Almost all SCR nuclei heavier than protons and most solar protons are stopped by ionization energy losses in the outer ~0.1-1 cm of solid matter in space.<sup>1,4</sup> The few

reactions induced by SCR particles are low-energy ones that emit few secondaries and produce residual nuclei close in mass to that of the target nucleus. The heavy nuclei in the GCR are also mainly stopped by ionization energy losses within  $\sim 20 \text{ g cm}^{-2}$  before they can react, but most GCR protons and  $\alpha$  particles react and produce a cascade of secondary particles, including many pions and neutrons. These secondary particles, especially the penetrating neutrons, induce all types of nuclear reactions down to depths of  $\sim 10^3 \text{ g cm}^{-2}$  (several meters of solid or the thickness of the Earth's atmosphere) in large objects exposed to GCR particles.<sup>4</sup> Secondary particles made by the interaction of the primary GCR particles are usually important in producing cosmogenic nuclides: in the Moon there are about 7 neutrons produced per primary GCR particle.<sup>4</sup> In most objects, nuclear reactions induced by secondary particles are more probable than those from the primary GCR particles, and GCR-induced reactions dominate over SCR-induced reactions.

Cosmogenic Products. There are two major types of cosmic-ray products that can be detected as having resulted from cosmic-ray interactions: rare nuclei and "tracks". The cosmogenic nuclei that can be identified readily as having been produced by cosmic-ray-induced reactions are radionuclides (like  $^{10}\text{Be}$ ) and the minor isotopes of the noble gases (like  $^3\text{He}$  and  $^{21}\text{Ne}$ ) that are normally not present in any abundance in matter.<sup>1,2</sup> GCR particles can produce almost any nucleus lighter in mass than the target,<sup>4</sup> and the types of reactions vary from high-energy spallation reactions, such as  $^{56}\text{Fe}(p,X)^{10}\text{Be}$  (where X can be any of a great variety of nucleon and particle combinations), to low-energy reactions induced by low-energy secondary neutrons, such as  $^{24}\text{Mg}(n,\alpha)^{21}\text{Ne}$ . The low-energy protons and  $\alpha$  particles in the SCR mainly induce reactions that produce residual nuclei close in mass to that of the target,<sup>4,5</sup> e.g.,  $^{28}\text{Si}(p,n2p)^{26}\text{Al}$ . The paths traveled in certain crystalline dielectric phases (e.g., certain minerals like olivine and pyroxene) by individual cosmic-ray nuclei with  $Z \geq 20$  near the end of their ranges contain enough radiation damage that they can be etched by chemicals and made visible as tracks.<sup>1,2</sup> While cosmogenic tracks have been very useful in many extraterrestrial studies, they haven't been used much in studies related to antarctic meteorite stranding surfaces. Thus the discussion below will only be about cosmogenic nuclides.

The distributions of cosmogenic products in meteorites and lunar samples have been well studied and imply a build up of the fluxes of secondary particles from GCR interactions for some distance inside these objects, the amount of build up being dependent on the particle's type and energy.<sup>4,7,8</sup> Only for high-energy ( $E > 1 \text{ GeV}$ ) particles or for large (radii greater than  $\sim 300 \text{ g cm}^{-2}$ , such as deep in the Earth's atmosphere) bodies are there decreases in flux away from the object's surface.<sup>7</sup> The largest increases in the fluxes of cosmic-ray particles are for neutrons, with the amount of the increase tending to be inversely proportional to the neutron's energy.<sup>4,7,8</sup>

While the energetic GCR primary and secondary particles are very penetrating in matter and have fluxes that change slowly with the object's size or a sample's location, fluxes of solar energetic particles decrease rapidly with increasing depth. The relatively low-energy protons from solar-flare events are rapidly stopped in matter,<sup>4,5</sup> usually within less than a few g cm<sup>-2</sup>. As such superficial layers in meteorites are usually lost by ablation during passage through the Earth's upper atmosphere, SCR-produced nuclides are seldom seen in meteorites. A material in which SCR-produced nuclides are important is cosmic dust, small particles (<1 mm) in space that can reach the Earth's surface intact.<sup>9</sup> Ablation material produced during the atmospheric entry of meteorites also can contain many SCR-produced nuclides. The main cosmogenic nuclide detectable from such sources is <sup>53</sup>Mn, and <sup>55</sup>Mn of such origin has been reported in antarctic ice.<sup>10</sup> Extraterrestrial <sup>53</sup>Mn in ice samples could possibly be used to characterize the ice's history. Another cosmogenic product that has been reported in antarctic ice samples is nitrate (NO<sub>3</sub><sup>-</sup>) made by GCR and SCR ionization-induced chemical reactions in the stratosphere<sup>11</sup>. Because SCR-produced nuclides are rarely made in or seen on the Earth, SCR and their products won't be discussed here any more.

Cosmogenic Nuclides. Because of the high energies of GCR primary particles and the great range in varieties and energies of their secondary particles, almost any nuclide can be made if there is a suitable element present in the target. In almost all targets considered here (extraterrestrial matter, the Earth's atmosphere, ice, and terrestrial rocks), there are only a few major elements, and thus there is a restricted number of cosmogenic nuclides readily available for study. Table 2 lists the most common cosmogenic nuclides usable in studying antarctic ice surfaces and gives the target elements in the various media. For example, in ice the target is oxygen, while nitrogen, oxygen, and argon are the main constituents of the atmosphere. (Argon as a target for <sup>26</sup>Al is listed in parentheses because <sup>26</sup>Al is made only in very low amounts in the atmosphere.) The target elements for <sup>81</sup>Kr are in low abundances in chondritic meteorites, making it very hard to measure <sup>81</sup>Kr in chondrites, especially if there has been decay while on the Earth. Note that atmospheric cosmogenic nuclides are the most abundant on Earth, and they can be present in or on other terrestrial materials, such as ice or rocks. Thus measurements of in-situ-produced cosmogenic nuclides must avoid contamination by atmospheric cosmogenic nuclides.

Only radionuclides with half-lives greater than ~10<sup>3</sup> years and only nuclides that are routinely measured are listed here. There are many shorter-lived radionuclides that have been studied (e.g. 53-day <sup>7</sup>Be or 12.3-year <sup>3</sup>H), but they are of limited use in dating and studying antarctic ice surfaces. Stable <sup>3</sup>He and <sup>21</sup>Ne are only studied in solid matter and integrate the cosmic-ray exposure of a sample over its entire life, complementing the record over the various time periods represented by the radionuclides. Note the big gap in

available half-lives between 5730-year  $^{14}\text{C}$  and  $2.1 \times 10^5$ -year  $^{81}\text{Kr}$ . Some of this gap could be filled by radionuclides not now routinely measured, such as 76,000-year  $^{59}\text{Ni}$  or  $1.0 \times 10^5$ -year  $^{41}\text{Ca}$ . At present, these two radionuclides are occasionally measured by low-level counting of their relatively weak decay radiations, which requires fairly large samples. The three noble-gas isotopes in Table 2 are counted by high-sensitivity conventional mass spectrometers, and  $^{53}\text{Mn}$  is measured by converting some of it to  $^{54}\text{Mn}$  in a reactor, which amplifies the activity that is actually measured. The other radionuclides listed in Table 2 are measured by accelerator mass spectrometry (AMS), where the atoms of the radionuclide are accelerated and individually counted<sup>12</sup>. All of these nuclides are useful in antarctic ice-surface studies mainly because they can be measured in small samples and in materials with low concentrations of the cosmogenic nuclide, such as terrestrial rocks.

The exposure record of any sample (except the Earth's atmosphere) always begins with the object having been "shielded" from the cosmic rays by many thousands of  $\text{g cm}^{-2}$  of material such that there is a negligible production of cosmogenic nuclides. When the object is brought much closer to cosmic-ray particles, then the production of cosmogenic nuclides is considered to have been initiated, and the total length of this exposure to a non-negligible flux of cosmic-ray particles is called the object's "exposure age". Meteorites and terrestrial rocks have finite lives, and typical exposure ages are  $\sim 10^7$  years for stony meteorites and much less for terrestrial rocks on the geologically active surface of the Earth. If the object was exposed to cosmic rays in only one geometry, the exposure is termed "simple". However, the exposure conditions of a few meteorites and most terrestrial rocks vary with time, making the exposure record a "complex" one; and it is much harder to interpret the sample's history from measurements of its cosmogenic products.

As an object is first exposed to cosmic rays, the concentrations of all cosmogenic nuclides increase with time. A cosmogenic radionuclide's activity eventually will reach a constant when its rate of decay equals its production rate. This equilibrium, or saturation, activity is approached after several half-lives. The concentration of a stable nuclide (e.g.,  $^{21}\text{Ne}$ ) continues to increase, making it an excellent indicator of the object's total exposure. After a shielding change, production rates and, eventually, radionuclide activities usually are different. The length of time that a meteorite has been well shielded from cosmic rays on the Earth's surface is called its "terrestrial age". Stony meteorites in non-antarctic locations weather away fairly fast and seldom have terrestrial ages  $> 10^4$  years, much shorter than the terrestrial ages of most antarctic meteorites<sup>13</sup>.

The rate that a cosmogenic nuclide is made in a sample is usually needed to fully interpret its measurement. Most production rates vary with the geometry of the parent object and the location of the sample. These factors are often

collectively termed the sample's "shielding" and usually need to be known to get the production rate of a cosmogenic nuclide. The main nuclear reactions that make a cosmogenic nuclide are important factors in determining a production rate. For example, a low-energy reaction like  $\text{Si}(p,X)^{26}\text{Al}$  results in a range of  $^{26}\text{Al}$  production rates even in one meteorite, whereas a high-energy product, like  $^{36}\text{Cl}$  in iron phases of meteorites, can have much less spread in its possible production rates in most meteorites. The relatively low variation in  $^{36}\text{Cl}$  production rates in the metal from ordinary chondritic meteorites is why Nishiizumi<sup>13</sup> emphasizes such samples in his studies of terrestrial ages of meteorites. See Englert<sup>14</sup> for additional discussion on cosmogenic nuclides in meteorites and their applications.

Terrestrial Cosmogenic Nuclides. The nuclides made by cosmic-ray particles in the Earth's atmosphere or surface are made with a great variety of rates. The Earth's geomagnetic field prevents most GCR particles from reaching the atmosphere, except for very high-energy particles or above the polar regions (geomagnetic latitudes  $> 60^\circ$ ) where low-energy particles can penetrate<sup>15</sup>. The amount of material between a sample and the top of the atmosphere also affects the production rates of cosmogenic nuclides, with samples from low elevations or buried in the Earth's surface having low production rates<sup>15</sup>. Dynamic processes in the atmosphere or on the Earth result in the transport of cosmogenic nuclides after they are produced, adding an additional complication in interpreting cosmogenic nuclides found in most terrestrial samples.

Although radiocarbon ( $^{14}\text{C}$ ) has been measured in terrestrial samples since the late 1940s, other cosmogenic nuclides made in the Earth's atmosphere or in situ in surface materials have only recently been studied in any detail<sup>1,15</sup>. Atmospheric-produced  $^{10}\text{Be}$  is now often measured, especially in deep-sea or ice cores<sup>16-18</sup>. Other atmospheric cosmogenic nuclides that could be used to study ice are  $^{36}\text{Cl}$  and  $1.6 \times 10^7$ -year  $^{129}\text{I}$ .

Very recently (since about 1985), much emphasis has been placed on studies of in-situ-produced cosmogenic nuclides, including  $^3\text{He}$ ,  $^{10}\text{Be}$ ,  $^{21}\text{Ne}$ ,  $^{26}\text{Al}$ , and  $^{36}\text{Cl}$ <sup>15</sup>. Production systematics for these in-situ-produced nuclides are being determined from simulation irradiations at accelerators and with natural samples having simple histories. To date, most studies with in-situ-produced radionuclides have involved quartz from surface rocks, as quartz has a simple composition ( $\text{SiO}_2$ ) and has a tight crystal structure that prevents atmospheric (or "garden variety") radionuclides from entering a quartz grain<sup>19</sup>. Measurement of both  $^{10}\text{Be}$  and  $^{26}\text{Al}$  concentrations in quartz from a rock can be used to determine both the rock's surface-exposure age and its erosion rate<sup>15,19</sup>. Elevation changes and glacial histories could also be studied with cosmogenic nuclides measured in quartz from terrestrial rocks<sup>15</sup>. It also has been proposed that net accumulation or ablation rates of ice sheets could be measured with cosmogenic  $^{10}\text{Be}$ ,  $^{14}\text{C}$ , and  $^3\text{H}$  made in situ in ice<sup>20</sup>.

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Table 1. Energies, Mean Fluxes, and Interaction Depths of Galactic and Solar Cosmic Rays.

Radiation	Energy <sup>a</sup> (MeV nucleon <sup>-1</sup> )	Mean flux (cm <sup>-2</sup> s <sup>-1</sup> )	Effective depth(gcm <sup>-2</sup> )
<u>Galactic cosmic rays</u>			
Protons & particles	~100-3000	~ 3	~0-1000
Heavy nuclei (Z>20)	~100-3000	~ 0.0015	~0-50
<u>Solar cosmic rays</u>			
Protons & particles	~1-100	~100 <sup>b</sup>	~0-10
Heavy nuclei (Z>20)	~1-50	~0.002 <sup>b</sup>	~0-0.3

<sup>a</sup>Typical energies; actual energies range to lower and much higher values.

<sup>b</sup>Long-term averages at 1 AU from Sun; actual fluxes vary from zero to much higher values.

Table 2. Long-lived or stable cosmogenic nuclides made in extraterrestrial matter, the Earth's atmosphere, or in situ in ice or rocks that can be used to study meteorite stranding surfaces.

Nuclide	Half-life <sup>a</sup> (years)	Main Targets <sup>b</sup> in Meteorites, Rocks	Main Targets <sup>b</sup> in Atmosphere, Ice
<sup>3</sup> He	S	O, Mg, Si, Fe	----
<sup>10</sup> Be	1.5x10 <sup>6</sup>	O, Mg, Si, Fe	N,O
<sup>14</sup> C	5730	O, Mg, Si, Fe	N,O
<sup>21</sup> Ne	S	Mg, Al, Si, Fe	----
<sup>26</sup> Al	7.1x10 <sup>5</sup>	Si, Al, Fe	(Ar)
<sup>36</sup> Cl	3.0x10 <sup>5</sup>	Cl, K, Ca, Fe	Ar
<sup>53</sup> Mn	3.7x10 <sup>6</sup>	Fe	----
<sup>81</sup> Kr	2.1x10 <sup>5</sup>	Rb, Sr, Zr	Kr

<sup>a</sup>S denotes that the nuclide is stable.

<sup>b</sup>Elements from which most production occurs.

**COSMOGENIC RADIONUCLIDES FOR HISTORICAL  
STUDIES OF ANTARCTIC METEORITES**

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Cosmogenic nuclides are those stable and radioactive isotopes produced by nuclear interaction of the galactic and solar cosmic radiation with extraterrestrial bodies. Exposure and production conditions of cosmogenic nuclides in meteorites and in the terrestrial environment are described by R.C. Reedy (this volume) [1]. Both stable and radioactive cosmogenic nuclide abundances are used to measure time in the recent history of a meteorite. Cosmogenic radioisotopes are used to determine terrestrial residence times, i.e., the time a meteorite spent at the surface of the Earth, shielded from the cosmic radiation. Terrestrial residence times can provide valuable information on antarctic meteorites and their influx rates and indirectly on the many processes in the antarctic ice that lead to the formation of meteorite stranding surfaces. The importance that a specific radioisotope has for terrestrial age estimations is evaluated in this contribution.

Our understanding of exposure ages and terrestrial residence times of meteorites is based on some model assumptions. Meteorites preexist (as virtual objects) at such depths in an asteroidal parent body that they are shielded from the primary and secondary galactic cosmic radiation, usually at a depth of several 1000 g/cm<sup>2</sup>. In case an impact event brings the virtual meteorite closer to the parent body surface, i.e., within the range of nuclear interacting particles, cosmogenic nuclide production begins. The impact event can also eject fractions of the parent body as meteoroids into space to be exposed to cosmic radiation. During space travel the meteoroid may break up into smaller fragments by further collisions; this changes the exposure geometry and has influence on cosmogenic nuclide production. Entry into the Earth's atmosphere leads to the loss of surface material, changing the meteoroid's size and shape and ends cosmogenic nuclide production, at least to a large extent. In fragments from observed meteorite falls short-lived radioisotopes have been measured; as time passes, these isotopes decay away at a rate determined by their half-life. Meteorites that fall on antarctic snow and ice may be buried and transported for long times such that even radioisotopes with half-lives of several hundred thousand years can decay significantly. Once back at the surface, antarctic meteorites are again exposed to cosmic radiation, the fluxes depending on altitude and latitude of the stranding surface [1]. However, the cosmic ray particle fluxes and production rates are very low. Up to recovery a meteorite may have undergone any logical sequence of the events mentioned above. Many of these events have influence on the production rate of cosmogenic nuclides and hence the correct interpretation of exposure and terrestrial ages.

The most simple sequence of events for an antarctic meteorite, i.e. the one least difficult to interpret, consists

of the formation of the meteorite from a non-irradiated part of the parent body, travel through space without further collisions, fall on antarctic ice, residence in and on the ice. Cosmogenic nuclide abundances measured in such a meteorite (after recovery) depend on the following parameters: the time of exposure to cosmic radiation (exposure age), the time of shielding from cosmic radiation in and on the ice (terrestrial age), the variation/stability of cosmic ray fluxes and composition with time during the exposure in space, the target element composition of the meteorite, the preatmospheric size of the meteorite, and the sample location within the meteorite. The only two parameters that can be measured directly are the cosmogenic nuclide abundances and the elemental composition. In addition it is generally assumed that the cosmic ray flux and particle composition were constant over the lifetime of the meteorite or at least over time spans in the order of several half-lives of the radioisotopes used. Consequently, four unknown parameters that are dependent on each other have to be unraveled.

As the preatmospheric size of the meteorite and the location of the sample analyzed within it are important for the production rate of a cosmogenic nuclide and hence for exposure and terrestrial ages, much work in the past has been devoted to study of these effects [2, and references cited there]. Production rates for stable cosmogenic nuclides have been established recently by several authors [3-5]. For all practical purposes of exposure age determination, shielding depth corrections are sufficiently well established for stable nuclides.

The situation is very different if radioactive cosmogenic nuclides are considered. The ones being used to study meteorites from stranding surfaces are listed in Table 2 of reference [1], this volume. Not all cosmogenic nuclides are suitable to determine terrestrial ages when they have exceeded several hundred years [6]. In the ice and on the stranding surfaces meteorites are preserved much longer, but terrestrial ages determined so far seem to be between several ten thousand and hundred thousand years.  $^{14}\text{C}$  ( $T=5730$  y) is not any more useful above 30000 years [7]. The half-lives of the radioisotopes  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{53}\text{Mn}$  and  $^{81}\text{Kr}$  are too long to determine terrestrial ages below about 70000 years; therefore a very important terrestrial age range for stranding-surface meteorites is not covered by virtue of the physical properties of presently measured cosmogenic nuclides.

In addition, the problem of shielding depth correction for the production rates has been solved only for a few of these radionuclides. This correction has consequences for the accuracy and precision of any age derived from the measured isotope abundance.  $^{14}\text{C}$  derived terrestrial ages, so far, have been calculated using an average production rate obtained from random measurements of the isotope in meteorite falls, under the assumption that saturation of  $^{14}\text{C}$  is achieved in all meteorites [8]. The implication is that the  $^{14}\text{C}$  production rate is almost shielding-depth independent. Recent studies of  $^{14}\text{C}$ -

depth profiles from terrestrial simulation experiments with thick targets, however, confirm that the  $^{14}\text{C}$  production is significantly depth-dependent as predicted by nuclear systematic studies [7]. Therefore  $^{14}\text{C}$  terrestrial ages could have larger uncertainties than as generally given; these uncertainties could be as large as 40%. Systematic shielding correction studies for  $^{14}\text{C}$  are necessary to provide more reliable production rates for terrestrial age studies.

The conventional way to investigate depth and size effects on the production of a cosmogenic radionuclide are depth profile studies in meteorites. A different approach is to establish that the production ratio of two cosmogenic nuclides is independent of the shielding depth; this is often the case when the production mechanisms of these isotopes are similar; (the target element composition can be considered constant for a certain meteorite group); again meteorite analysis must prove the hypothesis. For  $^{10}\text{Be}$  [e.g., 9],  $^{26}\text{Al}$  [e.g., 10], and  $^{53}\text{Mn}$  [e.g., 11] many depth profile measurements give information. Correlations for shielding effects are generally established by comparing the production rates in the depth profile to another depth dependent and also time independent parameter, such as the cosmogenic  $^{22}\text{Ne}/^{21}\text{Ne}$  ratio. A recent depth profile study of Nishiizumi et. al. (1988) [12] proves that the  $^{36}\text{Cl}$  production rate in the metal phase of meteorites does not vary significantly with depth and size in stony meteorites; the stony phase was not analyzed. The  $^{26}\text{Al}/^{53}\text{Mn}$  production ratio, for example, is independent of shielding depth [13].

$^{26}\text{Al}$ , in combination with the  $^{22}\text{Ne}/^{21}\text{Ne}$  ratio or with  $^{53}\text{Mn}$ , does not provide terrestrial ages below 200-300 thousand years.  $^{10}\text{Be}$  and  $^{53}\text{Mn}$  are only useful in extreme cases.  $^{81}\text{Kr}$  is very difficult to measure in ordinary chondrites [4], i.e., the majority of antarctic meteorites. This means that  $^{36}\text{Cl}$  is the isotope best applicable to terrestrial age determinations, though age determinations are limited to 70000 years and up.

There is considerable terrain to be covered between  $10^4$  and  $10^5$  years, a time interval of interest in stranding surface research. The two cosmogenic radioisotopes that would be perfectly suited to fill the gap are  $^{59}\text{Ni}$  ( $T=76000$  y) and  $^{41}\text{Ca}$  ( $T=100000$  y). Both radioisotopes have half-lives in the appropriate range. The production mechanism of  $^{41}\text{Ca}$  in the metal phase of meteorites is similar to that of  $^{36}\text{Cl}$ ; so we can expect that the production rate in the metal phase is independent of the size of the preatmospheric meteorite and the specific sample location.  $^{41}\text{Ca}$  has so far only been measured in iron meteorites and some terrestrial samples [14-16]. Cross section measurements performed in proton irradiated targets indicate that the half-life should be checked [16].

For  $^{59}\text{Ni}$ , mainly produced by neutron capture reactions in nickel, the minor constituent of the meteorite metal phase, significant depth and size effects on the production rate are predicted [17]. The nuclide almost shows the same depth dependence characteristic of the production rates as predicted and measured for  $^{60}\text{Co}$  [18]. If  $^{59}\text{Ni}$  will ever be available for routine accelerator mass spectrometric analysis, the first task should be to establish a correction scheme for shielding effects before extensive analyses of antarctic meteorites are considered.

The previous considerations are also important for the single cosmic ray effect survey measurements such as the  $^{26}\text{Al}$  and thermoluminescence surveys. It now can be understood that a single cosmogenic nuclide (or cosmic ray effect) cannot be used to provide information on the shielding conditions of the sample analyzed, on the exposure age and/or the terrestrial age. A single radioisotope, at least, has the advantage that production and decay only depends on a few parameters, including half-life, but is independent of the thermal history of the meteorite prior to, and/or after its fall to Earth. A low  $^{26}\text{Al}$  content can mean a short exposure age, shielding at large depth or exposure in a very small meteorite (and antarctic meteorite fragments are generally very small), or a long terrestrial age, or a combination of all these effects. Measurements of additional cosmogenic nuclides are needed for further interpretation. Thermoluminescence data (natural TL), may in addition be influenced by factors such as heating by the sun due to orbital parameters, heating during entry into the atmosphere if the sample analyzed was too close to the ablating surface, and sun exposure on the ice. There is no guarantee that interesting objects spotted by the surveys may not be absolutely dull (in terms of exposure and terrestrial history) after the completion of the full set of cosmogenic nuclide analyses.

The analysis of more than one cosmogenic nuclide per antarctic meteorite seems therefore to be inevitable to survey terrestrial ages of different stranding surface areas. Cosmogenic radionuclides with half-lives between 5000 and 100000 years have to be added to the ones routinely determined at present;  $^{59}\text{Ni}$  and  $^{41}\text{Ca}$  are the best candidates. Shielding depth studies are necessary to reduce the uncertainties in exposure terrestrial age determination, especially for  $^{14}\text{C}$ . The most reliable cosmogenic nuclide for terrestrial age measurements is presently  $^{36}\text{Cl}$ .

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### UPDATE ON TERRESTRIAL AGES OF ANTARCTIC METEORITES

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The terrestrial age of meteorites is one of the most vital pieces of information for studies of antarctic meteorite stranding surfaces. This paper presents the current state of our knowledge of the terrestrial ages of antarctic meteorites; also it gives a general picture of terrestrial age studies.

Three cosmogenic nuclides,  $^{14}\text{C}$ ,  $^{81}\text{Kr}$ , and  $^{36}\text{Cl}$ , are used for terrestrial age measurements. The 5730 year half-life  $^{14}\text{C}$  data were measured by Fireman and his collaborators, the Arizona and Tokyo groups [e.g. 1,2].  $^{14}\text{C}$  can be used to measure ages up to 30,000 years. Beyond that point, the  $^{14}\text{C}$  age is not reliable due to contamination by atmospheric  $^{14}\text{C}$  and by  $^{14}\text{C}$  produced in-situ in the sample. Since many meteorites have terrestrial ages outside this range, about 2/3 of the measurements give only lower limits. However, this method is very useful for the Yamato meteorites since their terrestrial ages are relatively short. The 210,000 year half-life  $^{81}\text{Kr}$  was measured by Schultz and Eugster [e.g. 3,4]. The detection limit for this nuclide depends on the trapped gas content and the concentration of target elements. Only achondrite data are presently available. The 301,000 year half-life  $^{36}\text{Cl}$  was measured by our group [e.g. 5,6]. This nuclide can be used to measure ages up to 3 million years or older. The overall uncertainty due to variations of the saturation value of the nuclide is about 70,000 years.  $^{36}\text{Cl}$  can be measured in any type of meteorite, preferably in the metallic phase. So far 183 meteorites have been studied using these three nuclides including paired objects.

A  $^{41}\text{Ca}$  (half-life ~ 100,000 year) dating method was proposed during the last Mainz meeting to fill the gap between  $^{14}\text{C}$  and  $^{36}\text{Cl}$  dating [7], but the techniques are still under development [8].  $^{26}\text{Al}$  is a very useful cosmogenic nuclide, but the 705,000 year half-life is too long for most antarctic meteorites [e.g. 9]. This nuclide can be used for an initial survey, since the measurements are done non-destructively. The TL (Thermoluminescence) method is not reliably established for measurements of the terrestrial age of antarctic meteorites [e.g. 10].

After excluding paired objects and some of the  $^{14}\text{C}$  ages, 131 terrestrial ages from 18 locations are available for interpretation. These include 62 from Allan Hills, 30 from the Yamato area and 39 others. Fig. 1 shows a histogram of terrestrial ages of Allan Hills, Yamato, and other antarctic meteorites. Pairs of meteorites are shown as one object plotted at the average age. The 3 irons which were found on bedrock are not included in the figure. The width of the bars represents 70,000 years which is a typical uncertainty for  $^{36}\text{Cl}$  ages. The general trend of the terrestrial ages of the three

groups is similar to the results reported several years ago [11].

1. The terrestrial ages of Allan Hills meteorites are widely distributed between 11,000 years and 1 million years and are clearly longer than those of Yamato and other antarctic meteorites.

2. The terrestrial ages of many Yamato meteorites are shorter than 20,000 years.

3. There are only three meteorites with ages greater than 300,000 years, except the Allan Hills meteorites.

4. Only L and LL chondrites have terrestrial ages in excess of 360,000 years among the Allan Hills meteorites. I am not sure whether this is statistical or real. One possibility is that low iron chondrites have more resistance to weathering than other types of meteorites.

5. There is no clear correlation between the terrestrial age and weathering category A, B, and C.

Fig. 2 shows a comparison of the terrestrial ages at both Allan Hills main ice and subsidiary surrounding ice fields. So far all meteorites with long terrestrial ages are found on the main ice field. The interesting feature is the distribution of the terrestrial age in the main ice field.

Fig. 3 shows a map of Allan Hills main and near western ice fields and the locations and terrestrial ages of 67 meteorites. The open circles indicate meteorites with terrestrial ages shorter than 200,000 years and the filled circles indicate longer than 200,000 years.

1. There are no old meteorites in the western and northern areas of the ice field.

2. Meteorites 400,000 years or older were found in the cul de sac, and close to the eastern edge of the ice field.

3. The meteorites from the eastern area of the ice field are a mixture of young and old ages.

Fig. 4 shows a map of the Elephant Moraine area. The open circles indicate meteorites with terrestrial ages shorter than 200,000 years and the filled circles indicate longer than 200,000 years. In general, the meteorites found in the main basin are of shorter terrestrial age. Two meteorites collected just below the escarpment are 220,000 and 370,000 years respectively (see additional paper by Nishiizumi in this report).

Three iron meteorites were found on bedrock. The terrestrial ages of these meteorites have unique information about the geologic sites.

Derrick Peak 78001-9 were collected between 1300 and 1650 m altitude and about 600 m above the Hatherton Glacier. The terrestrial age of these paired objects is about 1 million years. Therefore Derrick Peak has not been covered by ice during the last 1 million years.

Inland Forts 83500 was found in a glacial deposit over Beacon Sandstone. The preliminary terrestrial age is about 3 million years. Therefore, the till must have been formed less than 3 million years ago. The other possibility is that the low  $^{36}\text{Cl}$  activity is due to heavy shielding in the meteorite.



The Lazarev iron meteorite was found near Humboldt Mountains at 3000 m altitude. The specimen was found about 40 m from the surrounding glacier. It is not clear whether the meteorite was transported by the glacier or fell where it was found. The terrestrial age is about 5 million years. This age is the longest terrestrial age measured for any meteorite.

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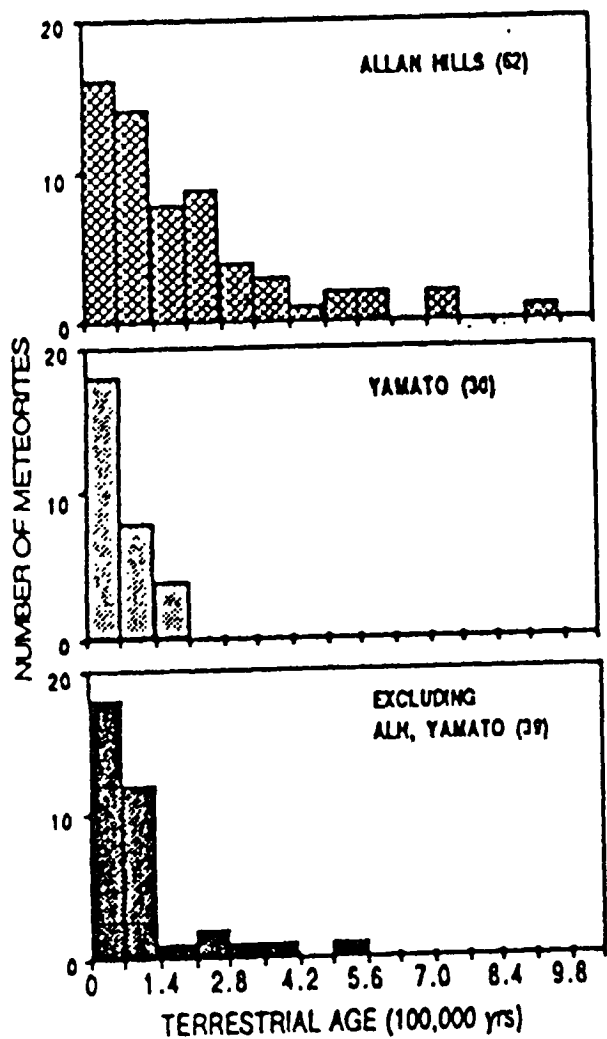


Figure 1

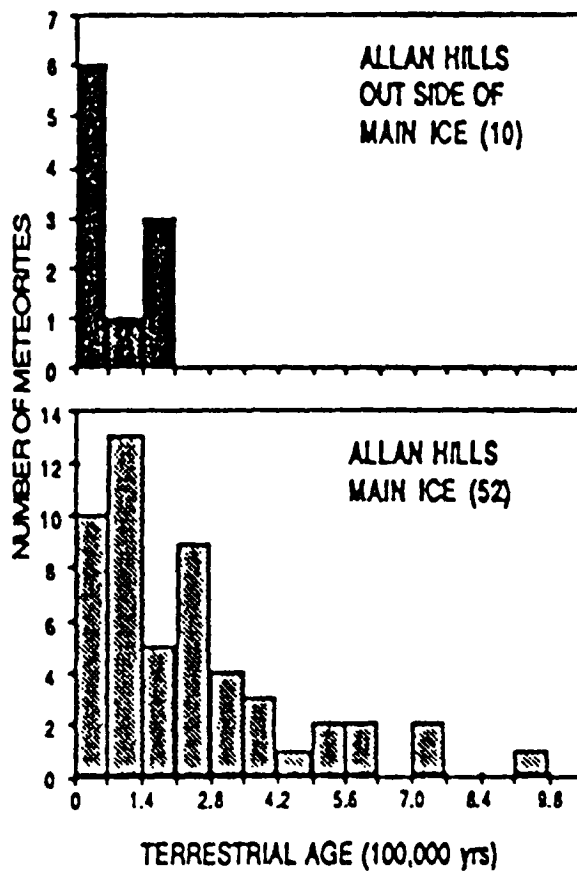


Figure 2

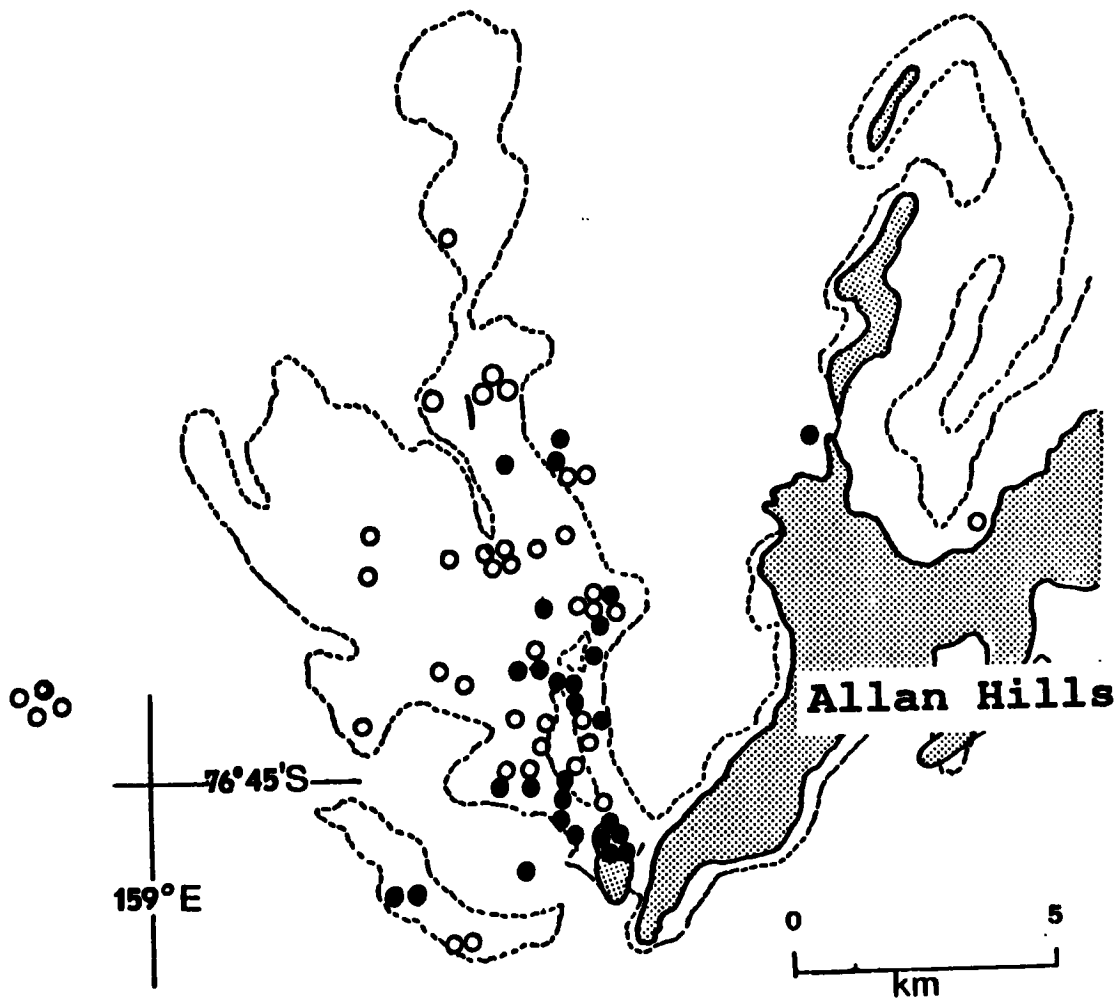


Figure 3. Allan Hills

TERRESTRIAL AGE

●  $> 2 \times 10^5$  years

○  $< 2 \times 10^5$  years

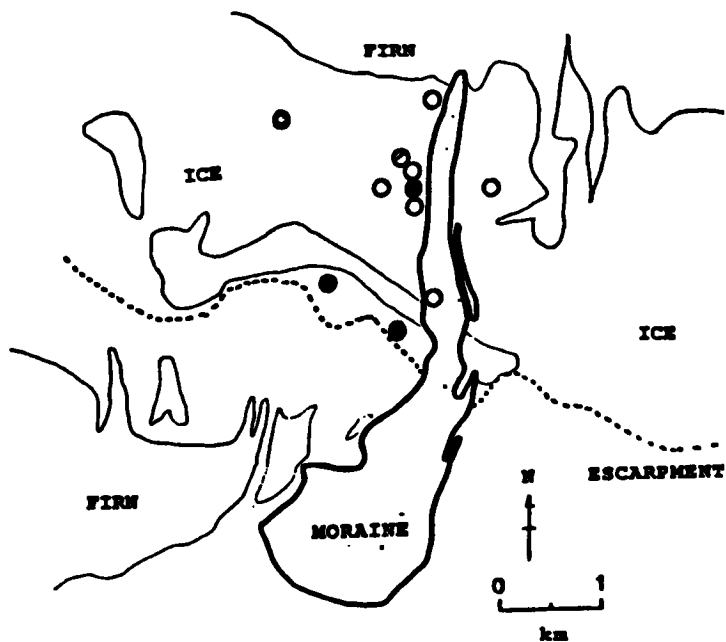


Figure 4.  
Elephant Moraine

**<sup>26</sup>Al SURVEY OF ANTARCTIC METEORITES**

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Since 1979, Battelle, Pacific Northwest Laboratories has continued to assay antarctic meteorites for the cosmic-ray-produced radionuclide <sup>26</sup>Al ( $t_{1/2} = 7.2 \times 10^5$  yr). Over 350 meteorites have been analyzed for <sup>26</sup>Al, which is measured rapidly and nondestructively by multiparameter gamma-ray spectroscopy. These measurements have been intended to provide a basis for estimation of the terrestrial residence time of meteorites that have accumulated on or in the antarctic ice. While the <sup>26</sup>Al method alone cannot provide a completely reliable terrestrial age for individual samples, <sup>26</sup>Al data can be used to evaluate trends for large groups of samples and provide useful guidance for selecting samples for more detailed study by other methods. Other investigators have also performed analyses on these same samples for noble gases and other cosmic-ray-produced radionuclides, including <sup>53</sup>Mn ( $t_{1/2} = 3.7 \times 10^6$  yr), <sup>10</sup>Be ( $t_{1/2} = 1.6 \times 10^6$  yr), <sup>36</sup>Cl ( $t_{1/2} = 3.0 \times 10^5$  yr), and <sup>14</sup>C ( $t_{1/2} = 5730$  yr.).

The interpretation of <sup>26</sup>Al data must take into account several factors. Ideally we may assume that <sup>26</sup>Al is produced in the meteoroid at a known and constant rate. If the exposure is long compared to the half-life of <sup>26</sup>Al (i.e.,  $> 1-2 \times 10^5$  yr), then the meteorite will fall to earth with a constant, saturated activity, which Evans and Reeves (1987) calculated to be 59 and 55 dpm/kg for L and H chondrites. However, undersaturated activities will result if the cosmic ray exposure period in space following break-off from the parent body is too short for saturation to occur. This is of occasional significance for <sup>26</sup>Al. The activity of <sup>26</sup>Al is also affected by shielding, which may reduce the production rate for either abnormally large or unusually small preatmospheric bodies. Unusual irradiation histories, such as exposure to solar cosmic rays, can increase the production of <sup>26</sup>Al and other low-energy products, particularly in very small objects.

The <sup>26</sup>Al activities in our data set range from 11 dpm/kg for ALHA76008 (H6) to 108 dpm/kg for META78019 (H6), with most activities falling between 30 and 50 dpm/kg. The peak in the activity distribution of the antarctic meteorites is lower than that for non-antarctic meteorites, which generally have terrestrial ages  $< 200$  years. These results are consistent with an average terrestrial age of  $\sim 200,000$  years (Nishiizumi, 1984) and suggest that  $\sim 1$  million years is the approximate age cutoff for the residence time in the Allan Hills region. There are not yet enough measurements available to draw firm conclusions about the other regions sampled; however, Nishiizumi (1984) has suggested that the Allan Hills meteorites have a wider range of terrestrial ages and are generally older than other Victoria Land and Yamato meteorites. The distribution of ages and the age cutoff represent important constraints for models of ice movement and meteorite accumulation in the Allan Hills region.

Thus, <sup>26</sup>Al is useful for survey work since it can be measured rapidly and non-destructively. Interesting samples -- those with either short or long terrestrial ages or unusual irradiation histories -- are quickly identified so that other radionuclides and noble gases can be analyzed. And although individual measurements may give only upper limits of terrestrial residence times, the distribution of <sup>26</sup>Al activities provides important information on the population as a whole.

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**TERRESTRIAL AGES AND WEATHERING OF ANTARCTIC METEORITES**  
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Introduction: The terrestrial age of a meteorite  $T_t$  (the time span between fall of the meteorite and today) can be measured. Cosmic-ray-produced ("cosmogenic") radionuclides of suitable half-lives:  $^{14}\text{C}$  ( $t_{1/2} = 5.73 \times 10^3$  yrs),  $^{26}\text{Al}$  ( $t_{1/2} = 7 \times 10^5$  yrs),  $^{36}\text{Cl}$  ( $t_{1/2} = 3 \times 10^5$  yrs), and  $^{81}\text{Kr}$  ( $t_{1/2} = 2 \times 10^5$  yrs) have been successfully applied to the determination of terrestrial ages of antarctic meteorites. A summary of results is given in [1].

To calculate  $T_t$ , the measured activity is compared to the expected saturation activity (at the time of fall), which is dependent on chemical composition and position of the measured sample within the meteoroid ("shielding") and thus, is not accurately known. Besides the half-life of the nuclide, this is a limiting factor in determinations of terrestrial ages. The saturation activity of  $^{36}\text{Cl}$  in metallic NiFe of chondrites, however, is fairly constant. Therefore, using this isotope reliable terrestrial ages of chondrites of  $>8 \times 10^4$  yrs can be obtained. Similarly, the  $^{81}\text{Kr}$  method avoids many of the uncertainties introduced by unknown shielding conditions or variation in chemical composition because it provides a self-normalization of production rates for each individual sample if other cosmogenic Kr isotopes can be obtained. However, due to low  $^{81}\text{Kr}$  concentrations in chondrites and the presence of other Kr components this method - with a few exceptions - has been applied to achondrites only [2]. Fig. 1 shows the ranges in terrestrial age that can be covered by the individual radionuclides.

Distribution of terrestrial ages: Freundel *et al.* [2] have discussed the distribution of terrestrial ages of meteorites from Victoria Land (Antarctica). Most of these meteorites were found on the ice of the Allan Hills Main Ice Field (AHMIF). The distribution (Fig. 2) is characterized by a maximum between  $1 \times 10^5$  and  $2 \times 10^5$  yrs and an exponential decrease to longer ages. This age distribution has been explained to be produced by three different processes: (1) Meteorites found at the AHMIF consist of two groups - direct falls and meteorites transported by the ice to this site. Both groups occur in about equal quantities. (2) The transported meteorites spent about  $1.5 \times 10^5$  yrs in the ice. (3) The exponential decrease in the age distribution is due to decomposition by weathering while the meteorites are sited on the ice surface. Assuming that the number of meteorites disintegrated by weathering is proportional to the total number of meteorites, the mean life time of a meteorite at the AHMIF is about  $2.3 \times 10^5$  yrs [2].

Antarctic Temperatures and Weathering: In general, the decomposition of meteorites is controlled by the availability of liquid water, which is responsible for the processes of physical and chemical weathering [e.g.3] The air temperatures at the antarctic polar plateau are permanently below the freezing point and it is expected that rates of weathering of

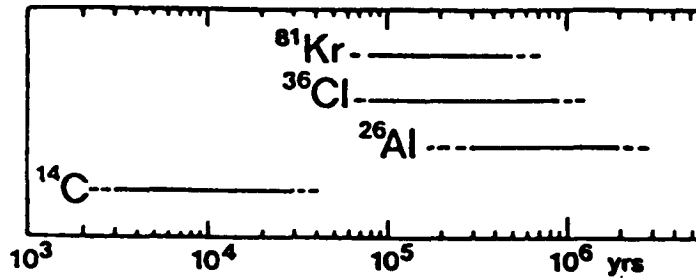
antarctic meteorites are smaller compared to non-antarctic meteorites found in more moderate climates. However, black meteorites sitting on blue ice in the Antarctic receive enough direct solar radiation that within the meteorite temperatures above 0°C can occur in spite of low air temperatures. To study this effect a piece of the Allende chondrite (310 gms) with about 80% fusion crust was exposed at the Elephant Moraine and Allan Hills Far Western Ice Field for several weeks. The meteorite was equipped with a temperature dependent resistor (Pt100) which was located within the meteorite, degree of cloudiness and wind speed were recorded at least once per day. The result for the Far Western Ice Field is shown in Fig. 3. The temperature within the meteorite is always higher than the air temperature. An important parameter for temperatures inside of meteorites is the wind speed; the wind acts as a fan cooling the stone. A correlation is observed for the difference of the meteorite's temperature and the air temperature with wind speed (Fig. 4) which, of course, is influenced also by the intensity of the incoming radiation, i.e. the degree of cloudiness. On two days with very low wind speeds the meteorite reached temperatures up to +5°C even with air temperatures less than -10°C. This experiment shows that liquid water is available in meteorites under the climatic conditions of the antarctic polar plateau.

Relative weathering rates: Based on 19 <sup>14</sup>C-terrestrial ages of non-antarctic meteorite finds, Boeckl [4] estimated a terrestrial "half-life" of about 3600 yrs for ordinary chondrites against disintegration by weathering, under the climatic conditions of the western U.S. This number corresponds to a lifetime of meteorites of about 5200 yrs, a value which is 44 times smaller than the mean lifetime for Allan Hills meteorites deduced from their age distribution [2]. If it is assumed that liquid water is available for these non-antarctic meteorites for about 10 months per year, the antarctic meteorites should have about 7 days per year with temperatures above 0°C e.g. with very low wind speeds. This number seems to be not in contradiction to the climatic situation at the Allan Hills.

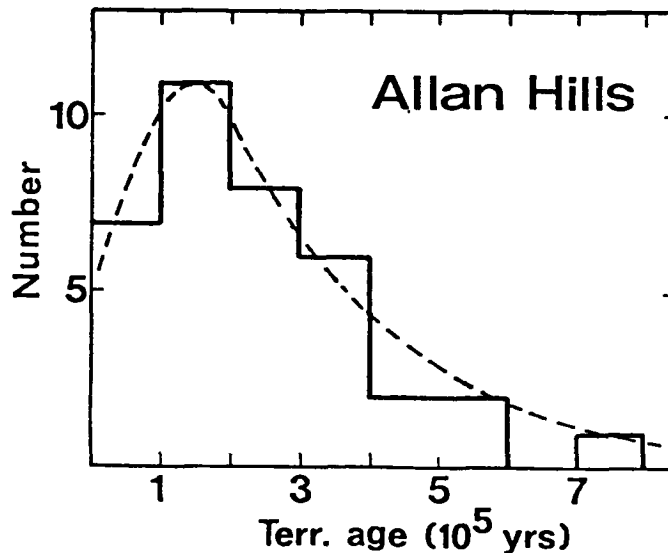
Other implications: The mean lifetime of  $2.3 \times 10^5$  yrs for chondrites sitting on ice surfaces in Antarctica show that the ice of the AHMIF did not overflow the blocking Allan Hills over the last  $10^6$  yrs. This is expected if the ice thickness would increase by about 50 m. The terrestrial age distributions of AHMIF meteorites and Yamato meteorites are different [5]. Yamato meteorites (and possibly also meteorites from other antarctic ice fields) generally have shorter terrestrial ages. This implies that the AHMIF may be in a steady state situation for more than  $10^6$  yrs, while other ice fields with meteorite concentrations are stranding zones which concentrate meteorites for a shorter time.

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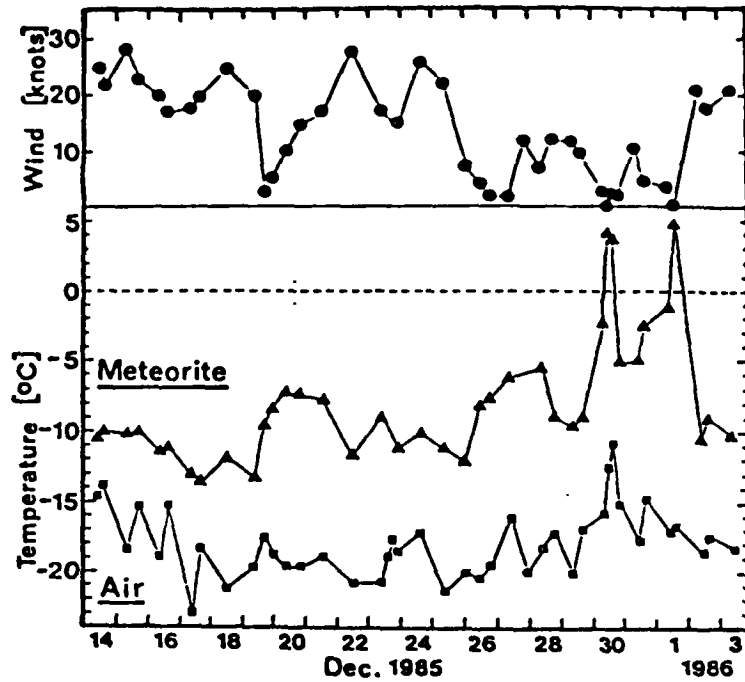
**Fig. 1:** Range of terrestrial ages which can be measured by different radionuclides. Note the gap between  $3 \times 10^4$  and  $7 \times 10^4$  yrs. For antarctic meteorites this important age interval is not covered by the presently used radionuclides.



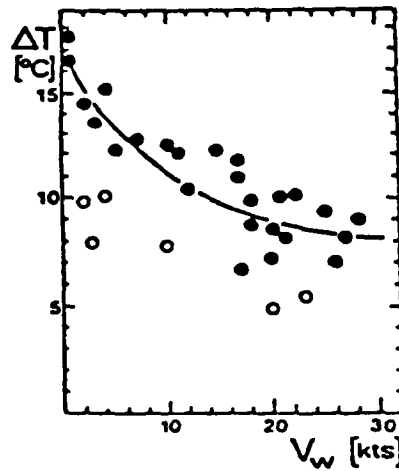
**Fig. 2:** Observed distribution of terrestrial ages of Allan Hills stone meteorites. The maximum between  $1 \times 10^5$  and  $2 \times 10^5$  y is explained by a mixture of meteorites from direct falls and transported meteorites which spent about  $1.5 \times 10^5$  yrs within the ice. The exponential decrease of the ages is interpreted by disintegration of meteorites by weathering processes while on the surface of the ice. The meanlife time for antarctic chondrites is about  $2.3 \times 10^5$  yrs.



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**Fig. 3:** Air temperature and temperature within a meteorite on an Allan Hills ice field (lower part). The upper part of the figure shows the measured air speed.



**Fig. 4:** Temperature difference ( $\Delta T$ ) between air and meteorite vs. wind speed. Due to absorption of solar radiation on the black surface of the meteorite up to 15°C higher temperatures can be observed within the meteorite. However, this is observed only during times with low wind speed (open symbols represent values observed for overcast sky).

**SUBAERIAL EXPOSURE AGES OF BEDROCK  
NEAR METEORITE STRANDING SURFACES**

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The terrestrial ages of antarctic meteorites contribute to a knowledge of meteorites themselves, i.e. past influx rates, and also can be used to set limits on the ages of ice sheets where they are found and to give information about ice movement, especially horizontal movement from the accumulation area to the ablation area. Exposure ages of antarctic rocks can add a great deal to this understanding of the dynamics of the antarctic ice sheet, in particular of past elevation changes. Examples of the problems open to this approach are: whether the ice sheet overflowed the Allan Hills in the past, and when moraines were produced.

When the bedrock is exposed above the ice sheet, cosmic rays bombard the rock. Recently we demonstrated the feasibility of using  $^{10}\text{Be}$  and  $^{26}\text{Al}$  produced in-situ in terrestrial quartz to trace the continental weathering/erosion process and to determine surface exposure time [1]. This paper presents the method in general terms and applies it to the history of antarctic bedrock and moraines near meteorite stranding surfaces.

In quartz  $^{10}\text{Be}$  is produced primarily by cosmic ray secondary-neutron-induced spallation of O, while  $^{26}\text{Al}$  is produced by neutron-induced spallation of Si [2].  $^{10}\text{Be}$  and  $^{26}\text{Al}$  are also produced by cosmic ray muon interactions.

Quartz is an ideal material for these studies. It is present in a wide variety of geologic settings. Its simple composition helps us understand and calculate the nuclear reactions. Its tight crystal structure minimizes possible contamination from "garden variety"  $^{10}\text{Be}$  produced in the atmosphere, it has a low Al content which allows measurement of  $^{26}\text{Al}$ , and it can be separated from other minerals fairly easily.

To apply this method, production rates and, in particular, the production ratio of these two nuclides must be well known. Recently the values were experimentally determined using glacially polished granite from the Sierra Nevada [3]. The production rate of  $^{10}\text{Be}$  is 6.2 atom/g  $\text{SiO}_2$  per year at sea level (geomagnetic latitude  $>50^\circ$ ). The production rate of  $^{26}\text{Al}$  is 37 atom/g  $\text{SiO}_2$  year. The production ratio of  $^{26}\text{Al}$  to  $^{10}\text{Be}$  is 6.0 [3]. The production rates increase with increasing altitude due to the change of atmospheric depth as shown below.

Altitude	Relative Production rate
0 km	1
1 km	2.3
2 km	5.1
3 km	10.3

The production rates also change with latitude due to the higher cut-off energy toward the equator.

The concentration of each nuclide increases with exposure

## SUBAERIAL EXPOSURE AGES OF BEDROCK: K. Nishiizumi

time exactly as for meteorites. Fig. 1 shows the  $^{10}\text{Be}$  concentration vs. exposure time. The units are atom/g  $\text{SiO}_2$ , and the curve is normalized to the production at sea level. The present detection limit for both  $^{10}\text{Be}$  and  $^{26}\text{Al}$  by AMS (accelerator mass spectrometry) is about  $10^6$  atoms. Although the production rates are extremely low, 10,000 years exposure at sea level produces enough  $^{10}\text{Be}$  and  $^{26}\text{Al}$  in 10 g quartz for measurements to be meaningful.

However, the surface of terrestrial material is continuously eroded. The nuclide concentration in most terrestrial samples is controlled by the erosion rate. For the simple case of a constant erosion rate ( $\epsilon$ ), the steady state nuclide concentration (C) is given by the following equation.

$$C = P_0 / (\lambda + \rho\epsilon / \Lambda)$$

Since the production rate ( $P_0$ ), the decay constant of the nuclide ( $\lambda$ ), the density of rock ( $\rho$ ), and the absorption mean-free-path ( $\Lambda$ ) are known, the erosion rate can be calculated from the nuclide concentration.

Fig. 2 shows  $^{10}\text{Be}$  concentration vs. erosion rate for the steady state condition. The graph for  $^{26}\text{Al}$  shows a similar profile, but the  $^{26}\text{Al}$  to  $^{10}\text{Be}$  ratio changes with erosion rate due to their different half-lives.

However, nature is not always so simple, especially in Antarctica. Sometimes a thick ice sheet has covered the rock and cosmic ray production stopped. Then glaciation suddenly eroded the old exposed surface. Although a simple erosion model can't be applied to many samples, the combination of erosion and exposure time can constrain the surface history of rocks. Some application of these methods to antarctic rocks and glacial history are presented below, even though the data are still preliminary. The detailed discussion will be presented elsewhere.

Four rock samples were collected from Elephant Moraine by the Cassidy group and by Faure. According to G. Faure, Elephant Moraine consists of pieces of bedrock which were fairly recently transferred to the surface by upward ice movement. In this case, the cosmogenic nuclides in the moraine rock were produced after the rock was exposed on the surface of the ice. Using  $^{10}\text{Be}$  and  $^{26}\text{Al}$  data, the exposure ages of four rocks are calculated to be about 300, 2000, 5000, and 60,000 years. Although all samples were collected in the same area (station 114), the exposure ages are very different. This is evidence for continuous production of Elephant Moraine to this day. We conclude that the age of the moraine is greater than 60,000 years. The terrestrial age of an iron meteorite which was found in the moraine is also about 60,000 years. These young ages are interesting in contrast to the old terrestrial ages of two meteorites which were found just below the escarpment (see additional paper by Nishiizumi in this report). Measurements of rocks from other locations in

Elephant Moraine and meteorites from south of the moraine are required for further understanding of the formation of Elephant Moraine and of ice movement in this area.

Nine bedrock samples were collected from Allan Hills by J. Schutt for this study. Table 1 lists the altitude and the distance above the current ice for each sample. The exposure ages and the erosion rates have been calculated using  $^{10}\text{Be}$  and  $^{26}\text{Al}$  concentrations and are shown in the table. Since the current ice surface is very close to the sample location, long steady state cosmic ray exposure is not expected. The minimum exposure age is calculated assuming no erosion. If we assume more than a few million years continuous exposure, the maximum erosion rate can be obtained. In any case, the Allan Hills have been exposed above the ice surface for more than a half million years and the erosion rate for these rocks is less than a few times  $10^{-5}$  cm/y. The unanswered question is whether the Allan Hills were continuously exposed for more than a half million years or whether a thick ice sheet overflowed the Allan Hills within the last few 100,000 years. In the former case, the 1 million year old meteorites which are found on the Allan Hills ice field could have been sitting there for a long time and their presence does not require a long transportation time from another source region. In the latter case, ice movement overflowing the Allan Hills would push old meteorites out of the area, requiring them to have been transported to the Allan Hills ice field by a long transportation mechanism. Although the detailed discussion will be found elsewhere, model calculations suggest that the Allan Hills bedrock had a complex exposure history during the last million years. A possible scenario is that the Allan Hills were exposed to cosmic rays for a long time, then covered by ice 500,000 years ago and exposed again 300,000 years ago. Other combinations are possible as well. We need further studies including cosmogenic noble gas measurements to construct the model.

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## SUBAERIAL EXPOSURE AGES OF BEDROCK: K. Nishiizumi

Table 1. Exposure age and erosion rate of Allan Hills Rocks

ID	Altitude	Above Ice	Min. Exposure Age	Max.
	Erosion rate (m)	(m)	( $10^5$ y)	( $10^{-5}$ cm/y)
1	2085	15	13	2
2	1955	4	3	11
3	2150	60	8	4
4	1807	8	11	3
9	1645	0.2	8	4
5	1652		7	5
6	1625		6	6
7	1610		6	7
8	1615		5	7

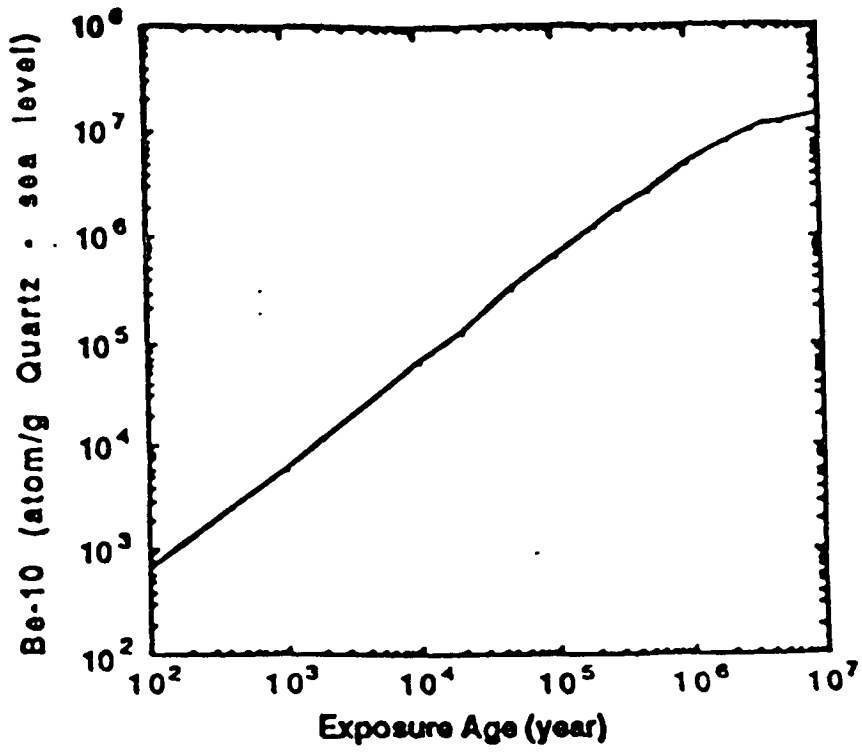


Figure 1.

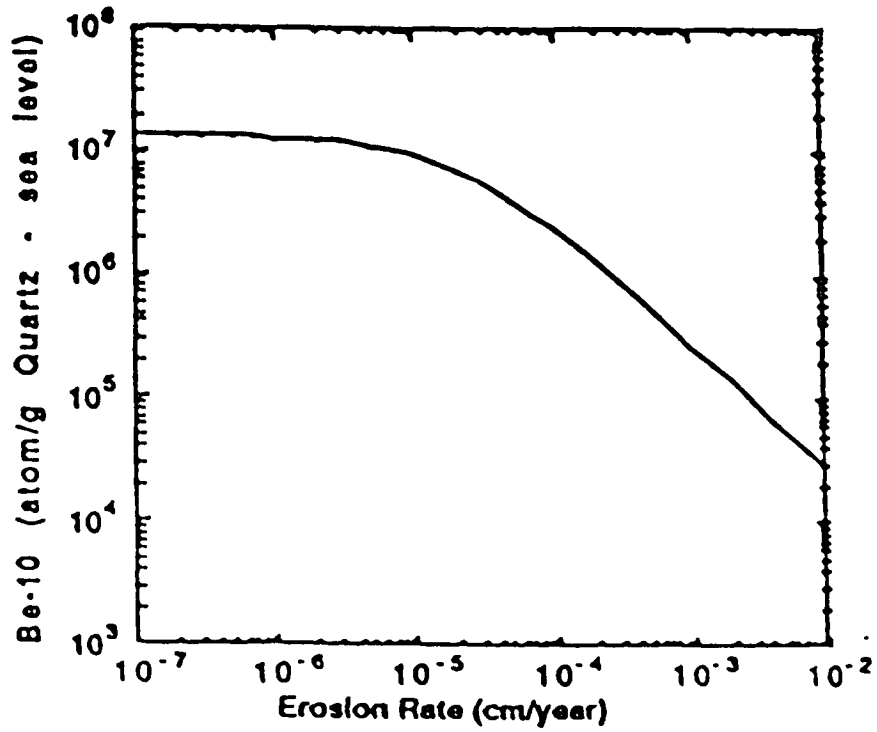


Figure 2.

### ICE CHEMISTRY PERSPECTIVES

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Over the last ten years, large numbers of meteorites have been collected from the blue ice zones of Antarctica where old ice becomes exposed at the surface. However, these blue ice zones are presently poorly understood. One fundamental question to be answered is how old is the blue ice. Evidence from the analysis of meteorites suggests that the Yamato Mountains blue ice zones have ages of up to 100,000 years whereas the Allan Hills site may represent much older ice which is several hundred thousand years old.

Using modern analytical techniques, it is possible to analyze antarctic ice samples for a variety of chemical species including major anions and cations as well as oxygen isotopes. Presently only oxygen isotope data are available for some of the blue ice areas. These data show variations that may correspond to glacial/interglacial transitions, however it is difficult to distinguish these differences from those attributable to changes in elevation of the source areas for the ice. A complete chemical analysis should provide much more information and will aid in distinguishing between elevational influences and glacial/interglacial changes.

To date, there have been four deep cores drilled in Antarctica which provide records extending back in time at least into the last ice age. Chemical data from these cores have established that during glacial times the precipitation contained higher levels of dust and impurities and that the CO<sub>2</sub> content of the atmosphere was lower than that during the present interglacial period. Since atmospheric gases such as CO<sub>2</sub>, which are trapped in the ice when the bubbles are sealed off at the firn/ice transition, should have no elevation gradient, they would appear at first to be the best candidate for use in distinguishing between ice age and interglacial ice. However, because the gas bubbles in the blue ice have been subjected to complete dissolution and then have become reestablished due to pressure changes, it is not presently known if the original gas content of the bubbles has been preserved. However, this is something that should be investigated further in order to determine if there is any usable trace gas data to be obtained from samples of blue ice.

Based on results from the analysis of surface snow samples collected along traverses, each impurity in antarctic snow shows characteristic variations in concentration from the coast toward the interior. However, with the exception of high chloride and sodium values which occur near the coast due to the high influx of seasalt the elevational differences are much smaller than the differences between glacial and interglacial periods based on the results of the deep core studies. Of all the major anions and cations, sodium and chloride show the largest overall differences between glacial and interglacial periods when compared to those attributable to elevational

## ICE CHEMISTRY PERSPECTIVES: M. J. Spencer

changes if the immediate coastal zone is excluded. Thus, a more complete chemical analysis of ice from the blue ice zones should add significantly to the information that can be used to establish the ages for each blue ice zone, since the ice can be categorized as glacial or interglacial. In addition, since the different chemical species show different concentration vs. elevation profiles, the chemical composition data will also aid in the identification of source areas for the ice. These two sets of data will also provide data for constraining the ice flow models which are currently being used to explain the history of the blue ice.

In addition to being a source of useful information for the meteorite community, the blue ice zones are also fundamentally important to glaciochemists. If the ice in these areas is truly more than 10,000 years old then these sites will be extremely valuable as sites for obtaining old ice for further chemical studies. If the ice is in stratigraphic order along the flow lines, then shallow cores collected in these areas have the potential for the recovery of very long time records which may even extend back further than the present limit of 220,000 years, which has been obtained from the deep drilling at Vostok. Since the old ice is at much shallower depths, ice cores can be collected much more easily and considerably larger quantities of ice can be obtained which will enable other trace analyses requiring large sample volumes to be carried out as well. These samples should add greatly to our store of knowledge gained from the small number of ice cores that have already been obtained from Antarctica.



**<sup>18</sup>O RESULTS FROM BLUE-ICE AREAS : "OLD" ICE AT THE SURFACE?**  
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Ice in blue-ice ablation areas west of the Transantarctic Mountains is emerging after following some unknown flow pattern from its location of origin. Models attempting to explain the meteorite concentrations found in some of these blue-ice areas (Nishio *et al.*, 1982; Whillans and Cassidy, 1983; Cassidy, 1983) have made different assumptions about this ice flow.

In East Antarctica the average  $\delta^{18}\text{O}$  of the snow today decreases gradually from about  $-2\text{‰}$  at the coast to  $-50\text{‰}$  in the interior at Dome C (Lorius *et al.*, 1979) and Vostok (Lorius *et al.*, 1985) respectively. On the polar plateau just west of the Transantarctic Mountains values around  $-40\text{‰}$  seem to be typical (Lorius, 1983). A local versus a central inland origin of the ice in this area thus can lead to differences in  $\delta^{18}\text{O}$  of  $10\text{‰}$  to  $15\text{‰}$ . In the Vostok and the Dome C core (central East Antarctica) the average  $\delta^{18}\text{O}$  is about  $5\text{‰}$  higher during interglacial times than during glacial times. A rapid change in average  $\delta^{18}\text{O}$  of about  $5\text{‰}$  is a good indicator of glacial-interglacial change because climate variability within a glacial or interglacial period causes changes in the average  $\delta^{18}\text{O}$  value of not more than  $2\text{‰}$  to  $3\text{‰}$ . The  $^{18}\text{O}/^{16}\text{O}$  ratio of the ice in the blue-ice areas can thus give some clues about the location at which, and the climate under which, the ice originated.

We measured the oxygen isotope abundance ratio  $^{18}\text{O}/^{16}\text{O}$  in three sets of blue-ice samples collected at: (i) the Reckling Moraine (by G. Faure), (ii) the Lewis Cliff Ice Tongue (by W.A. Cassidy, submitted by P. Englert), and (iii) the Allan Hills (by J. O. Annexstad). Most samples were cut out of the ice at 5 to 10 cm below the surface. In addition a number of 1-m cores was taken.

Reckling Moraine.

Near-surface ice samples were collected every 100 m along a south to north transect across the Reckling Moraine and the surrounding blue-ice.  $\delta^{18}\text{O}$  varied between  $-42\text{‰}$  and  $-50.4\text{‰}$ . South (upstream) of the moraine fluctuations in  $\delta^{18}\text{O}$  of about  $5\text{‰}$  were found over short horizontal distances. This suggests that the ice, now exposed at the surface, originated in different glacial and interglacial periods. Another possibility is that folding of ice masses of different origin produced the repeated  $\delta^{18}\text{O}$  changes. Folding could be caused by a bedrock high that reaches to near the surface near the Reckling Moraine (Faure *et al.*, in prep.).

Detailed  $\delta^{18}\text{O}$  profiles of eight 1-m core sections show that contamination and enrichment generally become negligible at a depth of 5 to 10 cm below the ice surface. Thus it is unlikely that the observed  $\delta^{18}\text{O}$  changes of the south transect result from contamination and enrichment.

Lewis Cliff Ice Tongue.

$\delta^{18}\text{O}$  of a set of 38 near-surface ice samples from the Lewis

<sup>18</sup>O RESULTS FROM BLUE-ICE AREAS: P. M. Grootes

Cliff Ice Tongue blue-ice field range from  $-40.7^{\circ}/\text{oo}$  to  $-58.8^{\circ}/\text{oo}$ . In a 200-m transect sampled every 10 m a 60-m area of "yellow" or "dirty" ice has an average  $\delta^{18}\text{O}$  value of  $-42.8 \pm 1.4^{\circ}/\text{oo}$ , while blue-ice has an average  $\delta^{18}\text{O}$  value of  $-54.4 \pm 0.3^{\circ}/\text{oo}$ . Lighter  $\delta^{18}\text{O}$  values also seem associated with the meteorite-carrying ice (P. Englert and J. Schutt, pers. comm., 1988). Detailed sampling on 5 samples showed no signs of sample contamination and enrichment.

The  $18^{\circ}/\text{oo}$  range requires ice from different areas. The most negative value of  $-58.8^{\circ}/\text{oo}$  would, under the present conditions, require an origin of the ice in the highest central part of East Antarctica (Pole of Relative Inaccessibility,  $\delta^{18}\text{O} = -57^{\circ}/\text{oo}$  Lorius, 1983). Presence of ice from a glacial period would allow a source area closer by. The less negative isotope values of the "yellow" ice may belong to ice of local origin.

Allan Hills.

Average  $\delta^{18}\text{O}$  values of four 1-m blue-ice cores collected in the Allan Hills area by Annexstad are between  $-36.8^{\circ}/\text{oo}$  and  $39.5^{\circ}/\text{oo}$ , while the average of a 4-m firn core is  $-35.7^{\circ}/\text{oo}$ . These few numbers do not allow a conclusion about the origin of the ice in the Allan Hills area, but are in line with our observations at the Reckling Moraine.

Conclusion.

The preliminary  $\delta^{18}\text{O}$  data indicate that ice exposed at the surface in a blue-ice area may have originated in different areas of the ice sheet during different climates. A systematic study of the  $\delta^{18}\text{O}$  of exposed blue-ice helps unravel the flow history of the ice and benefits the interpretation of the meteorite finds in the blue-ice areas. It also identifies old ice near the surface for paleoenvironmental studies.

Acknowledgements.

The samples were obtained by Drs. Faure, Cassidy, Englert, and Annexstad as part of their research projects. I appreciate their willingness to make the  $\delta^{18}\text{O}$  results and their field data available for a combined discussion at this workshop. The  $\delta^{18}\text{O}$  measurements of the Quaternary Isotope Laboratory were supported by the National Science Foundation grant DPP-84-00574.

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**DUST BANDS IN BLUE ICE FIELDS IN ANTARCTICA AND THEIR  
RELATIONSHIP TO METEORITES AND ICE**

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Introduction

Blue ice fields in Antarctica are well known as source regions for meteorites. The exact transportation and concentration mechanism for antarctic meteorites is still a point of discussion. By investigating the structure, dynamics, and history of the blue ice fields that carry meteorites we are able to constrain the meteorite accumulation process. Structures in the ice are of great value if they allow us to determine the dynamics or the age of different parts of the ice fields. The most important of these structures are dust bands that are visible in many parts of the blue ice fields. In order to use them for studies of the ice field, their origin, composition, stratigraphy, and age have to be determined.

Dust bands in blue ice fields

Initially, dust layers have been found in ice cores from different stations throughout Antarctica. Several sources for impurities (soluble and insoluble) are possible. The most important ones would be (1) material from subglacial bedrock debris scraped up from the ground by the movement of the glacier, (2) volcanic material deposited on the ice after large-scale eruptions of antarctic (or sub-antarctic) volcanoes that is incorporated in the ice, (3) cosmic particles falling as micrometeorites or meteorite ablation spherules, and (4) continental and marine dust and aerosols transported by wind. Most dust layers in ice cores have been identified as being of volcanic origin (e.g., Kyle *et al.*, 1982). In some cases, correlations (based on chemical and petrological studies) have been suggested between the dust in the layers and some specific source volcanoes.

Dust bands cropping out on bare blue ice fields in Antarctica have received less attention so far. Dust and debris bands in glacial ice at the Skelton Neve and at the Kempe Glacier in South Victoria Land have been studied by Keys *et al.* (1977). They found that some of the bands consisted of tephra, while others are of dolerite composition and have most probably been formed from local bedrock. The source of the tephra at the Skelton Neve was probably a vent in the Royal Society Range which was active a few thousand years ago.

Most ice cores date back only a few thousand years, while the ice in the blue ice fields is usually much older, up to several hundreds of thousands of years. Fireman (1986), using the uranium series method to date the ice, found ages of up to 300,000 years in the Allan Hills region. The ages of different ice fields may vary, according to different source regions, flow durations, accumulation and ablation rates. Blue ice

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fields form mainly in zones where the ice flow is obstructed by some barrier and the katabatic winds lead to a high ice ablation rate.

#### Structure of dust bands

Field studies have been made recently at three major meteorite accumulation areas, namely the Allan Hills, the Yamato Mountains, and the Lewis Cliff Ice Tongue. There seems to be direct relationship to the ice flow. Most of the bands have been observed to run perpendicular to the direction of the ice flow, although they curl back as much as 180° in some cases. They pinch and swell as they run across the ice fields, often for distances of over 1 km. Their surface expression width varies, but is generally between 10 and 30 cm. If they get too wide they seem to thin out, indicating that the initial amount of dust per dust band does not vary that much. In the case of the Lewis Cliff Ice tongue, variable angles of dip have been observed (Koeberl *et al.*, 1988), depending on the location on the ice field. Shallow angles of dip prevail in the middle part of the ice tongue, while toward the end of the ice tongue the angles are steeper or even show signs of overturning.

#### Chemical correlation studies

As in the case of the ice core samples, chemical and petrological arguments have been used to correlate tephra layers in the blue ice areas with specific antarctic (or sub-antarctic) volcanoes. Also, grain sizes are of some importance. Volcanic debris usually has small grain sizes, while bedrock debris shows larger grain sizes. Subglacial bedrock debris is usually found near moraines that develop above subglacial topographic heights that lead to retardation and subsequent upward movement of the ice flow, or near barriers (mountain ranges) obstructing the flow of the glacier. The material is found in shear zones. Chemical analyses show the nature of the material. In the case of the Lewis Cliff, Koeberl *et al.* (1988) have identified a dust band (with very large grain sizes) consisting of sedimentary material, probably of the Beacon Supergroup formation.

Tephra bands have been found at all three sites. Nishio *et al.* (1985) have analyzed volcanic ash from the Allan Hills and have suggested that local volcanoes from the McMurdo volcanic group may be the source. The glass shards have trachybasaltic composition, and crystal fragments of plagioclase, feldspar, olivine, and others have been found. Other material from that area (Marvin, 1986, and this volume) may have at least two different sources, one of them as far away as the South Sandwich Islands. (Ed. Note: Marvin has now retracted this claim. See Marvin, this volume.)

Volcanic material from the Yamato Mountains was analyzed by Nishio *et al.* (1985), who were able to demonstrate that they have a tholeiitic andesite composition. Basaltic island arc tholeiite is not known from Antarctica, but is common at the South Sandwich Islands. Table 1 gives the composition of tephra from the Yamato Mountains in comparison with andesites

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from the South Sandwich Islands, showing a good correlation. Also given is material from the South Pole core, showing a similar composition.

Table 1. Chemical correlations (after Nishio et al., 1985)

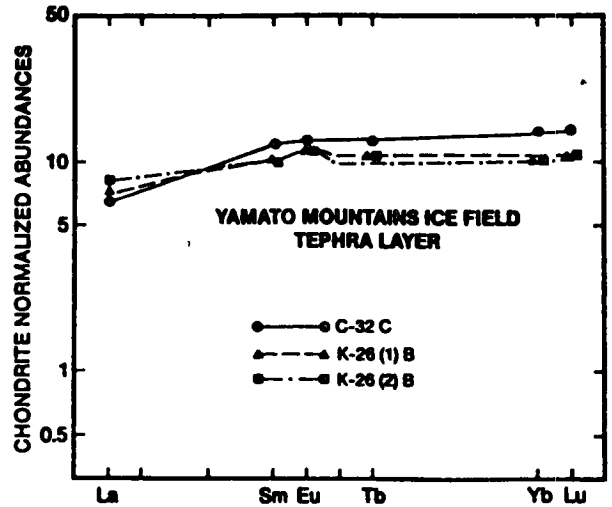
	YAMATO MOUNTAINS	SOUTH POLE CORE	SOUTH SANDWICH ISLANDS	
	TEPHRA	TEPHRA	BELLINGHAUSEN ISLAND	CANDLEMAS ISLAND
			ANDESITE	ANDESITE
SiO <sub>2</sub>	57.9	60.0	57.0	60.9
TiO <sub>2</sub>	1.00	0.78	0.91	0.95
Al <sub>2</sub> O <sub>3</sub>	13.98	16.03	16.14	14.8
FeO	11.03	7.37	10.59	8.34
MnO	0.23	0.16	0.18	0.11
MgO	2.81	1.71	2.80	2.35
CaO	7.57	6.79	8.32	6.09
Na <sub>2</sub> O	2.71	5.94	3.44	3.67
K <sub>2</sub> O	0.39	0.39	0.60	0.39

All data in wt. %, all Fe as FeO

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Fig. 1

The validity of this correlation is demonstrated by trace element studies (Fukuoka *et al.*, 1987). The trace element chemistry of the tephra from the Yamato Mountains is that of a typical island arc tholeiite. This is clear from Fig. 1, showing a chondrite-normalized rare earth element plot of the Yamato volcanic ash.



Studies on dust bands at the Lewis Cliff/Beardmore Glacier area by Koeberl *et al.* (1988) have shown that most of the dust is very fine grained and consists of a mixture of glass shards and crystal fragments (such as quartz, feldspar, pyroxene, olivine). The glass composition is variable, suggesting an evolving magma chamber as a source. The composition of the glass is that of a basanite, K-trachyte, and peralkaline K-trachyte, respectively.

Table 2 lists the compositions of different glass shards from the Lewis Cliff Ice Tongue, in comparison with material from the proposed source volcano at The Pleiades, Northern Victoria Land. The relationship between volcanic rocks from The Pleiades and the Lewis Cliff dust is further validated by trace element studies (Koeberl *et al.*, 1988).

Table 2. Chemical correlation, Lewis Cliff dust (Koeberl *et al.*, 1988)

	LEWIS CLIFF VOLCANIC GLASS SHARDS				THE PLEIADES VOLCANIC ROCKS		
	86-1-10	86-1-12	86-3-16	17-02-9	K-trachyte	Peralkaline K-trachyte	Basanite
SiO <sub>2</sub>	58.4	58.5	64.7	44.4	60.0	64.4	44.3
TiO <sub>2</sub>	1.07	0.83	0.23	4.16	0.70	0.14	3.66
Al <sub>2</sub> O <sub>3</sub>	17.38	17.79	17.76	14.66	17.67	16.85	14.82
FeO	6.74	6.80	3.37	12.65	5.70	3.64	12.20
MnO	0.21	0.32	0.03	0.19	0.17	0.15	0.20
MgO	1.00	0.75	0.38	5.08	0.75	0.08	7.21
CaO	2.82	3.04	1.28	10.54	2.47	0.93	10.98
Na <sub>2</sub> O	4.07	6.06	6.37	4.19	7.09	8.26	3.80
K <sub>2</sub> O	4.20	5.37	3.26	1.20	4.74	5.24	1.74

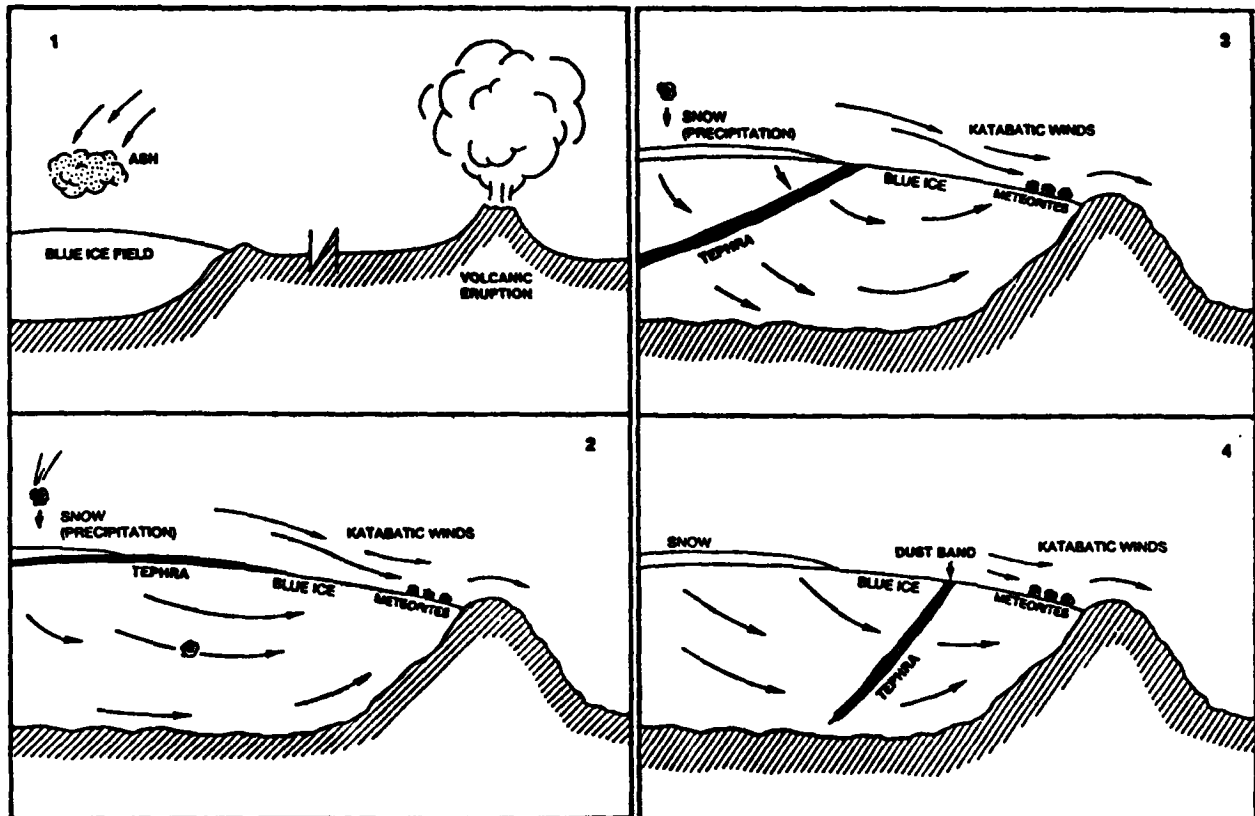
All data in wt. %, all Fe as FeO

### Conclusions

The dust bands at the blue ice fields are mostly of volcanic origin and may be correlated with individual Cenozoic volcanoes in Antarctica and the sub-antarctic regions. Volcanic eruptions disperse large quantities of volcanic dust over Antarctica, where it falls on snow accumulation areas, is incorporated in the ice, and transported to the ablation zones (see Fig. 2). There the dust layers constitute an isochronous layer that is of great value for the study of the ice fields and may be used for dating.

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Fig. 2. Cartoon showing the development of a dust band on a blue ice field.





## Diverse Components of Dust Bands In Allan Hills Ice Samples

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Dust components in ice samples collected from two sites in the vicinity of Cul de Sac differ strikingly from each other and from those in samples taken near Geodetic Stations 11 and 12 west of the Allan Hills Main Icefield. Samples labeled Cul de Sac 100 and Cul de Sac 150 were collected from dust bands about 50 meters apart near the southern extremity of the meteorite stranding surface. Samples 85-1 and 85-2 were taken about 1 km apart near the crest of the monocline that rises west of the stranding surface (Figure 1).

**Cul de Sac 100.** Particles of olivine basalt tephra are the dominant constituents of Cul de Sac 100. Glass shards, most of which are tawny-brown and transparent, range in size up to 250  $\mu\text{m}$  but cluster at about 100  $\mu\text{m}$ . Some of the shards contain phenocrysts of olivine or crystallites of other phases. Glasses also occur as dark, rounded masses that are virtually opaque due to an abundance of microvesicles. A few transparent spherules, rods, and tear drops are also present. The range of refractive indices of the glass shards is  $n = 1.605\text{-}1.635$ , indicating basaltic compositions. Electron microprobe analyses show that the great majority of the Cul de Sac 100 glasses are undersaturated, olivine-nepheline-normative basalts with 43-47 wt. %  $\text{SiO}_2$  (Table 1), although a few analyses cross the boundary to quartz-normative compositions.

Mineral grains make up about 5% of the Cul de Sac 100 samples. Olivine (mainly Fo<sub>80-83</sub>; but also Fo<sub>73</sub> and Fo<sub>93</sub>), is the most abundant mineral. Other common minerals include augite, aluminous titanite, plagioclase (An<sub>20-73</sub>Ab<sub>26-77</sub>Or<sub>1-3</sub>), hematite or magnetite with <0.15 wt.%TiO<sub>2</sub>, and two varieties of titanomagnetite: picotite and chromium hercynite. Sparse grains of amphibole (kaersutite ?) were observed optically but not in electron microprobe mounts. In addition to these minerals, which have been reported by previous investigators, our Cul de Sac 100 samples contain quartz, often in grains that are larger and more rounded than the other constituents, rare grains of zircon, aluminous sphene, rutile, epidote [piemontite = Ca<sub>2</sub>FeAl<sub>2</sub>Si<sub>3</sub>O<sub>12</sub>(OH)], virtually pure end-member alkali feldspars (Or<sub>99</sub>) and (Ab<sub>99</sub>), an unidentified claylike material with low refractive indices, and a Ca-Al zeolite, probably epistilbite. The latter two phases occur in particles too delicate to be removed from microprobe mounts for x-ray determinations.

**Cul de Sac 150.** This sample contains particles of olivine basalt tephra similar to those in CS-100 but in lesser abundance. In addition, CS-150 yielded five polyminerally aggregates 2 to 3 mm across. The aggregates consist mainly of irregular quartz fragments admixed with K-rich feldspars (Or<sub>73-96</sub>Ab<sub>4-23</sub>An<sub>0-4</sub>), augite, titanomagnetite, sphene (embedded in feldspar), and the Ca-Al zeolite. The aggregates are loosely cemented by porous materials that yield low analysis totals and remain unidentified. The aggregate constituents also occur as individual fragments in both of the Cul de Sac samples, but they are more plentiful in CS-150.

**Sources of Cul de Sac Dust.** The constituents listed above clearly represent more than one type of source rock. All of the analyzed Cul de Sac glasses fall well within the range of the olivine basalts, basanites, and trachybasalts erupted on Ross Island and along the coast of Victoria Land (e.g. Goldich, 1975). Most of the olivine grains (Fo<sub>73-83</sub>) contain 0.23-0.36 wt.% CaO; values characteristic of olivines from extrusive basalts. The highly magnesian olivines (Fo<sub>93</sub>) have low values of 0.02-0.04 wt.% CaO, indicative of a deep-seated origin. These grains may represent mantle xenoliths of the type found in some of the Ross Island basalts. Our tephra analyses confirm the conclusions of earlier investigators (e.g. Nishio and others, 1985) that the Allan Hills ice fields contain ash from nearby eruptive centers in Victoria Land.

A small component of windblown particles also occurs in CS-100 and CS-150. The rounded quartz grains, zircons, and K-rich feldspars are most likely to be erosional debris from felsic crystallines or sandstones in the Transantarctic Mountains. Most fragments of K-feldspars (Or<sub>73-96</sub>) have a porous, spongy texture suggestive of alteration. In any case, K-feldspars of this compositional range are unstable at high temperatures and hence of nonvolcanic origin. Windblown dust and tephra particles may occur throughout much of the "clean" ice between visible dust bands. Small quantities of both were recovered from a clean sample taken about 10 centimeters from CS-100.

The large CS-150 aggregates of quartz, K-feldspars, trace accessory minerals, and zeolites, appear to be mixtures of erosional detritus, alteration products, and secondary minerals. They may be windblown particles of older volcanic deposits such as the pillow lavas, containing quartz and zeolites, that occur in the upper horizons of the Beacon Sandstone, which is well exposed in the Allan Hills. Their source would be difficult to pinpoint, but their large (2-3 mm) sizes suggest that they were swept up within a few hundred kilometers of the site where they were frozen into the ice.

Dates on the ice samples, determined by the uranium series method (Fireman, this volume), indicate that eruptions, which occurred approximately 295,000 and 195,000 years ago, deposited tephra now lying at Cul de Sac 100 and 150, respectively. These tephra came from the same, or similar, eruptive sources. The windblown materials arrived at the same time.

**Samples 85-1 and 85-2.** The 85-1 particles cluster at 7-10  $\mu\text{m}$  and those of 85-2 cluster at 30-50  $\mu\text{m}$  in grain size, with a few 85-2 particles ranging up to 120  $\mu\text{m}$ . The dust consists mainly of quartz-corundum-normative glasses, with refractive indices of 1.505 - 1.525 and 63-67 wt.% SiO<sub>2</sub> (Table 2). Many of the glass shards are crowded with minute crystallites of alkali feldspars, chiefly anorthoclase (Ab<sub>55-68</sub>Or<sub>22-44</sub>An<sub>1-10</sub>). Sparse mineral grains include aegirine (Na-Fe pyroxene), aegirine-augite, riebeckite (Na-K amphibole), and ferrohedenbergite (Ca-Fe pyroxene). Titanomagnetites and angular particles of SiO<sub>2</sub> (tridymite or quartz?) are also present. These samples are derived from sodium-rich eruptives of moderately high silica content, best classified as trachytes or quartz trachytes.

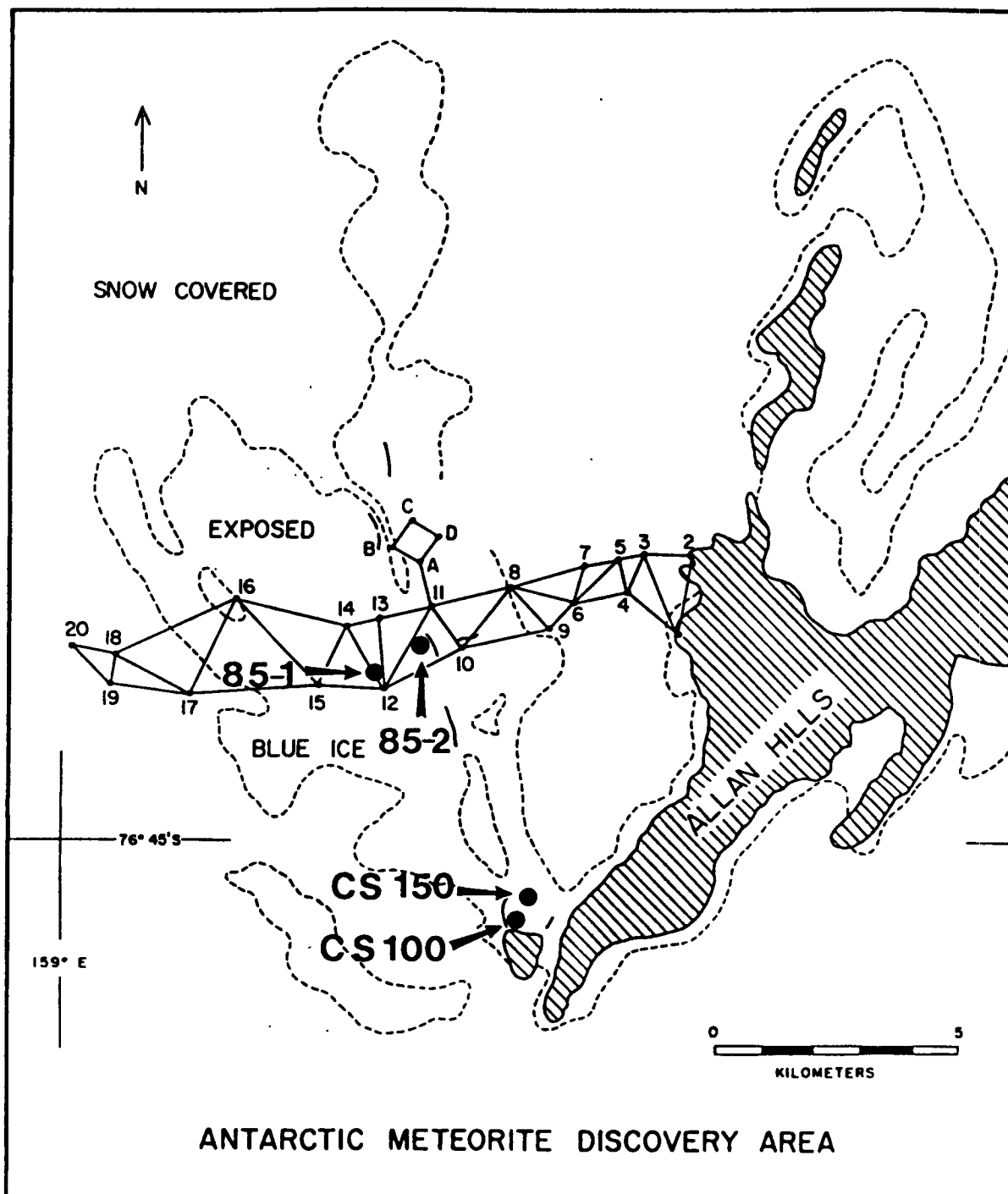
**Source of 85 Dust.** Dust bands consisting primarily of trachytic tephra have not been reported previously in the Allan Hills region. However, trachytes and quartz trachytes are minor members of the Ross Island complex and also of the eruptives of Marie Byrd Land and the South Shetland Islands (e.g. Gonzales-Ferran and Vergara, 1972; Katsui, 1972). It seems reasonable, therefore to assume that the 85 tephra were derived from an Antarctic source, which, ultimately, may be identified by trace element analyses. Although the Cul de Sac and 85 tephra may come from relatively nearby sources, no overlap was observed between the two pairs of samples: the Cul de Sac samples contain no aegirine or anorthoclase; the 85 dust contains no olivine or plagioclase feldspar. The finer grain size of the 85 dusts suggests a more distant source than that of Cul de Sac. Age determinations on the ice yield values of about 95,000 and 85,000  $\pm$  10,000 years for 85-1 and 85-2, respectively. (Fireman, 1989). These dates may well refer to the same event, or to successive eruptions of the same volcano.

Note: The text and conclusions of this abstract differ in part from those presented orally at the Pittsburg Workshop, where the author suggested a source in the South Sandwich Islands for the 85 tephra. Analyses of additional samples indicate that an Antarctic source is more likely.

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## COMPONENTS OF DUST BANDS IN ALLAN HILLS: U. B. Marvin

Figure 1. Sketch map of the Allan Hills area and sampling sites CS-100 and CS-150 at Cul de Sac, and 85-1 and 85-2 near Geodetic Stations 11 and 12 on the monocline at the western margin of the main meteorite-rich stranding surface.



## COMPONENTS OF DUST BANDS IN ALLAN HILLS: U. B. Marvin

**Table 1. Comparative analyses of Allan Hills dust and Ross Island volcanics**

	<b>Cul de Sac 25-84</b>	<b>Cul de Sac 24-52</b>	<b>Cul de Sac 27-73</b>	<b>AH Ash<sup>1</sup></b>	<b>Ross Is. 14<sup>2</sup></b>
<b>SiO<sub>2</sub></b>	<b>43.52 wt.%</b>	<b>43.52</b>	<b>46.37</b>	<b>44.23</b>	<b>44.60</b>
<b>TiO<sub>2</sub></b>	<b>3.78</b>	<b>4.09</b>	<b>4.39</b>	<b>3.76</b>	<b>3.46</b>
<b>Al<sub>2</sub>O<sub>3</sub></b>	<b>16.20</b>	<b>15.99</b>	<b>14.83</b>	<b>16.29</b>	<b>16.90</b>
<b>Cr<sub>2</sub>O<sub>3</sub></b>	<b>.00</b>	<b>.00</b>	<b>.03</b>	<b>.01</b>	<b>.00</b>
<b>Fe<sub>2</sub>O<sub>3</sub></b>	<b>1.49</b>	<b>1.51</b>	<b>1.48</b>	<b>1.33</b>	<b>1.40</b>
<b>FeO</b>	<b>9.94</b>	<b>10.07</b>	<b>9.86</b>	<b>8.86</b>	<b>9.30</b>
<b>MgO</b>	<b>6.00</b>	<b>4.70</b>	<b>4.25</b>	<b>4.06</b>	<b>3.78</b>
<b>MnO</b>	<b>.15</b>	<b>.12</b>	<b>.21</b>	<b>.22</b>	<b>.22</b>
<b>CaO</b>	<b>11.53</b>	<b>11.49</b>	<b>10.96</b>	<b>9.91</b>	<b>9.44</b>
<b>Na<sub>2</sub>O</b>	<b>3.56</b>	<b>3.22</b>	<b>2.89</b>	<b>4.29</b>	<b>5.37</b>
<b>K<sub>2</sub>O</b>	<b>1.42</b>	<b>1.77</b>	<b>1.94</b>	<b>2.95</b>	<b>2.01</b>
<b>P<sub>2</sub>O<sub>5</sub></b>	<b>.96</b>	<b>1.12</b>	<b>1.12</b>	<b>1.57</b>	<b>1.39</b>
<b>TOTAL</b>	<b>98.55</b>	<b>97.60</b>	<b>95.33</b>	<b>97.51</b>	<b>97.87</b>

**CIPW Normative Minerals**

<b>Apatite</b>	<b>2.21 wt.%</b>	<b>2.58</b>	<b>2.58</b>	<b>3.62</b>	<b>3.20</b>
<b>Chromite</b>	<b>.00</b>	<b>.00</b>	<b>.04</b>	<b>.01</b>	<b>.00</b>
<b>Ilmenite</b>	<b>7.18</b>	<b>7.77</b>	<b>8.34</b>	<b>7.14</b>	<b>6.57</b>
<b>Orthoclase</b>	<b>8.39</b>	<b>10.46</b>	<b>11.46</b>	<b>17.44</b>	<b>11.88</b>
<b>Albite</b>	<b>11.12</b>	<b>12.83</b>	<b>15.93</b>	<b>11.05</b>	<b>15.91</b>
<b>Anorthite</b>	<b>24.04</b>	<b>23.95</b>	<b>21.78</b>	<b>16.49</b>	<b>16.08</b>
<b>Magnetite</b>	<b>2.16</b>	<b>2.19</b>	<b>2.15</b>	<b>1.93</b>	<b>2.03</b>
<b>Diopside</b>	<b>22.05</b>	<b>21.23</b>	<b>20.89</b>	<b>18.51</b>	<b>18.01</b>
<b>Olivine</b>	<b>11.11</b>	<b>8.77</b>	<b>7.54</b>	<b>7.63</b>	<b>8.19</b>
<b>Nepheline</b>	<b>10.29</b>	<b>7.81</b>	<b>4.61</b>	<b>13.68</b>	<b>15.99</b>

For norm calculations iron analyses are recalculated to FeO:Fe<sub>2</sub>O<sub>3</sub>=1:0.15.

1. Nishio, *et al.* (1985). Also includes NiO 0.03 Wt.%.
2. Goldich, *et al.* (1975)

## COMPONENTS OF DUST BANDS IN ALLAN HILLS: U. B. Marvin

Table 2. Glasses with and without alkali feldspar crystallites from 85-1 and 85-2.

	85-1 #13	85-1 #24	85-2 #31	85-2 #59	85-1#103
SiO <sub>2</sub>	67.00 wt.%	69.73	66.75	62.88	63.40
TiO <sub>2</sub>	.53	.12	.10	.28	.48
Al <sub>2</sub> O <sub>3</sub>	14.52	18.62	18.29	16.68	12.82
Cr <sub>2</sub> O <sub>3</sub>	.02	.00	.00	.00	.04
Fe <sub>2</sub> O <sub>3</sub>	1.16	.20	.16	.61	1.71
FeO	7.74	1.36	1.04	4.03	11.43
MgO	.03	.02	.00	.00	.07
MnO	.34	.00	.03	.10	.52
CaO	1.49	1.26	.98	2.23	3.95
Na <sub>2</sub> O	1.03	5.69	6.19	7.21	3.89
K <sub>2</sub> O	2.94	5.49	4.76	3.76	3.64
P <sub>2</sub> O <sub>5</sub>	.32	.02	.05	.10	.12
TOTAL	97.12	102.51	98.35	97.88	102.07

## CIPW Normative Minerals

Apatite	.74 wt.%	.05	.12	.23	.28
Chromite	.03	.00	.00	.00	.06
Ilmenite	1.01	.23	.19	.53	.91
Orthoclase	17.37	32.44	28.13	22.22	21.51
Albite	8.71	48.14	52.37	60.99	32.91
Anorthite	5.30	6.12	4.54	2.06	6.78
Corundum	7.70	1.09	1.30	.00	.00
Magnetite	1.68	.29	.23	.88	2.48
Diopside	.00	.00	.00	7.45	10.72
Hypersthene	13.07	2.17	1.67	2.66	14.20
Quartz	41.51	11.98	9.82	.85	12.24

For norm calculations iron analyses are recalculated to FeO:Fe<sub>2</sub>O<sub>3</sub>=1:0.15.

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**DATING OF TEPHRA LAYERS IN POLAR ICE:  
OPPORTUNITIES AND PROBLEMS**

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The most promising method to determine the time of deposition of tephra layers in polar ice is fission track dating. Fission tracks in terrestrial materials result from the rare spontaneous fission of  $^{238}\text{U}$  (only ~1 fission decay for every million  $\alpha$  decays). The damage zones formed by the recoil of fission fragments are enlarged by etching and observed with an optical microscope (for a comprehensive review of the fission track method, see Fleischer *et al.*, 1975).

The three factors that determine whether or not a sample can be dated by this method are its uranium concentration, its ability to retain fission tracks and the absence of flaws that can be confused with tracks. There must be enough uranium so that a statistically significant number of tracks can be counted in a reasonable time and tracks must be retained once they are formed. The most common cause of loss or "annealing" of tracks is heating, with different minerals annealing at different temperatures. For the dating of Quaternary tephra, only zircon and glass can be used; each has advantages and limitations and, because glass from a single source tends to have a uniform uranium content whereas zircon crystals from the same source tend to have inhomogeneous uranium distributions, glass and zircon require the use of two different dating techniques. Zircon is dated by the external detector method and glass by the population method (e.g., Naeser and Naeser, 1984).

Zircon is best suited for these studies: its uranium concentration is relatively high and it is particularly resistant to annealing. However, zircons are not present in all tephra (e.g., basic tephra tend to have no zircon crystals). In addition, fine-grained zircons in tephra collected far from the vent they originated from are too small to be dated.

Glass shards have much lower uranium concentrations and their fission tracks easily fade. It is possible though that this is not a problem in Antarctica and that, thanks to the frigid temperatures, tracks are retained. Glasses are abundant in tephra but their low uranium concentrations imply that fission tracks will have to be looked for and counted in areas on the order of  $1\text{ cm}^2$  (or more). It is also difficult to count tracks in very fine-grained or pumiceous shards.

In summary, the fission track method can be used to date zircon and glass shards older than  $10^5$  years but young samples require long counting times and have large associated analytical uncertainties. Well calibrated standards and experienced observers are essential and, therefore, the fission track dating of quaternary tephra should only be attempted by researchers aware of the many difficulties of this method, when applied to young samples.

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**URANIUM-SERIES DATES FOR ICE  
AT THE MAIN ALLAN HILLS AND LEWIS CLIFF ICE TONGUE**

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The antarctic ice sheet preserves a long, continuous record of climatic conditions, volcanic activity, atmospheric contaminants and meteorite infall. The dating of horizons within the ice is a prerequisite for constructing meaningful records based on correlations between different sites. A 150,000 year chronology was obtained from the 2083-m-deep core at Vostok [1] by associating variations of  $^{18}\text{O}/^{16}\text{O}$  and  $^2\text{H}/\text{H}$  ratios of the ice with flow calculations and time of the Wisconsin glaciation. Ice cores are essential to many kinds of studies, but their small diameters, of 7 to 15 cm, and the difficulty of recovering deep core samples limit their usefulness. I report here on dates obtained, by the uranium-series method, on tephra-banded ice samples collected from four locations in the main Allan Hills ice field ( $76^{\circ}45'$  S;  $159^{\circ}\text{E}$ ), and one location in the Lewis Cliff ice tongue ( $84^{\circ}20'\text{S}$ ;  $162^{\circ}25'\text{E}$ ). U. Marvin [2] reported on the chemical and mineralogical compositions of the tephra particulates in the four ice samples from the main Allan Hills ice field. Previously reported [3] ages for two ice samples from this ice field lacked uranium and thorium measurements for the imbedded particulates. I have now obtained those values and increased the reliability of their ages.

The uranium-series ages are approximately 98000 years for ice-sample 85-1, 195000 years for Cul de Sac-150 ice, 295000 years for Cul de Sac-100 ice and 67000 years for 85 ice. The locations for 85-1, Cul de Sac-150, and Cul de Sac-100 ice samples from Allan Hills main ice field are well-known and their ages are consistent with the horizontal stratigraphy predicted from the ice flow pattern. The location of the sample 85 is uncertain. This problem may be decided by examining the labels on the unmeasured ice samples, which are stored at the Ice Core Laboratory in Buffalo.

The uranium-series age for sample 86-3 from the Lewis Cliff ice tongue is 25000 years; its location is well known.\* This result indicates that the ice in the Lewis Cliff ice tongue is much younger than the ice at the main Allan Hills icefield.

\*Sample 86-3 is located near the E edge of the lower Lewis Cliff Ice Tongue at  $84^{\circ}14'15''\text{S}$ ;  $161^{\circ}00'30''\text{E}$ -Editor

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**EVAPORITES FROM THE LEWIS CLIFF ICE TONGUE, ANTARCTICA**

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Nahcolite ( $\text{NaHCO}_3$ ), trona ( $\text{Na}_3(\text{CO}_3)(\text{HCO}_3) \cdot 2\text{H}_2\text{O}$ ), borax ( $\text{Na}_2\text{B}_4\text{O}_7(\text{OH})_4 \cdot \text{H}_2\text{O}$ ) and other associated minerals have been identified in samples taken from ice and moraine at the Lewis Cliff ice tongue,  $84^\circ 15' \text{S}$ ,  $161^\circ 25' \text{E}$ , Antarctica. These minerals occur around supraglacial kettle pond margins (trona), entrained in narrow fissures in the ice (nahcolite), in large, friable masses atop moraine along the northeast margins of the ice tongue (borax and nahcolite), and as tufa-like deposits in a large moraine field which marks the northern terminus of the ice tongue (nahcolite).

Deuterium isotope studies indicate that the trona has crystallized by direct precipitation from standing water in lateral kettle ponds whose surfaces are liquid for short periods during the austral summer. Nahcolite occurs both as a fissure infilling along the northeast margin of the ice tongue and in tufa-like masses within the large ice-cored moraine at the north end of the ice tongue. The geometry of the nahcolite-containing fissures resembles that of steeply dipping dust bands and regelated ice bands which are found elsewhere in the northern end of the ice tongue. The field occurrence and distribution of nahcolite found as tufa-like mounds within the moraine field strongly suggests that it has been deposited from waters rising from a point source beneath the ice tongue at this locality. Examination of fluid inclusions in these spring-type deposits has proven inconclusive to date. All nahcolite samples give uranium disequilibrium series ages on the order of 17,000 to 9,000 years bp and deuterium values which indicate isotopic equilibrium with south polar ice.

Borax occurs in large crystals, as much as 2 cm. in length, and comprises large erratics atop moraine at the northeast margin of the ice tongue. It is closely associated with clear, euhedral nahcolite. The borax crystals, when observed in the field, had already undergone at least one cycle of dehydration to tincalconite ( $\text{Na}_2\text{B}_4\text{O}_7(\text{OH})_4 \cdot 3\text{H}_2\text{O}$ ) and rehydration to borax. Scanning electron microscope examination of these borates indicates that they have been partially replaced with nahcolite from the outside, resulting in euhedral polycrystalline pseudomorphs with borax cores and nahcolite rims. Uranium disequilibrium series dates of segregated cores yield ages on the order of 75,000 years bp. These samples constitute the first reported occurrence of borax in Antarctica. Two additional as yet unidentified minerals were also noted in these samples.

It is felt that the occurrence and field distribution of these minerals indicates the presence of a subglacial sodium carbonate brine at this locality. Further work on the characterization and distribution of these minerals is currently in progress.

**IN SITU METEORITES: EVIDENCE FOR THE IMMINENT EMERGENCE  
OF BURIED METEORITES AT THE SURFACE OF THE ANTARCTIC ICE SHEET**  
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During the austral summer of 1982-83 a small, walnut-sized meteorite with just its tip protruding above the ice surface was recovered from the Far Western Ice Field near the Allan Hills, Antarctica. Because no evidence of melting was observed around the meteorite, an H5 chondrite designated ALH82102, it would appear that this meteorite was being exposed for the first time at the ablation surface after a period of protracted burial in the ice sheet. The meteorite was carefully removed, still embedded in a block of ice, and shipped to USA/CRREL for thin section examination of the structure of the ice in immediate contact with the meteorite. The structure of the ice exhibited no characteristics consistent with melting and refreezing. However, very strong evidence, consistent with deformation of ice crystals around the meteorite, indicate that the meteorite was in fact just beginning to emerge at the ablation surface when discovered on 2 January 1983, and that the ice enclosing the meteorite is coeval with the terrestrial age of the meteorite. Ice structural studies of a second meteorite, recovered from the Lewis Cliff area under identical circumstances to meteorite ALH82102, also indicate that it too was just emerging at the ice ablation surface.

**METEORITE FLUX CHANGES: EVIDENCE FOR DIFFERENT  
EXTRATERRESTRIAL METEORITE POPULATIONS  
AMONG NON-ANTARCTIC AND ANTARCTIC METEORITES**

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In a brief note, Dennison *et al.*, (1986) summarized evidence known at that time hinting that antarctic and non-antarctic meteorite populations derive from different extraterrestrial parent populations. Subsequently, a number of studies bearing on this point have been carried out and nearly all support the conclusion of Dennison *et al.*, (1986). The current list of differences, summarized below, seems to reflect sampling and thermal history differences in the parent populations.

Differences between antarctic and non-antarctic meteorite populations are reflected by:

1. Meteorite type frequencies
  - Irons
  - Stony-irons
  - Achondrites
    - Aubrites
    - Howardites
    - Ureilites
  - Chondrites
    - H/L chondrite ratio
2. Meteorite mass distributions
3. Meteorite textures
  - Eucrites
  - Cl, 2 Chondrites
4. Shock histories
  - H,L chondrites
    - thermoluminescence
    - petrography
5. Trace element contents
  - H chondrites
  - L chondrites
  - Cl,2 chondrites
  - Eucrites
6. Siderophile element contents
  - Ureilites
7. Hg-siting and retention
  - Achondrites
  - E<sub>4</sub>, 6 chondrites

8.  $^{13}\text{C}/^{12}\text{C}$  ratios  
C1,2 chondrites
9. Oxygen isotopic composition  
Ureilites
10. Cosmogenic  $^{53}\text{Mn}$  contents  
H chondrites

Differences between the sample populations are not reflected by:

1. Matrix composition  
C2 chondrites
2. Cosmogenic  $^{53}\text{Mn}$  contents  
L chondrites
3. Cosmic ray exposure age distribution  
H chondrites

As a working hypothesis, we believe that the Earth's sampling of meteoroidal material has changed with time. If true, conventional views derived from statistical Monte Carlo arguments - of meteorite derivation from asteroidal material must be modified.

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**TERRESTRIAL AGE MAPPING OF THE ALLAN HILLS MAIN ICEFIELD AND  
IMPLICATIONS FOR THE**

**WHILLANS-CASSIDY MODEL OF METEORITE CONCENTRATION**

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Using terrestrial ages gathered from the literature (1) and meteorite location data from other sources (2-4), a terrestrial age contour map of the Allan Hills Main Icefield has been produced (figure 1). The Whillans-Cassidy model for meteorite concentration by ice movement (5) predicts that older meteorites will be found closest to a barrier to ice flow, and younger meteorites will be found further "upstream". The map in general supports this, but also shows irregularity, possibly due to direct fall of meteorites onto the stranding surface, movement of meteorites by the wind, and irregularities in the exposure of ice of differing ages.

To investigate further how well the Whillans-Cassidy model describes the concentration of meteorites on the Allan Hills Main Icefield, a plot of distance east from the west side of the map vs. terrestrial age was created (figure 2). A linear regression best-fit straight line to this plot does show a statistically significant increase in age toward the barrier. The relative presence of noise on the right side of this graph does indicate that meteorite concentration by direct fall or by the wind has also played a role, although one not strong enough to drown out the background due to Whillans-Cassidy concentration.

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## TERRESTRIAL AGE MAPPING: R. Harvey

Figure 1. Origin of Terrestrial age map is at  $76^{\circ}42'47''\text{S}$   $150^{\circ}15'15''\text{E}$  Long. Contours are in  $10^3$  years.

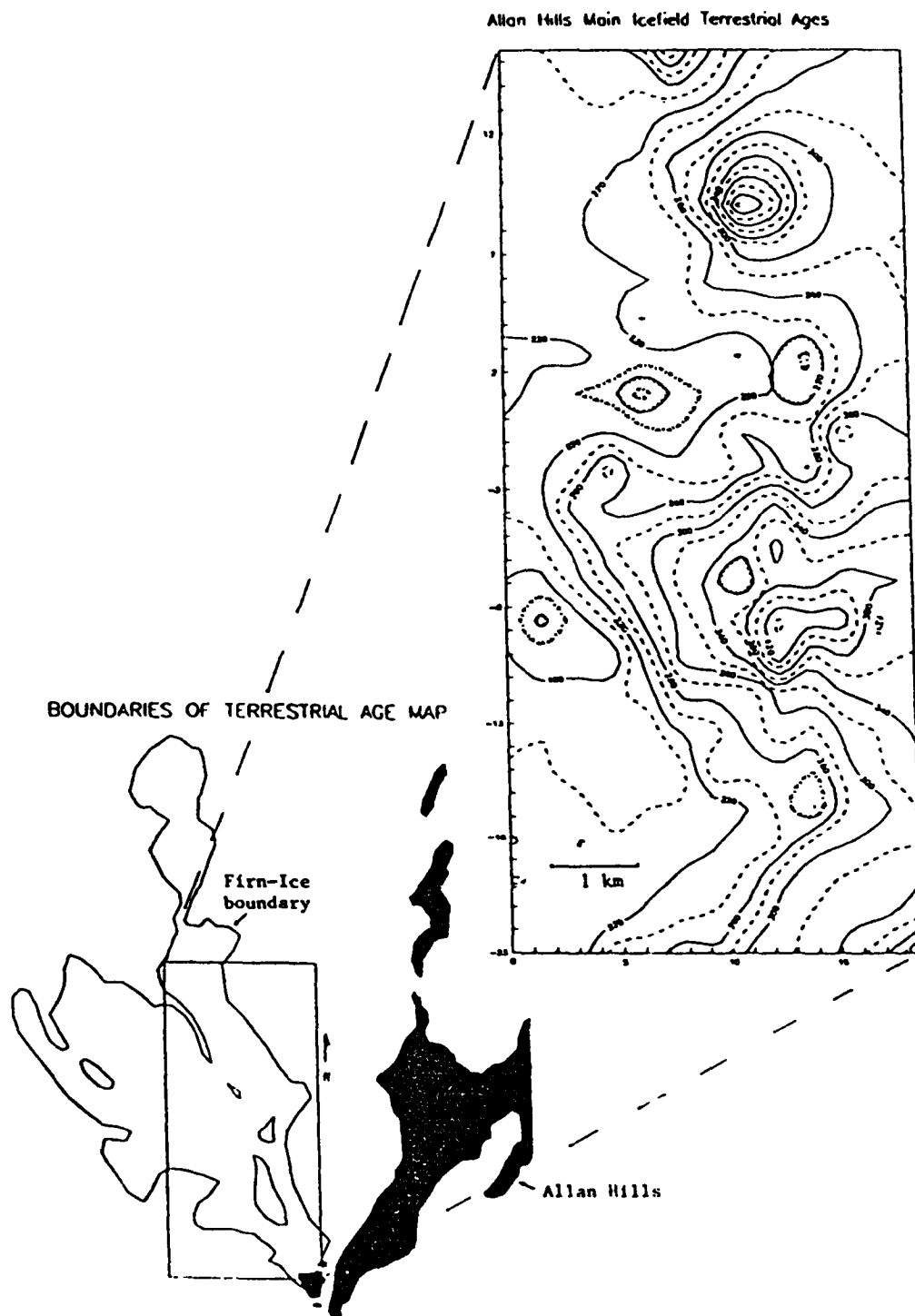
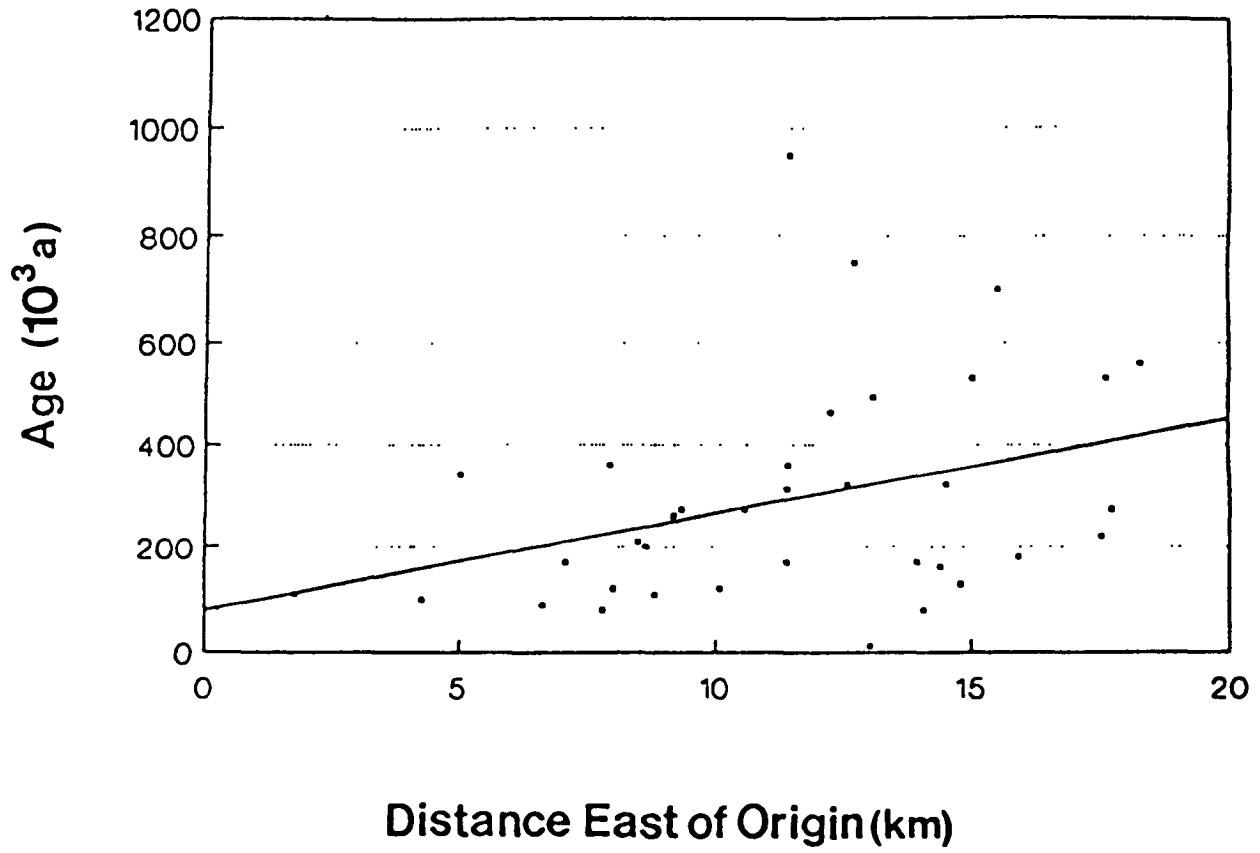


Figure 2.

### Distance East vs Age





**A NEW AND HIGHER ESTIMATE OF THE GLOBAL  
FREQUENCY OF METEORITE FALLS**

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**INTRODUCTION.** Before we can properly evaluate the stranding rate of meteorites in Antarctica we must firmly establish the global rate of meteorite falls. Previous estimates of this important value have relied upon 1) the recovery of meteorite falls in densely populated regions [1], 2) the worldwide recovery of meteorite falls [2], or 3) automatic camera networks set to photograph fireballs [3]. The meteorite fall rates derived by these studies [1 - 3] are shown in Fig. 1. This figure is a plot of  $\log N$  vs.  $\log M$ , where  $N$  is the number of falls per year in  $106 \text{ km}^2$  with mass exceeding  $M$  grams. In this figure "MORP" is the Canadian Meteorite Observation and Recovery Programs [3]. The estimated meteorite fall rates shown are observed to differ by an order of magnitude. While this would be considered good agreement in some scientific disciplines, this is hardly a satisfying situation for us.

Use of the recovery of meteorites to derive a meteorite fall rate is hindered if non-coordinated, piece-meal techniques are employed in the field, since this results in incomplete meteorite recovery. The use of camera data to derive meteorite fall rates is handicapped by incomplete knowledge of the luminous efficiency of fireballs and uncertain atmospheric conditions. All of these techniques suffer from the small amount of time over which the falls have been observed (from 8 years for the camera network [3] up to 250 years for the worldwide fall recovery study [2]). Therefore, the uncertainties in these studies probably account for the observed differences in the calculated meteorite fall rates. For these reasons, no definitive estimate has been made of the meteorite fall frequency over Antarctica.

**ROOSEVELT COUNTY METEORITES.** Second only to the blue ice regions of Antarctica, the Southern High Plains of Texas and New Mexico have yielded the greatest concentration of meteorite discoveries. At least 163 meteorites have been found in a small area of Roosevelt County, New Mexico, alone [Glenn Huss, personal communication, 1988]. Most of these meteorites have been found on the floors of recent surficial deflation basins. There is no evidence of recent (within the last 50,000 years) fluvial activity in this area. Therefore, meteorites accumulate there and their only net movement is downward, as deflation progresses. Therefore, in contrast to conditions in blue ice regions, the dating of sediments surrounding the meteorite finds in Roosevelt County, when coupled with a careful record of the absolute area searched for meteorites, allows a minimum figure to be determined for the global fall rate [4].

**CALCULATION OF THE METEORITE FALL RATE.** Of the 163 meteorites found in Roosevelt County (largely by Ivan Wilson), 153 were found in surficial deflation basins exposing Late Pleistocene and Holocene eolian sediments and topsoil [5, and Glenn Huss, personal communication, 1988]. In a manner similar to the ablation occurring in blue ice regions, wind erosion leaves meteorites as a lag deposit upon the deep coversands. The ages of the coversands are well-constructed, thanks largely to radiocarbon and thermoluminescence (TL) dating of the stratigraphy associated with Paleoindian archaeology sites in the region. An explanation of the TL dating technique may be found in [6]. In this region, the lowermost coversand member is a grey eolian mantle of Pleistocene Illinoian (~150ka BP) [7]. Of principal interest to us are two Pleistocene Wisconsinan eolian units. One is a bright reddish-brown unit extensive throughout the region, which has recently been TL-dated ~16 ka BP in a deflation basin in Roosevelt County [Helen Rendell, personal communication, 1988]. The other is an orange dune sand deposited during the final phase of Pleistocene aridity ~10 ka BP [Helen Rendell, personal communication, 1988].

153 meteorites found in Roosevelt County were discovered within a limited, carefully searched area (11 km<sup>2</sup>) of recent deflation basins (Ivan Wilson, personal communication, 1988) which expose the bright reddish-brown eolian unit whose floor has been locally dated at 16 ka BP. Once emplaced by impact into the Pleistocene coversands, no frost-heaving or other processes capable of uplifting meteorites from depth have occurred in the Southern High Plains. In addition, as noted earlier, there is no evidence for recent fluvial activity. As a consequence, the age of the deflated surface upon which a meteorite is located in Roosevelt County represents its maximum possible terrestrial age.

Before we can calculate the meteorite fall rate from these Roosevelt county finds, we must establish which of the meteorites are paired (belong to the same fall), and how many meteorites have been lost due to weathering. We must also correct for the population distribution. We undertake each of these tasks below.

Of the 153 meteorites found in deflation basins in Roosevelt county, only 68 have undergone sufficient study to permit pairing to be determined [8-11, Glenn and Gary Huss, personal communication]. By our conservative estimate there at least 49 separate falls represented among these 68 meteorites. Because this is a conservative estimate, and because fewer than  $\frac{1}{2}$  of the Roosevelt County meteorites have yet been properly examined, 49 falls is a minimum value.

Boeckl [12] measured the terrestrial age of 19 ordinary chondrites found in the American southwest, in order to derive their weathering rates. We note here that with the exception of only one howardite (Melrose b), all of the 49 Roosevelt County falls considered for our calculations are ordinary chondrites. From Boeckl's 19 meteorites we selected the 8 that were found on the Southern High Plains in eolian units

analogous to those found in Roosevelt County, to ensure similar weathering rates. By calculating a linear regression through the terrestrial ages of these 8 meteorites (correlation coefficient=0.9899), we derived a weathering half-life for ordinary chondrites on the Southern High Plains. The maximum terrestrial age of the Roosevelt County meteorites is 16 ka. Factoring in the weathering half-life for these meteorites, we conclude that only 1/5 of the initial meteorites remained to be found.

Finally, we have to correct for the fact that with the exception of one howardite, all of the meteorites considered for our calculation are ordinary chondrites. Since 80% of meteorite falls are ordinary chondrites [13], the 20% of meteorite falls which are not ordinary chondrites are not represented among these Roosevelt County finds, and have apparently weathered away.

When we combine all of these factors, we derive a meteorite fall rate shown in Fig. 1 (labeled North American Search for Meteorites-NASM).

**CONCLUSIONS.** Because of our conservative model assumptions and calculations the meteorite fall rate we have calculated is a minimum value. As more of the 153 Roosevelt County meteorites are characterized, undoubtedly more separate falls will be recognized, driving our calculated meteorite fall rate upward. Nevertheless, our preliminary meteorite fall rate is still considerably higher (by up to an order of magnitude) than the three previous estimates shown in Fig.1.

We believe that our estimate of the meteorite fall rate is superior to previous estimates for the following reasons: 1) arid conditions in the Southern High Plains have conspired to preserve meteorites, 2) because of the large expanses of freshly-exposed deflation basins, with good age control, Roosevelt County is one of the best places on Earth to perform coordinated searches for meteorites, 3) persons involved in the systematic meteorite searches in Roosevelt County kept exceptionally good records of their work, and 4) the Roosevelt County collections sample the meteorite fall record for 16 ka, which is orders of magnitude longer than the "data collection period" employed for any previous study. We note that a similar study could be performed at the Nullarbor Plains, Australia. Large numbers of meteorites have recently been recovered here due to coordinated field searching [Robert Hutchison, personal communication, 1988]. It is therefore possible that our meteorite fall rate estimate will soon be tested by another similar study, if appropriately dated surficial units are present in the Nullarbor Plains.

We recommend that this new NASM estimate of the global meteorite fall rate be employed in any modeling of the accumulation of meteorites in Antarctica. To do so, however, will involve the assumption that the meteorite fall rate for the past 16 ka has been constant for the past 300 ka.

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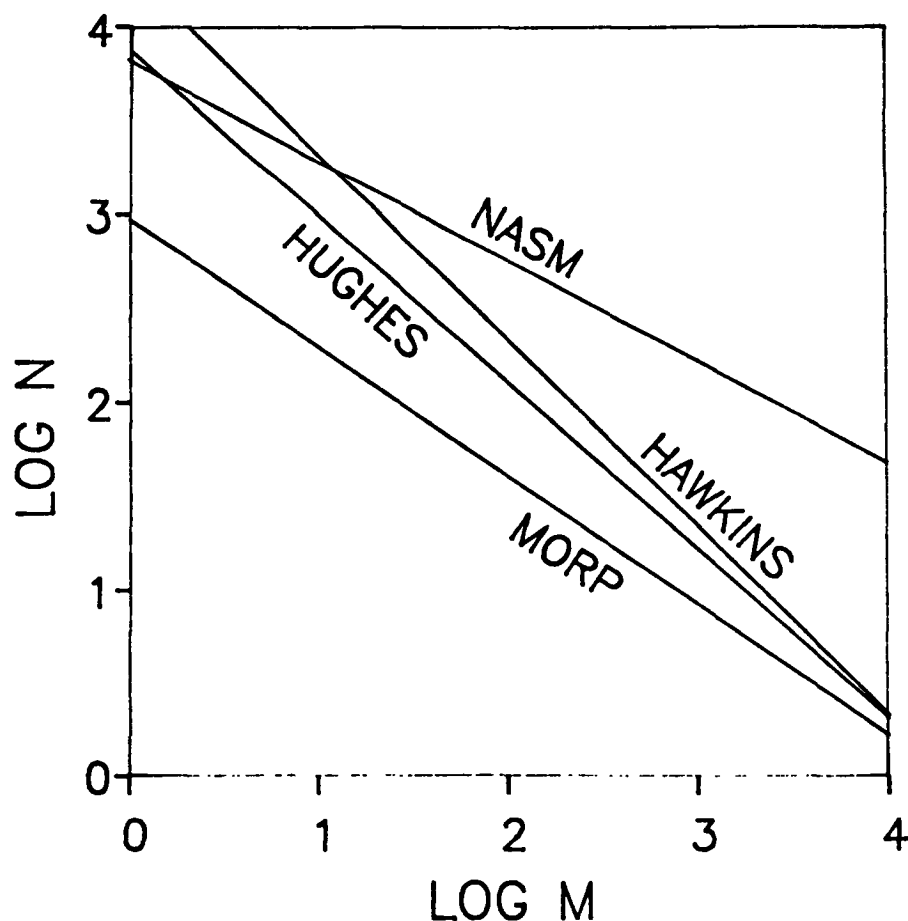


Figure 1

**TOPOGRAPHIC FORCING OF ANTARCTIC SURFACE WINDS;  
RELEVANCE TO ANTARCTIC METEORITE COLLECTION AREAS**

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The topographically-forced, continental-scale surface wind regime over Antarctica plays a key role in determining the behavior of the atmosphere and ocean in high southern latitudes. The boundary layer outflow from the continent is sustained by poleward mass transport in the troposphere and sinking over the ice sheet. Compressional heating in conjunction with the above circulation and radiative cooling are the dominant terms in the atmospheric heat budget. Where cold surface air crosses the continental margin, sea ice formation and salinization of shelf waters are substantially enhanced, and mesoscale cyclones tend to form.

From a knowledge of terrain slopes at 50 km resolution and estimates of the lower atmospheric stratification, the broadscale pattern of time-averaged surface air motion over the sloping ice fields of Antarctica can be diagnosed with a high degree of confidence (Parish and Bromwich, 1987). Surface winds are found to converge in a limited number of areas just inland of the steep coastal ice slopes. Such regions are believed from primitive equation model simulations (Parish, 1984) to contain much deeper and faster moving airstreams. These confluence zones in the interior windfield provide large cold air reservoirs to sustain intense coastal katabatic winds (e.g., Bromwich, 1988). The end result is that most of the boundary layer transport of cold air across the antarctic coastline is concentrated in a small number of zones with "extraordinary" katabatic winds.

Ablation in blue ice zones must be achieved by sublimation. The Allan Hills and Yamato Mountains meteorite collection areas are not associated with broadscale regions of enhanced surface winds. Therefore, it is probable that localized (10 km scale) modifications of the motion field exist at these sites and are causally linked to the generation of blue ice patches. Once these features are formed, they are likely to persist in part because the low albedo of blue ice promotes substantial sublimation in the summer half-year by absorbing much larger amounts of solar radiation than the surrounding firn-covered areas.

The dominant influence of topographic forcing upon Antarctic drainage winds coupled with the ability realistically to simulate their dynamics provides a sound basis for reconstructing past wind patterns. Ice sheet topographic configurations deduced by a variety of techniques including meteorite stranding studies together with the concentrations of radiatively-active trace gases obtained from ice cores provide the required boundary conditions for realistic modeling of the antarctic boundary layer circulation for different climatic conditions. As discussed above, the nature of air motions near the ice sheet surface has a profound impact upon the entire atmosphere above the ice sheet and upon the ocean surrounding

the continent. Diagnosis of the surface wind regime is an essential element for understanding the dynamics of climate change and climate variations in high southern latitudes.

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**MARINE DIATOMS IN EAST ANTARCTIC  
TILLS AND SUPRAGLACIAL MORAINES:  
CLUES TO ANTARCTIC ICE SHEET HISTORY**

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Diatoms, one-celled aquatic protists that form a durable siliceous skeleton, are incorporated into ice sheets through eolian deposition onto the ice sheet surface and by entrainment of sub-glacial sediments into basal ice. Their recovery in ice cores, in moraines on the ice sheet surface and in glacial deposits enables the correlation of ice stratigraphic horizons and the identification and dating of sediment sequences hidden beneath the ice, respectively.

Cenozoic marine diatoms recovered from the Sirius Group of glacial sediments in the Transantarctic Mountains originate from the Wilkes and Pensacola sub-glacial basins of East Antarctica. East Antarctic ice flow eroded Pliocene and older diatomaceous sediments from these basins and incorporated them into ice-marginal and basal till deposits of the Sirius Group, which are known from a 1300 km segment of the Transantarctic Mountains. Pliocene and Miocene marine diatoms recovered from till-clasts in the Elephant Moraine, which resemble compact sediments of the Sirius Group, support the interpretation that these diatoms originate from East Antarctica and that basal ice "outcrops" at Elephant Moraine.

The youngest marine diatoms recovered from the Sirius Group first appear in Southern Ocean sediments between ~3.3 to 3.1 Ma and lived until ~2.4 Ma. These fossils suggest an age for the most recent period when marine waters filled the East Antarctic basins and they suggest that the early Pliocene East Antarctic Sheet was significantly smaller than present; perhaps only 1/2 to 1/3 its present size.

This scenario limits the age of meteorites that might be found in antarctic ice to ~2 Ma or younger, allowing sufficient time for the ice sheet to build up and become stable, following this Pliocene deglaciation. The oldest meteorite recovered from antarctic ice in the Allan Hills (~0.9 Ma) suggests ice sheet stability by this time.

Late Pliocene-early Pliocene fossil wood recovered in-situ in the Sirius Group at Dominion Range at the head of Beardmore Glacier (86° S latitude) indicates a major episode of Transantarctic Mountain uplift in the early Pleistocene. The wood-bearing deposits are presently at 1800 m asl, an elevation too high to accommodate vegetation and still maintain reasonable temperatures at sea level in the Ross Sea (i.e. if the wood lived at its present elevation, sea-level climate in the Ross Sea would be subtropical!). Uplift of the Dominion Range (perhaps the Transantarctic Mountains as a whole) since the growth of these plants must have been between 1000 to 1300 meters in ~2.5 million years. This evidence is puzzling considering the present seismic quiescence of Antarctica, but there is evidence for vertical movements of this magnitude in the Dominion Range by the 600 m displacement of a fault that

cuts the late Pliocene-early Pleistocene Sirius Group. Rapid mountain uplift would surely play a role in the early Pleistocene reglaciation of East Antarctica. In order to explain the modern isostatically adjusted elevation of the Wilkes and Pensacola basins above sea level (according to Drewry) and their apparent Pliocene and older deep marine sediment history, broad uplift of these basins may have accompanied the mountain uplift.

Exposure ages collected systematically from vertical sections on nunataks along the Allan Hills ice-fields should help address questions regarding recent uplift and or ice sheet elevation changes. If all nunataks show similar exposure histories at given elevations, then ice sheet variability may be responsible. If the exposure ages are heterogeneous, then perhaps differential uplift histories for separate mountain blocks could be invoked. L. Gould noted that the Transantarctic Mountains appear to be rising from beneath the ice sheet: this may be so. In explaining the occurrence of supraglacial moraines, such as Elephant and Reckling Moraines, by ice flow patterns associated with subglacial highs and shallow buried mountains, we should ask whether the ice sheet is thinning, or whether the mountains are rising toward the ice sheet surface.



**INTERPLANETARY DUST PARTICLES RECOVERED FROM ANTARCTIC ICE**  
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**INTRODUCTION.** The discovery of large quantities of meteorites in blue ice regions of Antarctica, and the resultant explosive increase in meteorite research, has also sparked interest into the recovery and study of interplanetary dust particles (IDPs) from the ice. There are several reasons for this development. Modern laboratory studies of IDPs, as permitted by advances in microanalytical techniques, began to mature just as the first large concentrations of meteorites were discovered in Antarctica. Just as the ice prevents certain types of terrestrial contamination and alteration from harming meteorites, so the IDPs are also preserved. In addition, the steady stream of meteoriticists visiting the Antarctic to collect meteorites inevitably included some whose cosmopolitan interests included the study of IDPs.

**SOURCE OF LARGER IDPS.** To practitioners of IDP studies the principal interest in examination of particles recovered from the Antarctic has been the opportunity to broaden collection efforts beyond what is possible in the stratosphere, where the conventional collection of IDPs is made. Since the largest dust particles are usually destroyed during atmospheric entry, they rarely appear on stratospheric collection surfaces. It is believed that the chances of locating these rare large particles could be greatly increased through the melting of large quantities of polar ice, which had been accumulating IDPs for many thousands of years. This hypothesis has recently been verified by the studies of Maurette and Zolensky and their co-workers [1-5]. The availability of larger-sized IDPs allow a greater range of analytical techniques to be brought to bear on characterization studies, and permit consortium studies of individual particles.

**SOURCE OF NEW TYPES OF IDPS.** In addition, some IDPS are more easily recovered from antarctic ice than the modern stratosphere. One example is the refractory class of IDPs. These particles consist predominantly of oxides, silicates and carbides of aluminum, titanium and calcium, and are thought to contain very primitive nebular condensates and even interstellar dust grains. All of these materials were probably preserved from destruction in the solar nebula by their refractory composition [4-6]. Because of the increasing relative proportion of refractory spacecraft debris in the modern stratosphere, it has become very difficult to locate refractory IDPs from the stratospheric collections [7]. The solution has been to search for these particles within pre-industrial age antarctic ice. It is likely that in the future other significant IDP types will be recognized in pre-industrial age antarctic ice first, and from the stratosphere only afterwards, due to prior confusion with other man-made atmospheric pollutants.

Investigators have recently recognized types of IDPs from

antarctic ice which appear to be absent from the modern stratospheric collections. One example is IDPs rich in titania compounds called Magneli phases [5]. These particles are significant because Magneli phases are potentially exploitable as temperature-oxygen barometers of the early solar nebula. In addition, at least one of these IDPs has been shown to contain a core of titanium carbide of probable extrasolar origin [5].

**STUDY OF IDP POPULATION AND FLUX THROUGH TIME.** By studying the IDP population of well-dated ice, workers can examine extraterrestrial samples from a particular period in the past. This development presents the possibility of studying the particulate products of specific cometary or asteroidal events. For example, Ganapathy [8] has found the products of the Tunguska event in an ice core taken at the South Pole.

By extending these preliminary studies to a greatly increased number of dated ice horizons, it should become possible to determine the relative and absolute flux of various IDP types, and provide the potential of searching for differences in the IDP population and flux with time [9]. Some workers have already begun to exploit this field. Eberhardt and Eberhardt [10] have determined noble gas isotopic concentrations of dust extracted from firn at the South Pole, and used these values to determine the extraterrestrial dust concentration of ice. Through future efforts to normalize this concentration to values of the absolute IDP flux, this technique could become a simple procedure for the determination of the IDP flux as witnessed by the accumulating ice of different eras. These values could then be compared with the modern IDP flux, currently being measured at the South Pole by Witkowski, Cassidy and co-workers [11], on the antarctic ice shelf by Thiel and co-workers [12], and globally by Zolensky and co-workers [7].

**METEORITE ABLATION SPHERES.** Finally, there have also been several studies of meteorite ablation spheres recovered from antarctic ice, as reviewed briefly by Koeberl and co-workers [13]. The flux of meteorite ablation spheres should follow the flux of meteorites, and so could potentially be an important indicator of changes in the latter (see Zolensky and Wells, this volume). Since meteorite ablation spheres are easily recognizable and magnetically separable from other dust, measurements of the concentration of meteorite ablation spheres within well-dated ice potentially could provide a simple technique for following potential variations in the global meteorite fall rate.

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