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MICROSCOPIC EXTRATERRESTRIAL PARTICLES FROM THE ANTARCTIC PENINSULA TRAVERSE

by

Richard A. Schmidt

RESEARCH REPORT SERIES 63-3 - JULY, 1963

6021 South Highland Road
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Research Report Series
Number 63-3
July 1963

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ABSTRACT

Microscopic extraterrestrial particles were recovered from meltwater of snow core samples collected as a part of American oversnow traverse operations in the Antarctic Peninsula region of the Antarctic ice cap during the austral summer of 1961-62. While several types of particles were recognized, black, metallic spherules and yellowish glassy spherules were most common. The metallic spherules ranged from 10 to 170 microns in diameter, had physical properties similar to magnetite, and were iron-rich. The surfaces of some metallic spherules were pitted, apparently from impact of smaller, nanometeorites. Others had ridged and furrowed surfaces which gave an intersecting, lamellar pattern. The glassy spherules ranged from 10 to 300 microns in diameter, had physical properties similar to lechatelierite or tektites, and were silica-rich.

Both metallic and glassy spherules occurred at each station sampled, although in differing amounts which could not be correlated with annual snow layers. This was partially caused by the influence of snow accumulation and local and regional topography upon spherule occurrence. Direct relations of frequency of spherule occurrence and annual snow deposition were shown by most stations, while an inverse relation between snow accumulation and mean spherule size was discovered. Exceptions to these relations were attributable to local and regional topographical effects.

The cumulative rate of deposition of metallic spherules was found to be essentially constant for the area of the Antarctic Peninsula Traverse, although values for individual stations were divergent because of local factors. The annual mass deposition of these particles over the entire surface of the earth was about 1 x 10^5 metric tons. This area gave lower values for mass deposit than stations located at higher geomagnetic latitudes, suggesting the presence of a possible magnetic influence upon particle deposition.

Cratered surfaces of metallic micrometeorites suggest that they travelled with slow velocities and were gravitationally captured into the earth's dust cloud, where impacts of smaller particles could have etched their surfaces. Preservation of the fine details would be possible with low entry velocities and low angles of incidence with the atmosphere, preventing surface melting. Fast moving particles would experience surface melting, producing the fewer, polished spherules observed.

The deposition value for metallic spherules agreed well with other estimates and with those for the total deposit of all particulate matter

on earth as indicated by satellite measurements of the dust cloud. Under the principle of uniformitarianism, the observed accretion of micrometeorites may represent a modern, scaled-down continuation of the process by which the planets were formed.

TABLE OF CONTENTS

Page

PREFACE ix

INTRODUCTION 1

SAMPLES 1

APPARATUS 4
    Dust-free Box 4
    Melting Apparatus 4
    Filters 6

PROCEDURE 6

RESULTS 9
    Description of Particles 9
    Size 28
    Physical Properties 33
    Chemical Composition 40
    Occurrence 40
    Annual Deposit 50

DISCUSSION 59

REFERENCES CITED 63

LIST OF ILLUSTRATIONS

Page

Figure 1. Map of Antarctic Peninsula Traverse, showing sites sampled 3

Figure 2. Dust-free box 5

Figure 3. Melting apparatus 7

Figure 4. Cumulative percentage of metallic spherules, Antarctic Peninsula Traverse 31

Figure 5. Cumulative percentage of metallic spherules, comparison with previous studies 32

Figure 6. Cumulative percentage of glassy spherules 36

Figure 7. Mean diameter of metallic spherules as related to snow accumulation 45

Figure 8. Frequency of spherule occurrence as related to snow accumulation 46

Figure 9. Average number of metallic spherules per liter of meltwater 48

Figure 10. Relation of annual deposit to snow accumulation . . 54

Figure 11. Contours of surface elevation and snow accumulation 56

Figure 12. Rate of spherule deposition, Antarctic Peninsula Traverse 57

TABLES

Page

Table 1. Locations of stations 2
Table 2. Comprehensive classification of microscopic extraterrestrial particles 10
Table 3. Particle types, Antarctic Peninsula Traverse 11
Table 4. Size distribution, metallic spherules 29
Table 5. Size distribution, glassy spherules 34
Table 6. Physical properties of metallic spherules 38
Table 7. Physical properties of glassy spherules 39
Table 8. Chemical composition 41
Table 9. Annual snow accumulation 43
Table 10. Annual occurrence of metallic spherules 47
Table 11. Comparison of data for metallic spherules from the several stations sampled 51
Table 12. Mean annual mass deposit of metallic spherules . . . 52
Table 13. Annual deposit of metallic spherules on the earth's surface 53

PLATES

Page

Plate 1. Black, metallic spherules 14
Plate 2. Black, metallic spherules 16
Plate 3. Metallic particles of several types 18
Plate 4. Optical micrograph of a Type II metallic spherule . . 20
Plate 5. Electron micrograph of a Type II metallic spherule . 22
Plate 6. Electron micrograph of a Type III metallic spherule . 24
Plate 7. Glassy spherules 26

PREFACE

As a peripheral study during the 1959-1960 air-supported geophysical program in Antarctica, the late Dr. Edward C. Thiel recovered microscopic extraterrestrial particles from the meltwater of snow core samples. This method of particle collection offered many advantages over the methods used previously, because the age of snow at depth could be determined from glaciological studies and because industrial contamination in Antarctica could be considered negligible. The writer was introduced to this research by Dr. Thiel, who invited him to participate in examination of the original samples, and offered to assist in conducting continued investigations.

Following the successful pilot study, the writer, in collaboration with Dr. Thiel and Professor George P. Woollard, formulated a large-scale program for the study of microscopic extraterrestrial particles occurring in the Antarctic ice cap. This work was designed to obtain snow samples for particulate study from wide areas of Antarctica in connection with oversnow traverse expeditions.

The project began with the 1961-1962 oversnow traverse in the Antarctic Peninsula region. Snow core samples were obtained during normal traverse operations through the efforts of Mr. Hiromu Shimizu, glaciologist from Ohio State University, and Dr. John C. Behrendt, traverse leader from the University of Wisconsin. Their interest and cooperation in obtaining material for this work made the present study possible.

Although the project will continue in connection with traverse operations for several years, enough data have been obtained to provide better insight into the nature of microscopic extraterrestrial particles and their occurrence on the Antarctic ice cap, and on the earth as a whole. This report describes the first of a series of such investigations.

Many people have contributed to the success of this project, and it is with gratitude and thanks that their assistance is acknowledged.

The electron micrographs of spherules were made by Mr. K. V. Venkataraman and Dr. M. L. Jackson of the Department of Soil Science at the University of Wisconsin. These men deserve much credit for perfecting techniques by which individual spherules were prepared for study. The work was conducted in the electron microscope laboratory of Dr. Paul Kaesberg, Department of Biochemistry at the University of Wisconsin.

Density measurements were made in cooperation with Dr. Larry Haskin and Dr. W. E. Vaughan of the Department of Chemistry, University of Wisconsin. Their ingenuity in devising apparatus, skill in laboratory techniques, and patience in conducting the experiments were responsible in large measure for obtaining these data.

Optical properties of spherules were studied using instruments and laboratory facilities at the Department of Geology, University of Wisconsin. Dr. R. C. Emmons made available equipment and supplies needed

to study glassy spherules, and his helpful suggestions enabled the task to be more readily done. Dr. E. N. Cameron provided the instruments necessary for study of the optical properties of metallic spherules.

Electron probe analyses of spherules were conducted with the assistance and cooperation of Dr. Frances W. Wright of the Smithsonian Astrophysical Observatory, Dr. E. C. T. Chao of the U. S. Geological Survey, and Dr. J. V. Smith of the University of Chicago. The writer is deeply grateful for their good wishes, thoughtful comments, and unstinting effort in this task.

The entire staff at the Geophysical and Polar Research Center rendered invaluable assistance to this project. Their stimulating comments, useful suggestions, and constructive criticisms made significant contributions to the study and its results. The secretaries, in particular, deserve much credit for deciphering my handwriting, correcting my spelling, and typing several rough drafts and the final copy.

In closing, it is an honor to acknowledge the encouragement given the writer by Professor George P. Woollard. Truly, this paper and the larger research effort which it heralds were made possible by his interest and support.

This project was supported by a grant from the National Science Foundation.

Introduction

It has been known for many years that microscopic extraterrestrial particles occur in the snows of polar regions. As early as 1870, Nordenskiold discovered nickel-iron dust on the Greenland ice cap. He referred to this material as cryoconite ("ice-dust"), and suggested that the metallic particles might be of extraterrestrial origin. More recent studies of extraterrestrial particles from polar regions were undertaken, as suggested by Nininger (1952), to eliminate obvious sources of terrestrial and industrial contamination.

The onset of modern, large-scale expeditions to Antarctica during the International Geophysical Year opened the interior of the Antarctic ice cap to scientific investigation. During this period, the first collections of micrometeorites from Antarctic snows were made by Nishibori and Ishizaki (1959). This was followed by an independent pilot study by Thiel and Schmidt (1961) and by a study by Mrkos (1962). Each of these examinations were valuable because they clearly demonstrated that micrometeorites could be successfully recovered from Antarctic snows. However, each study employed different methods in collecting and studying particles from isolated localities, and it was not possible to compare data from the different areas to obtain areal representation of particle occurrence. To do this, a systematically collected series of representative samples from a regional area is necessary. In attacking this problem, snow core samples are now taken at regular intervals along the route of U. S. oversnow traverses in Antarctica.

This chapter describes the results of study of particulate matter recovered from snow cores obtained during the Antarctic Peninsula Traverse, 1961-1962. Although the project will continue in connection with future traverse operations, enough data have been obtained to provide better insight into the nature of microscopic extraterrestrial particles and their occurrence on the Antarctic ice cap. This report describes the first of a series of such investigations.

Samples

Snow cores 7.6 centimeters in diameter and 10 meters deep were recovered using a standard SIPRE coring auger from eleven stations along the route of the Antarctic Peninsula Traverse. The locations of these stations are given in Table 1 and are shown in Figure 1. At eight of the eleven stations, core samples were taken adjacent to shallow pits in which glaciological examinations of snow accumulation were conducted to provide an independent estimate of the age of the material recovered from each core.

TABLE 1

Locations of Stations
(Behrendt, Personal Communication, 1962)

Station	Latitude	Longitude
224	74°14'S	84°46'W
320	74°03'S	80°32'W
464	74°56'S	76°01'W
496	74°52'S	71°28'W
572	74°50'S	71°43'W
636	74°16'S	70°10'W
700	73°33'S	68°38'W
764	74°04'S	66°35'W
840	74°58'S	68°12'W
940	75°27'S	72°21'W
1008	75°22'S	74°56'W

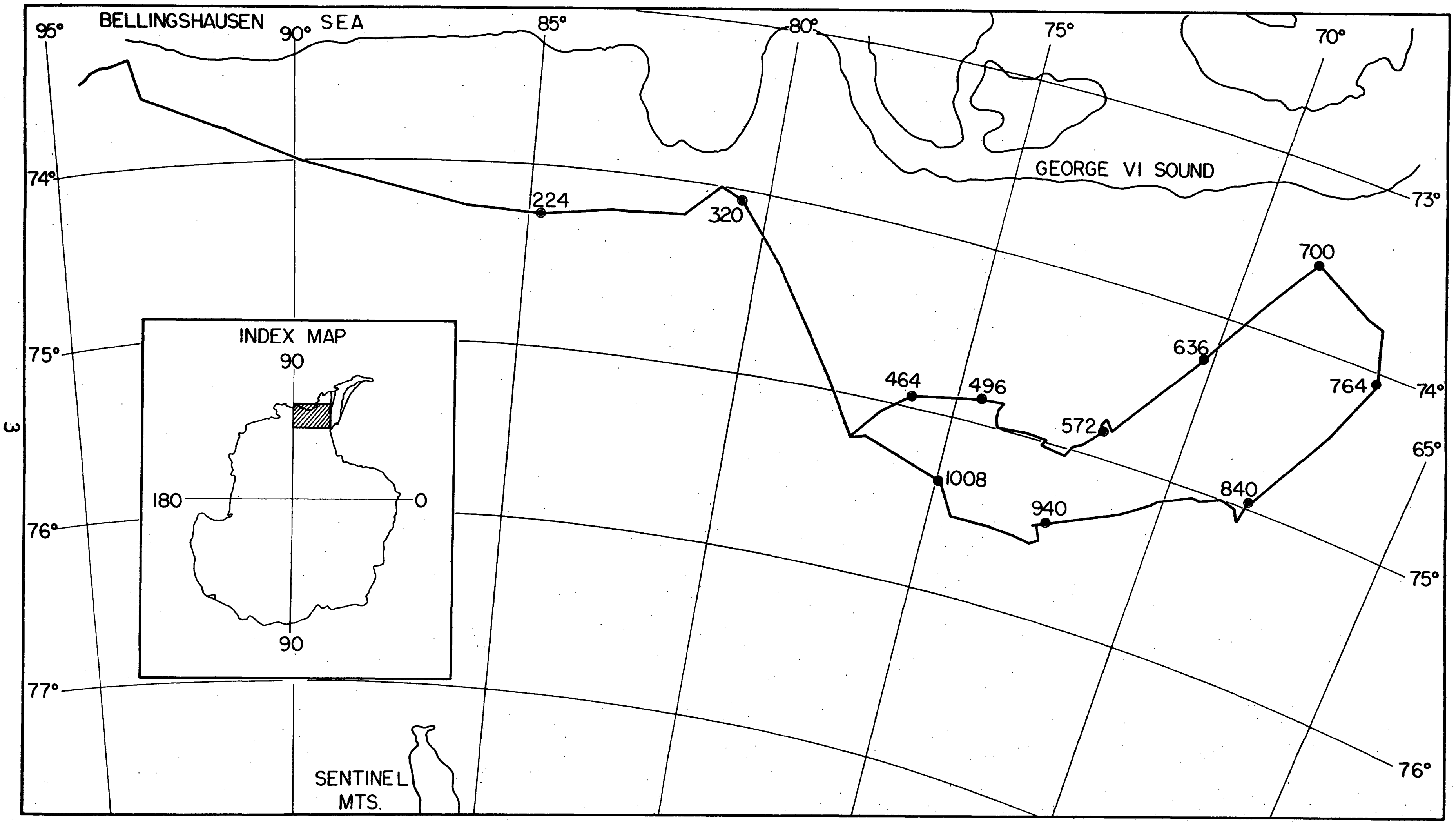

Figure 1. Map of Antarctic Peninsula Traverse, showing sites sampled for this project. (After Behrendt, 1963).

The core sections were placed in meter-long, aluminized cardboard tubes built especially for this purpose. While on the traverse, all cores were stored in a special refrigerator towed behind one of the vehicles in order to guard against recrystallization of the snow by solar radiation. Upon completion of the traverse, the cores were shipped by refrigerated carrier to the United States and then to our Laboratory at the Geophysical and Polar Research Center, where they were held under cold storage until processed. Shipment of snow cores rather than residues prepared from them was done to prevent fragmentation of fragile particles, discovered during the pilot study (Thiel and Schmidt, 1961). While a few sections of core apparently suffered minor recrystallization during shipment, this did not effect their value for particulate study. Considering the great distances over which they were transported, all core sections arrived in remarkably good condition.

Apparatus

Processing the snow cores posed several problems, one of the most serious being elimination of contamination from local sources. Apparatus employed to control contamination is described in this section.

Dust-Free Box

To guard against contamination of the samples by ordinary room dust or by particles of industrial origin, the entire processing operation was carried out in a dust-free enclosure designed and constructed especially for this project. The enclosure was a large plywood box, sealed inside and out to prevent flaking of the wood and introduction of foreign matter along joints. A positive pressure of filtered air was maintained in the box by high-speed fans at all times during sample processing. This was done as a safe-guard against airborne contamination. All air entering the enclosure was filtered by special, high-efficiency filters. As a further precaution, monitors were deployed throughout the box at the start of each processing sequence. These were subsequently scrutinized to determine the amounts and character of any particles found in the enclosure. Only very small amounts of particulate matter were observed on the monitors. Furthermore, this material was distinctly different from that recovered from the snow core meltwater. It would appear that the enclosure was successful in excluding contamination from local sources.

Access to the interior of the box during processing was provided by an air-lock enclosure. Equipment was manipulated by means of rubber gloves installed through ports cut in the front panel of the box. These items were also shown in Figure 2.

Melting Apparatus

In the pilot study, each snow sample was melted in a separate container, the meltwater transferred to another container, and then filtered. Contamination could be introduced during each of these several steps.

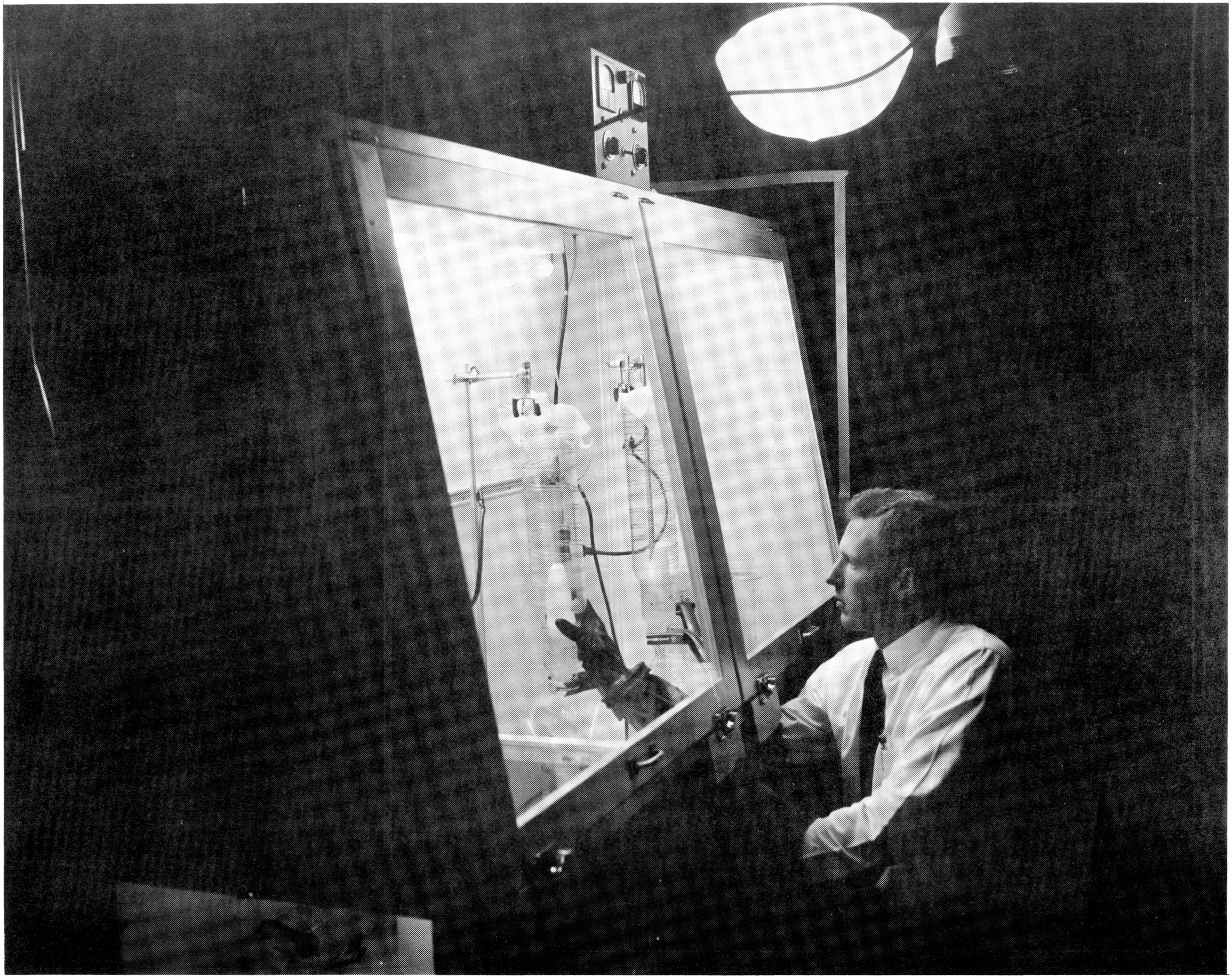

Figure 2. Dust-free box. Access to its interior is demonstrated by the writer.

Furthermore, each handling of the sample and meltwater provided an opportunity for spillage and sample loss. The processing procedure followed in the present work eliminated any transfer of samples.

The apparatus used to melt snow core sections was shown in Figure 3. It consisted of a standard laboratory filtering apparatus manufactured by the Millipore Filter Corporation, and an electrically heated pyrex "melting tube" with its power supply. Both the latter items were designed and built especially for this project. The power supply, shown on the left in Figure 3, provided electrical current for the melting tube, providing the thermal energy necessary for controlled melting of the snow core samples.

Filters

The meltwater resulting from each core section was passed through a high-efficiency cellulose membrane filter. This retained all particles larger than 0.5 micron in diameter. The filters were placed in sterile, plastic Petri dishes for storage prior to subsequent microscopic examination of the residue.

Procedure

While held under cold storage, the snow cores were removed from their shipping tubes and placed in a specially built, plastic lined miter box. The surface of the cores was carefully scraped to remove any foreign matter which might have been introduced during sample recovery or during shipment. Although cores were taken with a standard aluminum SIPRE auger, study of the residues suggested that wear on the auger contributed a negligible amount of contamination.

Care must be used in placing snow cores in the shipping tubes, for these as they are delivered from the factory frequently contained shavings and other foreign material. Some of the uncovered core sections displayed scattered pieces of shavings due to contamination from the tubes, but these were easily removed by light scraping of the surface. In these cases, about half a centimeter of snow was scraped from the surfaces of cores. This practice effectively removed the shavings. There was no reason to doubt the source of contamination, and the shavings were unlike anything found in the particulate matter of the cores.

It is possible that such contaminants as shavings could have penetrated to the interior of cores along pores and voids, so that scraping would not remove them. Shavings were not recognized in the residues however, and it seems unlikely that they permeated the cores. This may have been a result of precautions taken to prevent recrystallization of snow both on the traverse and during shipment.

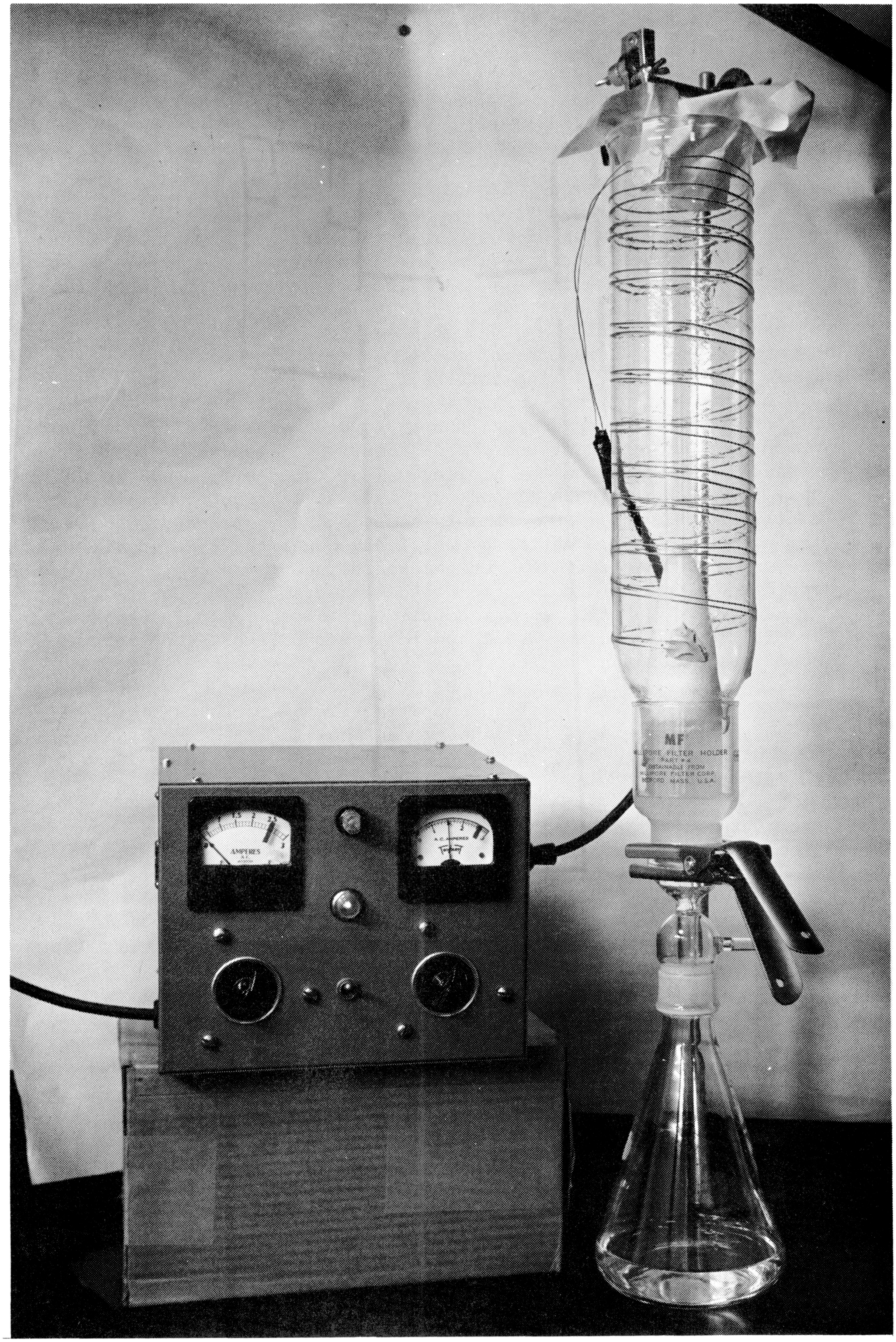

Figure 3. Melting Apparatus. Left, power supply. Right, melting tube and filter assembly.

The question of contamination has been examined from another angle. Dr. Lucy M. Cranwell (personal communication, 1962) melted and filtered a snow core from the Antarctic Peninsula Traverse (Station 668) to study contained pollen grains. She reported that the bulk of the organic matter was clearly derived from the northern hemisphere, and that she recognized no pollen grains of southern hemisphere types. It would appear that northern hemisphere pollen was introduced to the sample tubes along with shavings at the factory. Analyses of shavings from tubes is now in progress to investigate this further. This is extremely unfortunate, for pollen research could be a valuable adjunct to particulate studies. It is possible, of course, that severe contamination of the snow samples could have occurred during shipment, handling and processing in the northern hemisphere, but the writer regards this as improbable. At all times during shipment and handling, the snow cores were kept in their tubes, which in turn were kept under refrigeration. Even when freezer doors were opened, blower fans on the cooling units forced air out of the freezer, away from the samples. It does not seem likely that contamination could easily enter freezer compartments under such conditions. Should the contamination, in spite of the blower fans, enter the freezer, it would still have to penetrate the 1/8 inch cardboard tube (coated with aluminum foil inside and out) in order to reach the snow samples. This is more unlikely. Processing of the samples was carried out under controlled conditions in special low-dust rooms, and it would appear unlikely that contamination would come from that source.

In spite of the apparent contamination by northern hemisphere pollen, Dr. Cranwell considers the mineral particulate matter to have some value. Nothing similar to this material was observed in shipping tubes fresh from the factory.

After logging a description of the samples, they were cut into sections approximately 25 centimeters long. This length, one-quarter of the amount of snow contained in each tube, was arbitrarily selected as a convenient working size. The dimensions of each section were then carefully measured, and the section weighed. Inserted in a melting tube, the core section was then removed to the dust-free box, placed on the filter apparatus, and connected to the power supply. The meltwater passed downward through the filter, which collected the particulate matter. A flask at the base of the filtering apparatus retained the meltwater, whose volume was measured carefully. This was used in connection with other glaciological data to provide an estimate of the age of the samples. Most core sections were found to represent from one-quarter to one-third of a year by this method. The short span of time each section represented provided good control for the estimate of annual accretion of particles in this area.

The filtered meltwater was then carefully transferred to a sterile, polyethylene bottle for storage prior to subsequent analyses for trace element composition, density, radioactivity, and oxygen isotope ratios. This work will be the subject of a later paper. The present report is limited to presentation of the results of particulate studies.

Results

The residue obtained from each core section was examined under oblique illumination at 100X magnification using a Bausch and Lomb zoom-type binocular microscope. A mechanical stage was employed to manipulate the residues during study. At this time, particles were individually measured, identified, described, photographed, and selected for subsequent chemical and physical analyses.

A total of 1090 particles, representing six of the eight major particle classes listed in Table 2, were recognized and individually examined in the meltwater residues. Numbers of particles in each class were given in Table 3. It can be seen from this table that black, metallic spherules made up 65% of the total, while glassy spherules comprised about 29% of the total. These percentages agree remarkably well with those found by Buddhue (1950): metallic spherules, 69%; silicate spherules, 29%. However, both sets of values are in sharp disagreement with the abundances of macroscopic metallic and stony meteorites (6% and 94% respectively). The writer attributes this disagreement to excessively conservative identification practices for siliceous particles.

Meteoritic particles formed only a small part of the total residue. In an effort to concentrate on particles of extraterrestrial origin, the rule of thumb "when in doubt, throw it out" was rigidly observed during examination of the residues. Primary attention was devoted to spherical particles, because this form is rarely produced by ordinary terrestrial geological processes. Metallic spherules were identified with a high degree of certainty by means of criteria established through the results of previous studies (Schmidt, 1963). These criteria include (1) presence of smoothed surfaces, (2) presence of depressions (cupules) with distinct outlines on the surfaces of the spherules, (3) magnetic properties, (4) high specific gravity, and (5) high reflectivity. The metallic spherules satisfied these requirements and were readily recognized. Unfortunately, no set of criteria existed for identification of glassy or stony particles. To preclude the possibility that siliceous particles of terrestrial volcanic origin might be incorrectly assigned to an extraterrestrial source, only spherical, glassy particles were considered in this work. The basis for this requirement was Buddhue's (1950) discovery that volcanic dust consisted of "minute angular grains," and did not contain spherules. This precaution, coupled with doubt about the nature of any particle, probably caused an unknown number of cosmic, siliceous particles to be overlooked. It seems reasonable to suspect that sub-rounded to sub-angular shapes may be represented by siliceous extraterrestrial particles. However, these can best be sought using the data of the glassy spherules as a guide.

Description of Particles

The several types of particles recognized in this study are separately described below.

Black, metallic spherules. These were the most readily recognizable type of particle in the residues. A total of 715 were identified. The

TABLE 2

Comprehensive Classification of Microscopic Extraterrestrial Particles (After Schmidt, 1963)

	Description	Size (microns)
1.	Black, magnetic spherules with or without metallic nuclei	200
	a. Black, smooth, highly polished perfect spheres	20-200
	b. Black, smooth spheres of <u>COSMIC DUST</u>	0.01-1
	c. Shiny, black, hollow spheres with or without vase-like neck	100-500
	d. Larger black spheres with less luster, often roughened or pitted, light metallic gray color	100
2.	Mammillated particles, black and opaque clusters of minute spheres	100-200
	a. Mottled black, steel gray, faceted intergrown	100
3.	Silicate spheres which are white, gray, yellowish, brown, and sometimes black. Some transparent, usually with bubbles and dark inclusions (magnetite or metallic iron)	70-500
	a. Hybrid spherules: part semi-transparent glass, part metallic	20-100
4.	Irregular, angular fragments	100-200
	a. Irregular fragments of <u>COSMIC DUST</u>	0.1-1
	b. Stony spherules	15-500
5.	Scoriaceous or cindery particles	100
	a. Reniform, slag-like grayish to greyish brown particles	100-200
6.	Fibrous particles	100-200
7.	Metallic particles with amorphous (organic?) coatings (<u>METEORIC DUST</u>)	70x400
8.	Fluffy particles of <u>COSMIC DUST</u>	0.1-1

TABLE 3

Particle Types, Antarctic Peninsula Traverse, 1961-1962

Particle Type	Amount
1. Black, metallic spherules	715
2. Mammillated, metallic spherules	17
3. Glassy spherules	319
4. Irregular, angular fragments	6
5. Scoriaceous or cindery particles	25
6. Fibrous particles	n.o.*
7. Coated particles	8
8. Fluffy particles	n.o.*
TOTAL:	1090

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*n.o. = not observed

particles have been well named, because rarely does one depart from a perfectly spherical shape. Representative spherules were illustrated in Plates 1, 2, and 3. Their size ranged from 10 microns to 170 microns. While spindle-shaped, (Plate 3, No. 1) and oval particles were observed, these were uncommon. Invariably opaque, the color of the spherules was most frequently black to dark gray. Only one lighter, steely-gray spherule was observed, and it was unfortunately lost during mounting. All the spherules had a metallic luster. The spherules were magnetic, being readily attracted to the tip of a magnetized needle. The degree of magnetism varied considerably, however. The hardness of the spherules was estimated to be about 5 on the Moh scale; they could be broken, but only by exerting active pressure on the needle. When broken, the metallic spherules presented a dull gray to gray-black appearance and an irregular, hackly fractive surface. Spherules tested in this way by the writer differed from those described by Langway (1963) in that they were not hollow.

The largest surface feature on the metallic spherules was a shallow, elliptical depression (cupule) first recognized by Murray (1883). Cupules resemble the effect produced by gently pressing one's thumb onto a ball of soft clay. Although the occurrence of cupules on spherules was far from rare, not all of them possessed this feature. Some examples were shown at low magnification in Plates 1, 2, and 3.

Subtle variations in fine surface texture were present on the metallic spherules, and three types of particles were recognized from surface features (Schmidt _et_ _al_., 1963).

Type I. Smooth, polished spherules with no apparent surface relief.

Type II. Spherules with lower luster, and an irregular, corrugated surface comprised of two patterns of linear "ridges" and "furrows" which intersected at approximately right angles.

Type III. Spherules with dull luster, and an apparent, randomly distributed myriad of minute, shallow, roughly circular, unconnected depressions or "pits."

Plate 4, an optical micrograph of the surface of a Type II spherule at 5000X magnification, illustrates this type of surface feature.

Detailed examination of the surface microtopography of spherules was done using an electron microscope. Plate 5 shows the surface of a replica made from a Type II spherule, magnified 80,000X. At this magnification, the plate is equivalent to visual examination of a portion of a sphere more than 3 meters in diameter. Linear features identical to those shown in Plate 4 can be observed. Similar lamellae were present in the interiors of spherules, as revealed by polished surfaces. It would appear that this feature is an integral part of the spherules, and that surface relief was produced by differential hardness of the mineralogical lamellae comprising the particles. Results of polished surface studies will be described in a later section of this paper.

Plate 6 shows part of the surface of a Type III spherule. The nearly circular, shallow pits 0.5 microns in diameter could have been produced through the impact in space of nanometeorites 0.01 micron in diameter (Hemenway et al., 1961) upon the surfaces of the larger spherules (Schmidt et al., 1963).

Mammillated Particles. Composed of a cluster of black, metallic spherules, this type of particle occurred rarely in the residues; only 17 were found. The appearance and description of individual spherules in each cluster were identical with that given above for the isolated spherules. Plate 3, No. 6 illustrated this type of particle, which ranged in size from 40 microns to 100 microns.

Glassy Spherules. A total of 319 glassy spherules were found in the residues. These probably represented only part of the siliceous component. Resembling a child's marble, the most distinctive feature about the glassy spherules was their translucence. In contrast to the metallic spherules which cast a dark shadow under oblique illumination, the glassy spherules permitted the light to pass through them and focussed it to a brilliant spot on the opposite side. Representative samples were illustrated in Plate 7. The glassy spherules ranged in size from 20 microns to 300 microns. Color of the glassy spherules varied considerably. Clear, yellow, tan, brown, green-gray, and smoky black spherules were observed, although yellow and clear particles were most common. The spherules had a vitreous luster, accentuated because of their smooth, highly polished surface. Only faint suggestions of detailed surface texture were present. These consisted of pits similar to those shown by the metallic spherules. No cupules were found on glassy spherules. Even with active pressure on a metal needle, it was seldom possible to break a glassy spherule; it would jump from view like a tiddly-wink. Some spherules appeared to be broken, however, and these possessed a smooth, conchoidal fracture. Hollow spheres such as shown in Plate 7, No. 4 could be broken more easily, but considerable pressure was still required. Again, a conchoidal fracture was produced. The glassy spherules were non-magnetic, although some contained minute, opaque inclusions. Internal strains as illustrated in Plate 7, No. 2 were shown by several glassy spherules.

Irregular Particles. Angular and irregular particles of varying composition were present in considerable numbers on the filters, but most of these did not satisfy the criteria listed earlier and were not considered further. Only 6 particles of non-terrestrial type were recognized. These were each metallic in appearance, and except for their irregular shape were similar to the black, magnetic spherules.

Cindery Particles. This type of particle was similarly uncommon on the filters, and only 25 were recognized. Sub-rounded in shape, these particles were black to dull gray in color, ranging from 20 microns to 70 microns in size. They were opaque, with a dull luster most closely akin to that of the pitted, metallic spherules. The surfaces of the cindery particles were pitted and irregular, as shown in Plate 3, No. 8.

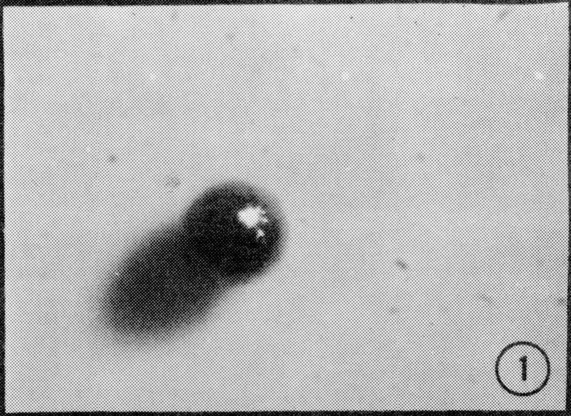
Coated Particles. These were found rarely on the filters, and only 8 were recognized. They had a black, metallic-appearing center surrounded by a frothy, yellowish coating which exhibited reniform shapes. Ranging

PLATE 1

Black Metallic Spherules

Magnification 200X

1. Metallic spherule with ridged and furrowed surface, station 496. Diameter 70μ.
2. Left, metallic spherule with ridged and furrowed surface, station 700. Diameter 20μ. Right, smooth metallic spherule, station 700. Diameter 30μ.
3. Metallic spherule with ridged and furrowed surface, station 636. Diameter 20μ. Note cupule (arrow).
4. Smooth metallic spherule, station 464. Diameter 30μ. Note cupule (arrow).
5. Metallic spherule with ridged and furrowed surface, station 764. Diameter 40μ.
6. Smooth metallic spherule, station 572. Diameter 40μ. Note cupule (arrow).
7. Metallic spherule with ridged and furrowed surface, station 1008. Diameter 60μ.
8. Smooth, polished metallic spherule, station 840. Diameter 50μ.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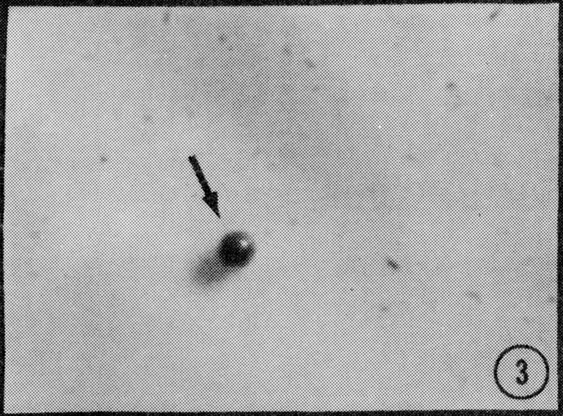
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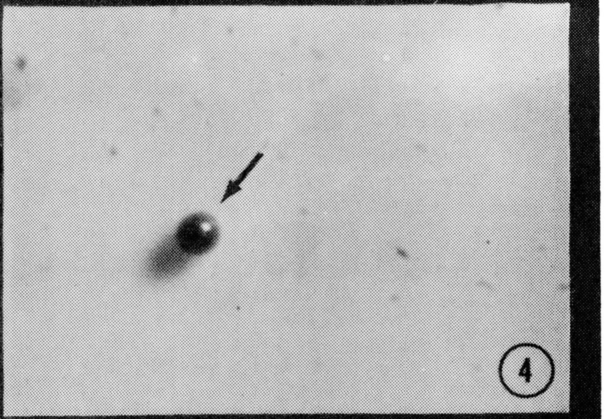
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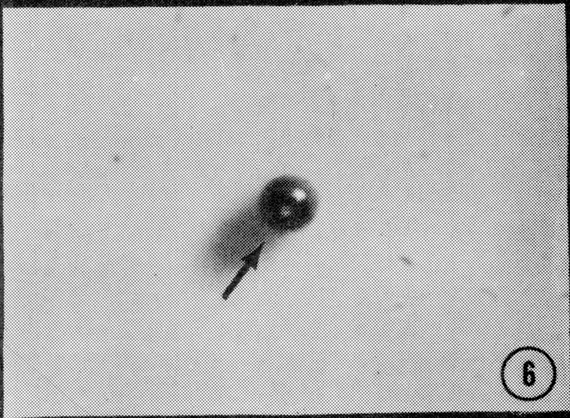
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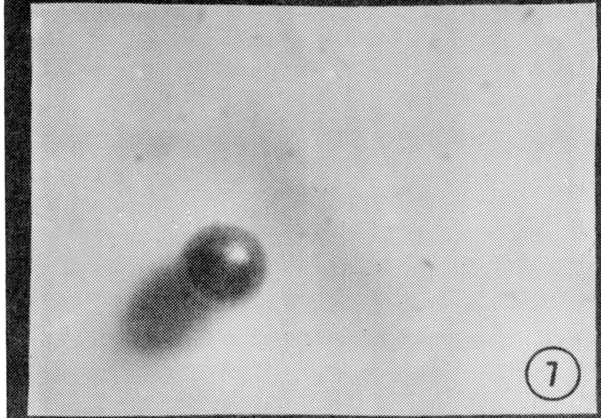
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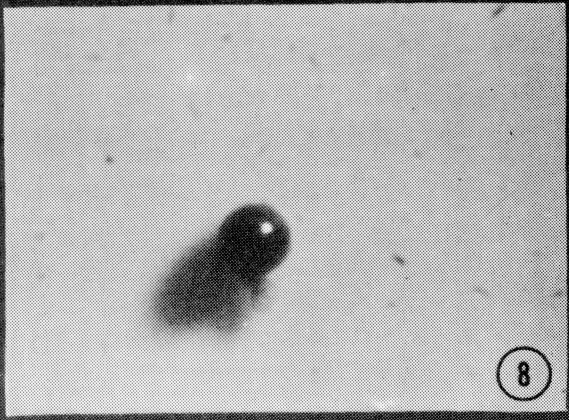
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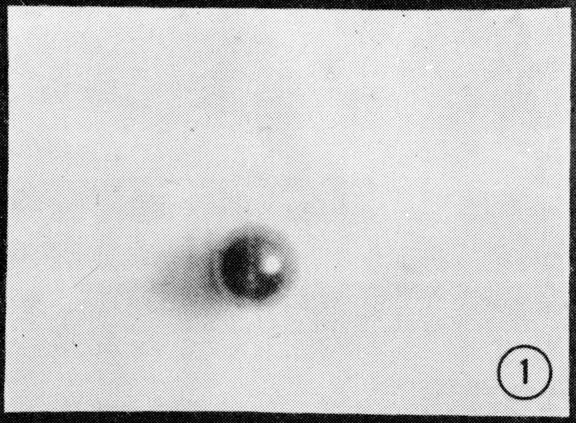
PLATE 2

Black Metallic Spherules

Magnification 200X

1. Metallic spherule with polished surface, station 572. Diameter 120μ (100X).
2. Smooth metallic spherule, station 940. Diameter 30μ.
3. Metallic spherule with ridged and furrowed surface, station 636. Diameter 40μ. Note cupule (arrow).
4. Smooth metallic spherule, station 320. Diameter 30μ.
5. Smooth metallic spherule, station 700. Diameter 40μ.
6. Metallic spherule with ridged and furrowed surface, station 464. Diameter 40μ.
7. Smooth metallic spherule, station 572. Diameter 100μ. (100X).
8. Metallic spherule with ridged and furrowed surface, station 840. Diameter 20μ.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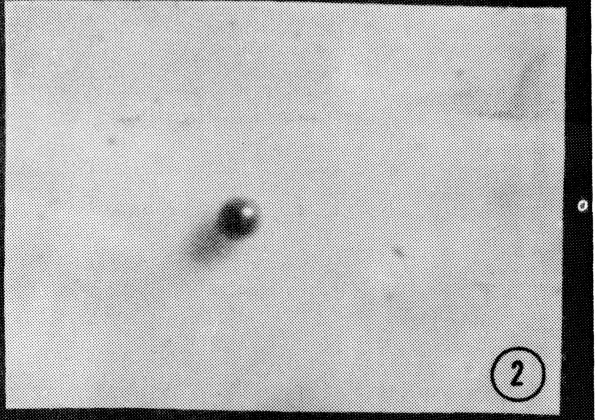
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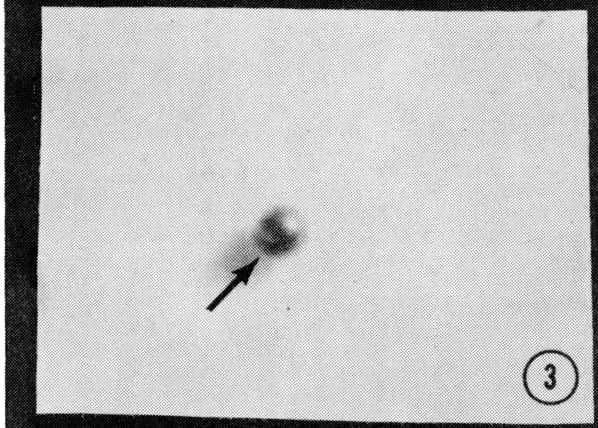
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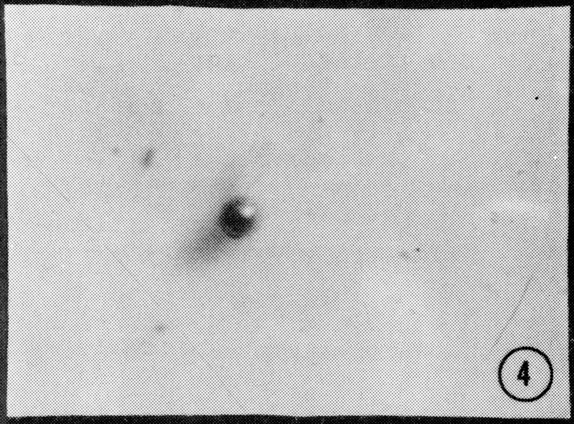
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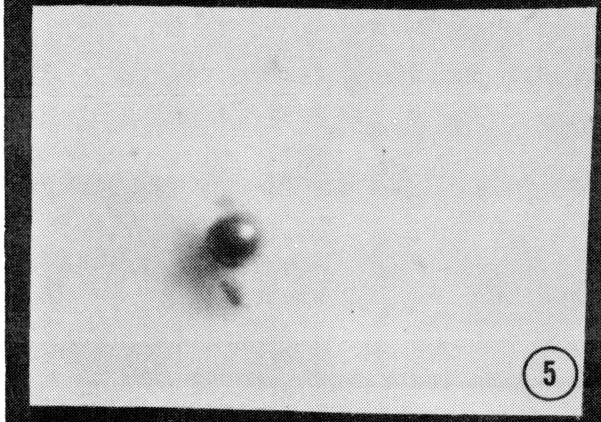
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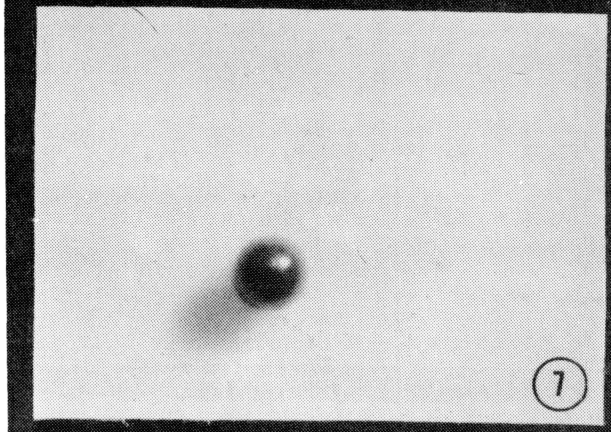
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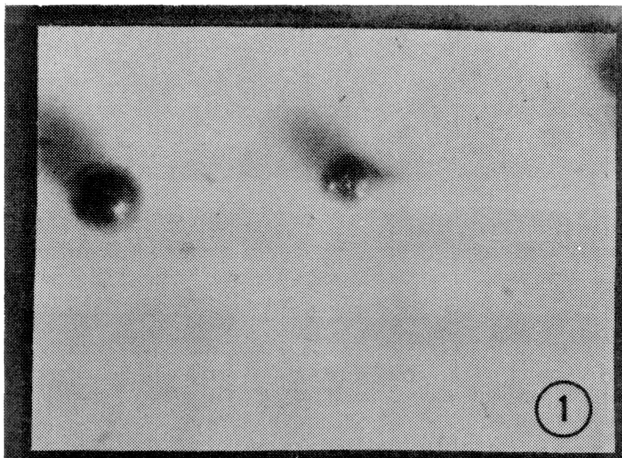
PLATE 3

Metallic Particles of Several Types

Magnification 200X

1. Left, metallic spherule with mottled surface, station 572. Diameter 50μ. Right, spindle-shaped metallic particle, same station, diameter 40μ.
2. Smooth, polished metallic spherule, station 496. Diameter 30μ.
3. Smooth, polished metallic spherule, station 764. Diameter 40μ. Note cupule (arrow).
4. Smooth metallic spherule, station 224. Diameter 30μ. Note cupule (arrow).
5. Pitted metallic spherule, station 1008. Diameter 30μ. Note cupule (arrow).
6. Mammillary particle, consisting of 60μ and 40μ pitted metallic spherules, station 840.
7. Smooth metallic spherule, station 700. Diameter 40μ.
8. Left, metallic spherule with ridged and furrowed surface, station 572. Diameter 30μ. Note cupule (arrow). Right, cindery metallic particle with irregular surface, station 572. Diameter 70μ.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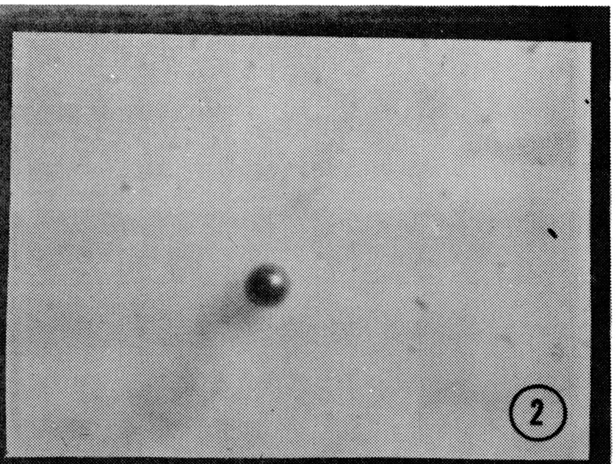
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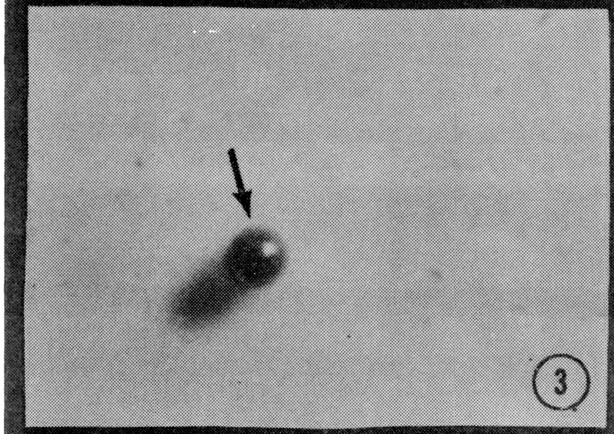
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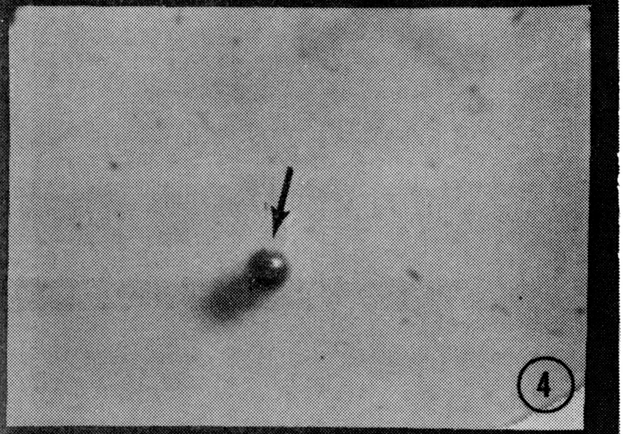
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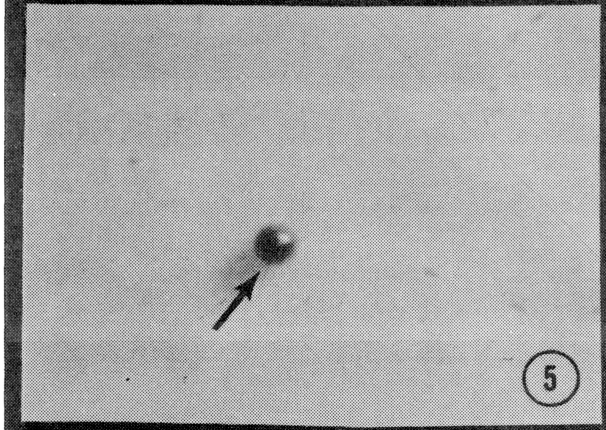
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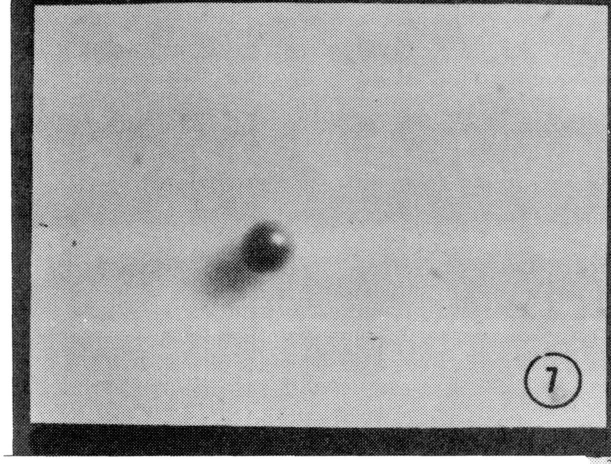
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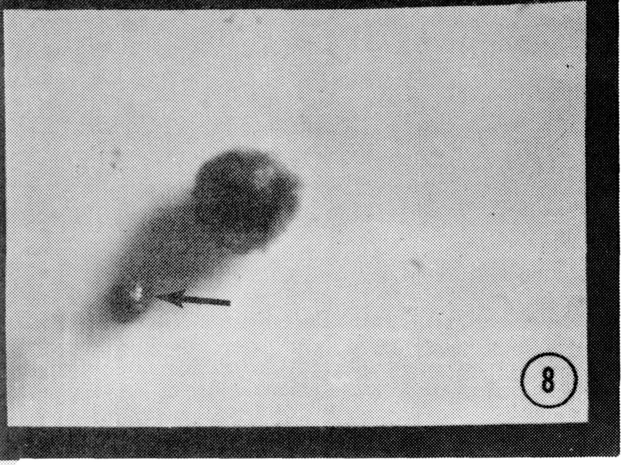
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PLATE 4

Optical micrograph of a Type II metallic spherule from Station 496, Antarctic Peninsula Traverse. Magnified 5,000X

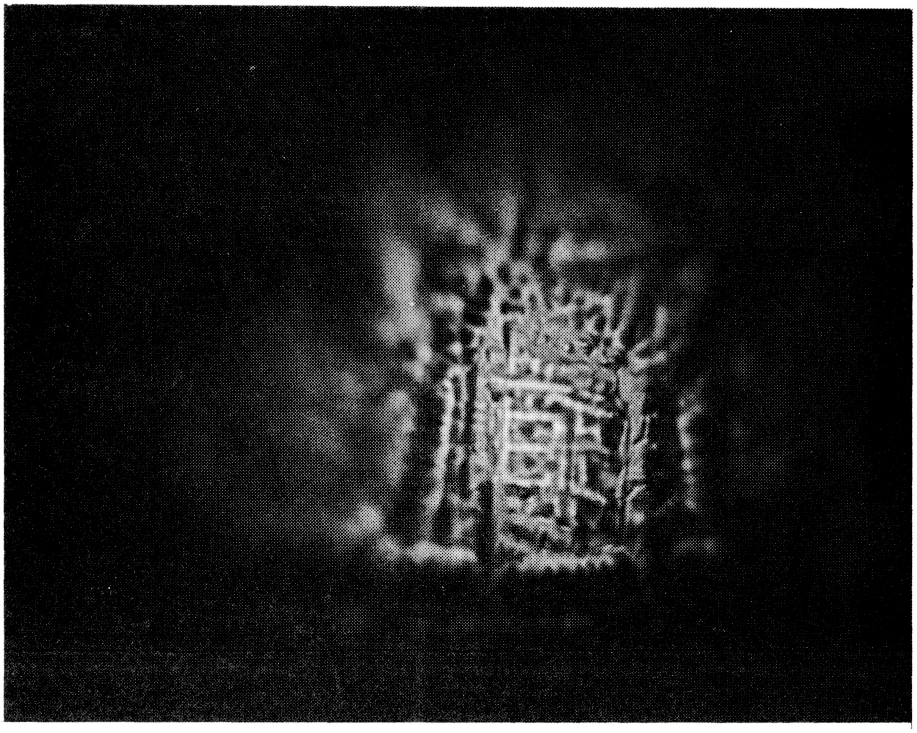


PLATE 5

Electron micrograph of Type II metallic spherule from Station 464, Antarctic Peninsula Traverse. Magnified 80,000X

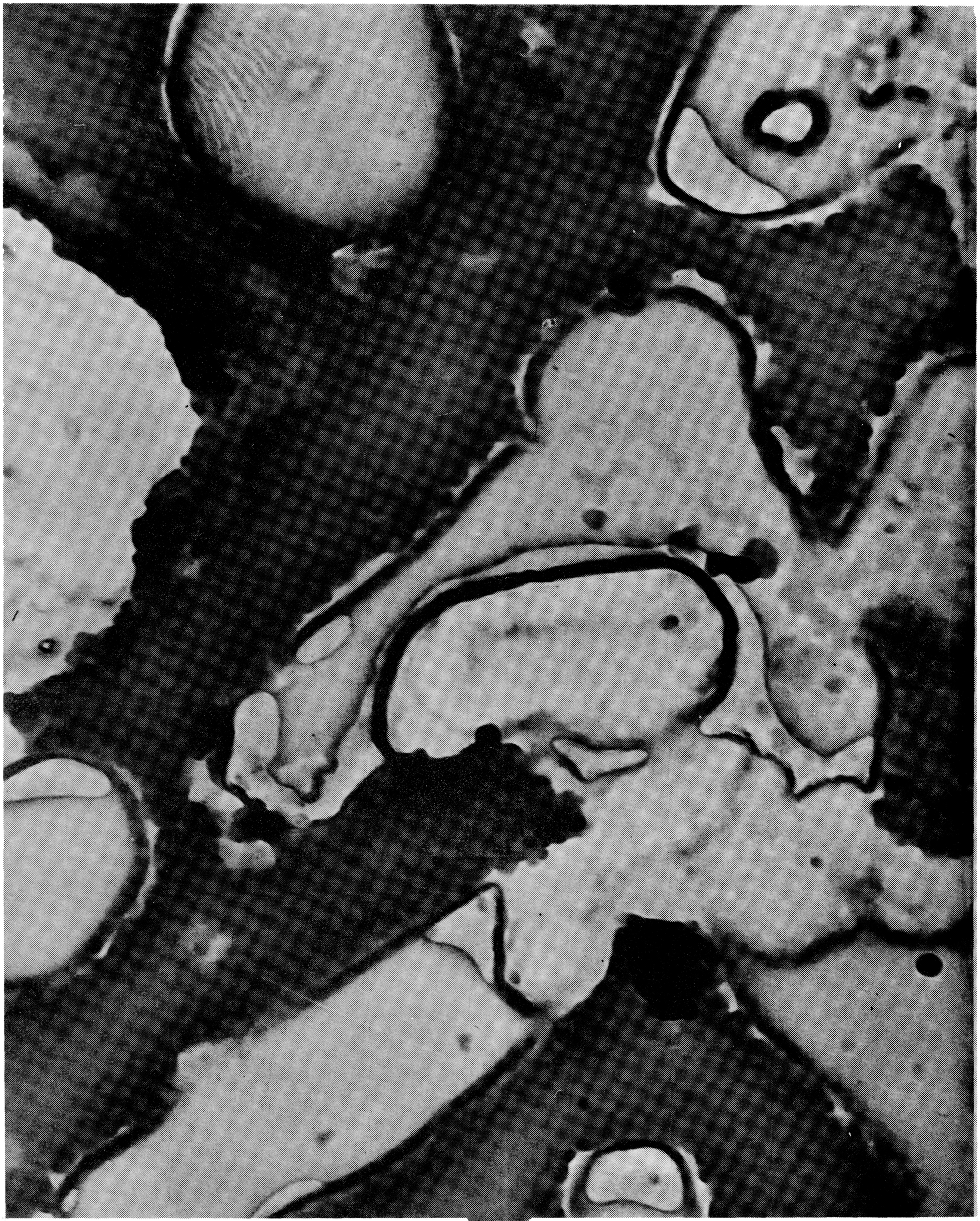


PLATE 6

Electron micrograph of Type III metallic spherule from Station 224, Antarctic Peninsula Traverse. Magnified 80,000X

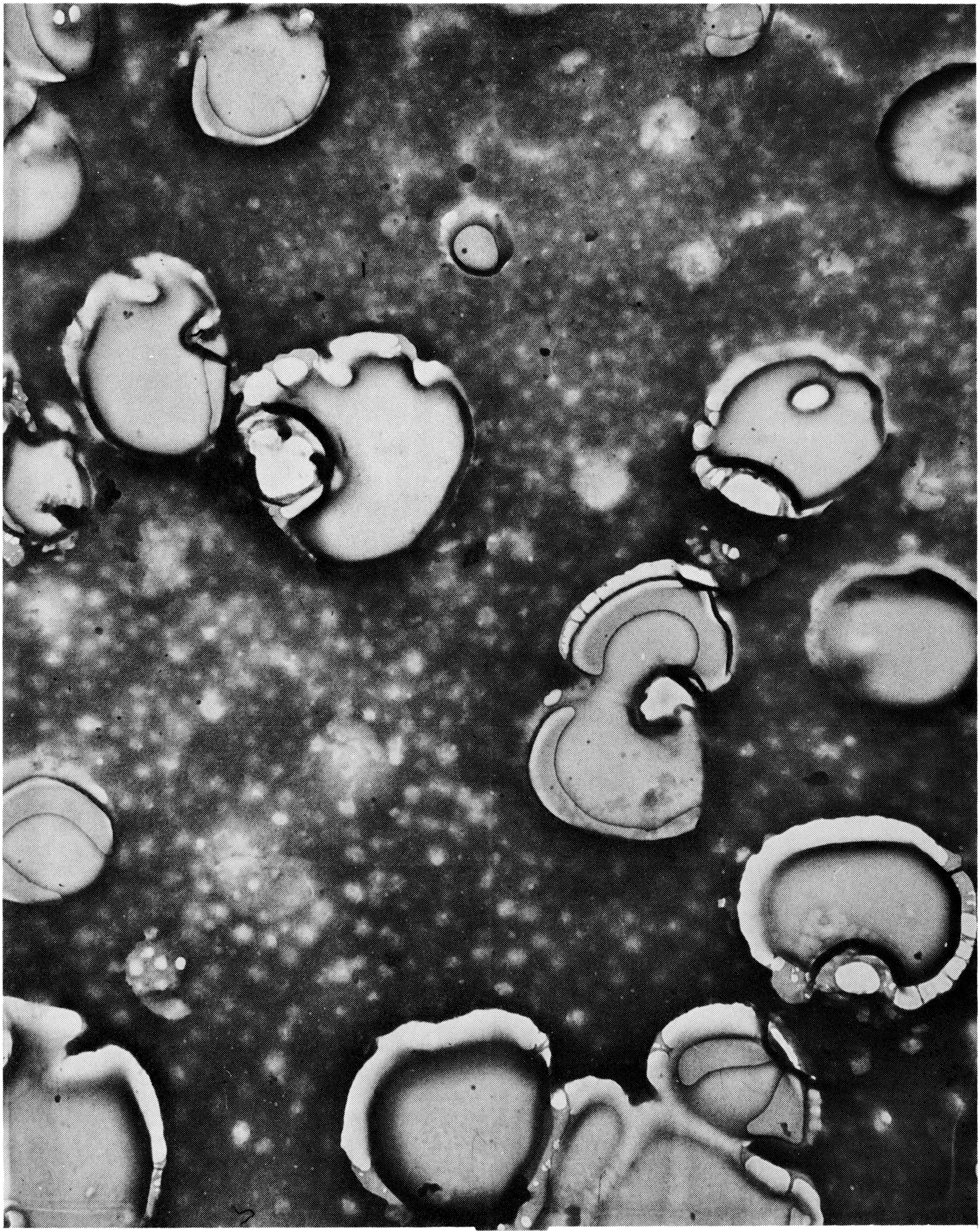
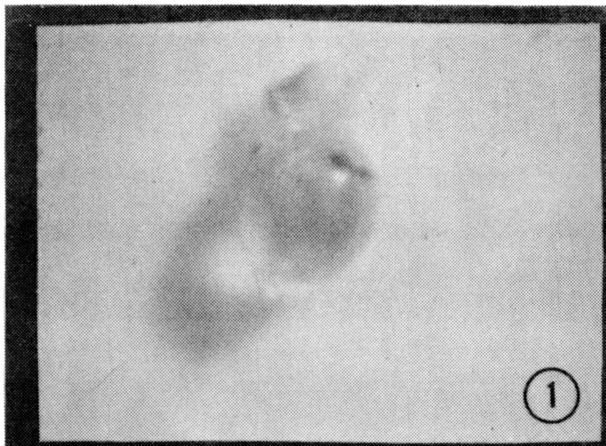


PLATE 7

Glassy Spherules

Magnification 200X

1. Light yellow glassy particle, station 940. Diameter 170μ (100X).
2. Yellow spherule, station 636. Diameter 150μ (100X). Note internal strain feature (arrow).
3. Yellow-orange spherule, station 940. Diameter 60μ. Note fractured portion (arrow).
4. Yellow hemisphere, station 700. Diameter 70μ. Note 5μ-thick walls (arrows).
5. Smoky gray spherule, station 224. Diameter 100μ (100X).
6. Smoky gray spherule, station 764. Diameter 100μ.
7. Clear spherule, station 464. Diameter 60μ.
8. Light yellow spherule, station 572. Diameter 70μ.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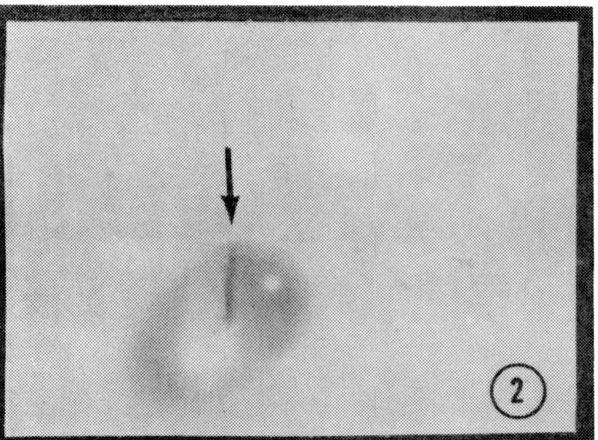
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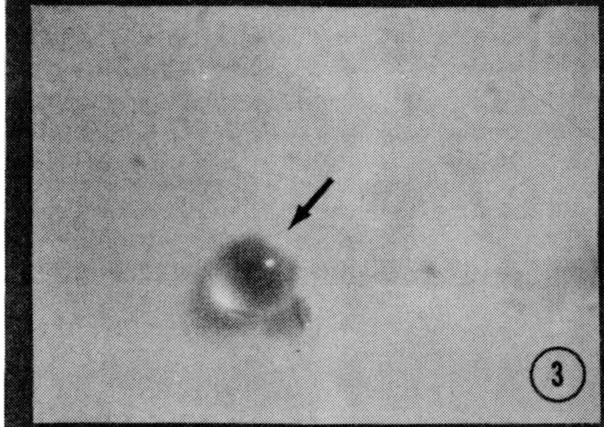
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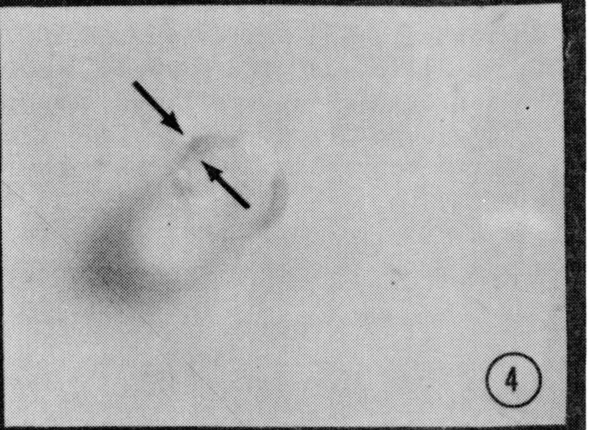
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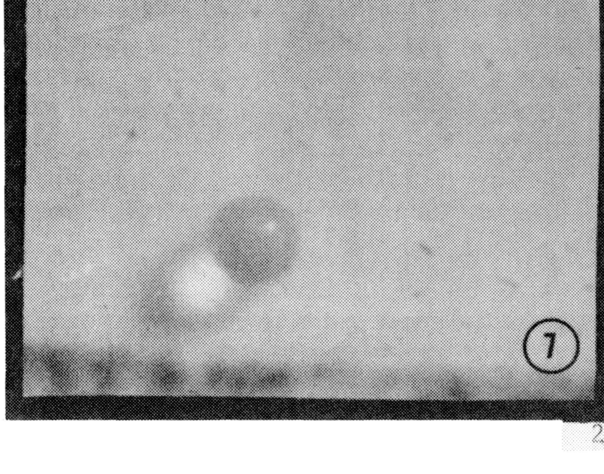
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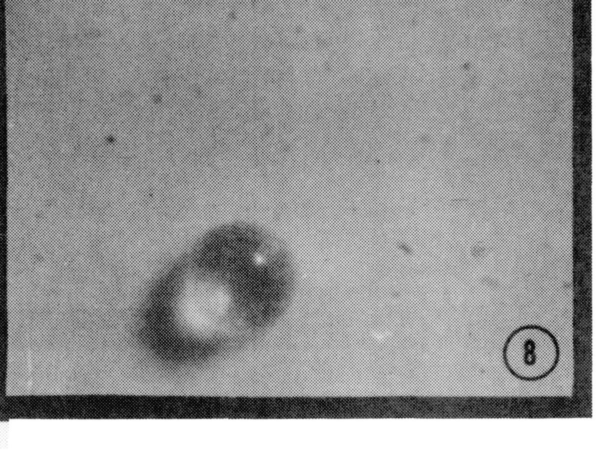
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in size from about 50 by 80 microns to 100 by 300 microns, these particles matched the description given by Parkin, et al. (1962). Unfortunately, these particles were extremely brittle, and shattered when attempts were made to transfer them for further study.

Size

Diameters of each particle larger than 10 microns were carefully measured to the nearest micron at 200X magnification by means of a calibrated eyepiece reticle. The lower limit of 10 microns was imposed by the scale divisions on the reticle chosen. Each particle was measured twice, the second reading being 90 degrees from the first; and their average was recorded. Infrequently occurring particles such as mammillary, cindery, irregular, and coated varieties were measured together with the predominant metallic and glassy types. However, because the uncommon particles were represented by small numbers, comprising but 5 percent of the total particle population, a detailed examination was not justified and only their size ranges are summarized here.

Type	Size range (microns)
Mammillary particles	40 - 100
Irregular particles	30 - 70
Cindery particles	20 - 70
Coated particles	50 x 80 - 100 x 300

The remainder of this section on particle size has been devoted to consideration of metallic and glassy spherules.

Metallic spherules ranged from 10 microns to 170 microns in diameter, as shown in the first column of Table 4. Only station 572 contained spherules representing both extremes of particle size. However, at this station and every other station, more than 95% of all metallic spherules were less than 100 microns in diameter, showing that large particles were uncommon.

Cumulative percentages of metallic spherules in each diameter interval were computed from the amounts at each station. These values are given in Table 4 and are shown in Figure 4. In the interests of clarity, only the total values were connected by a curve. The steepness of this curve in the region from 10 microns to 50 microns diameter clearly demonstrated that smaller spherules were predominant in the samples. The occurrence of the mean diameter value (40 microns) at the 70 percent level emphasized this fact. The cumulative percentage curve indicated by samples from the Antarctic Peninsula Traverse was compared to results of other studies in Figure 5. The figure shows that data from these samples agree well with values obtained for samples from deep sea sediments by Laevastu and Mellis (1955) and Hunter and Parkin (1960). The similarity in these curves indicated that these studies encountered similar spherule size distributions. On the other hand, the curve representing the Antarctic Peninsula Traverse samples was below those of Buddhue (1950), Thiel and Schmidt (1961), and Langway (1962). This indicates that each of these previous studies dealt with even greater proportions of small, metallic spherules. Comparison

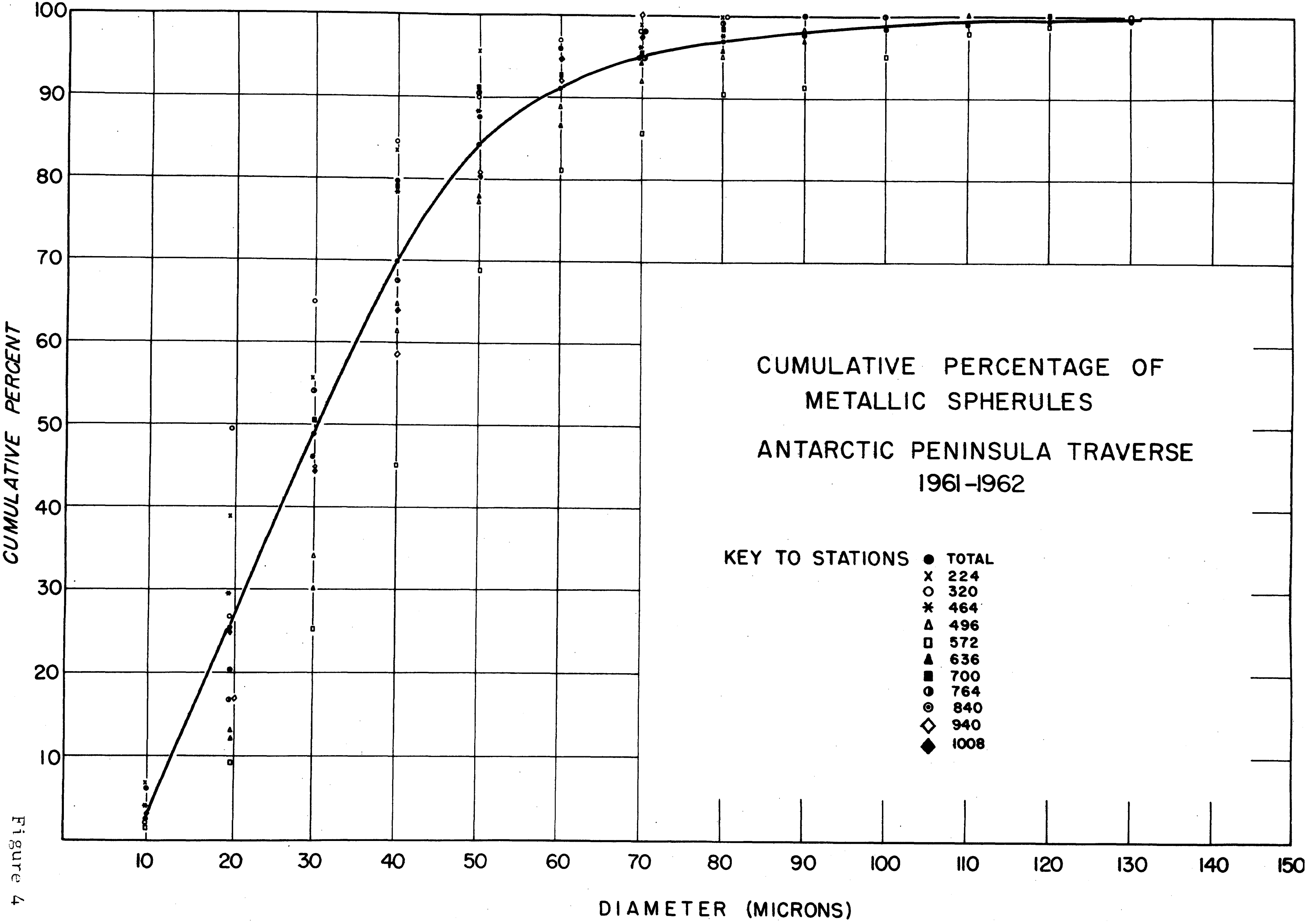
TABLE 4

Size Distribution of Metallic Spherules from Antarctic Peninsula Traverse, 1961-1962

Diameter (microns)	Totals			Sta. 224			Sta. 320			Sta. 464			Sta. 496			Sta. 572		
	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %
10	17	2.4	2.4	6	6.7	6.7	2	2.0	2.0	2	3.9	3.9	--	---	---	2	1.9	1.9
20	164	23.0	25.4	29	32.2	38.9	46	47.5	49.5	13	25.5	29.4	8	12.9	12.9	8	7.5	9.4
30	148	20.7	46.1	15	16.7	55.6	15	15.5	65.0	13	25.5	54.9	13	21.0	33.9	17	16.0	25.4
40	170	23.8	69.9	25	27.8	83.4	19	19.6	84.6	12	23.5	78.4	19	30.7	64.6	21	19.8	45.2
50	104	14.5	84.4	11	12.2	95.6	5	5.2	89.8	5	9.8	88.2	8	12.9	77.5	25	23.6	68.8
60	50	7.0	91.4	--	---	---	7	7.2	97.0	3	5.9	94.1	7	11.3	88.8	13	12.3	81.1
70	25	3.5	94.9	3	3.3	98.9	1	1.0	98.0	1	1.9	96.0	2	3.2	92.0	5	4.7	85.8
80	15	2.1	97.0	1	1.1	99.9	1	1.0	99.0	1	1.9	97.9	2	3.2	95.2	5	4.7	90.5
90	5	0.7	97.7										2	3.2	98.4	1	0.9	91.4
100	6	0.8	98.5													4	3.7	95.1
110	5	0.7	99.2										1	1.6	100.0	3	2.8	97.9
120	2	0.3	99.5													1	0.9	98.8
130	1	0.1	99.6				1	1.0	100.0									
140																		
150	1	0.1	99.7							1	1.9	99.8						
160	1	0.1	99.8															
170	1	0.1	99.9													1	0.9	99.7
TOTALS	715		99.9	90		99.9	97		100.0	51		99.8	62		100.0	106		99.7

TABLE 4 (con't)

Diameter (microns)	Sta. 636			Sta. 700			Sta. 764			Sta. 840			Sta. 940			Sta. 1008		
	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %
10	--	---	---	--	---	---	--	---	---	3	6.1	6.1	--	---	---	1	2.8	2.8
20	8	12.0	12.0	18	26.8	26.8	8	16.7	16.7	7	14.3	20.4	6	16.7	16.7	8	22.2	25.0
30	12	18.0	30.0	16	23.8	50.6	18	37.5	54.2	14	28.6	49.0	10	28.0	44.7	7	19.5	44.5
40	21	31.4	61.4	19	28.4	79.0	6	12.5	67.7	15	30.6	79.6	5	13.9	58.6	7	19.5	64.0
50	11	16.4	77.8	8	12.0	91.0	11	23.0	90.7	4	8.2	87.8	8	22.2	80.8	6	16.7	80.7
60	6	8.9	86.7	1	1.5	92.5	--	---	---	4	8.2	96.0	4	11.1	91.9	5	13.9	94.6
70	5	7.5	94.2	2	3.0	95.5	2	4.2	94.9	1	2.2	98.2	3	8.4	100.3	1	2.8	97.4
80	1	1.5	95.7	2	3.0	98.5	2	4.2	99.1									
90	1	1.5	97.2							1	2.2	100.4						
100	1	1.5	98.7				1	2.1	101.2							1	2.8	100.2
110																		
120				1	1.5	100.0												
130																		
140																		
150																		
160	1	1.5	100.2															
170																		
TOTALS	67		100.2	67		100.0	48		101.2	49		100.4	36		100.3	36		100.2


CUMULATIVE PERCENTAGE OF METALLIC SPHERULES
ANTARCTIC PENINSULA TRAVERSE 1961-1962
KEY TO STATIONS
● TOTAL
× 224
○ 320
✱ 464
△ 496
□ 572
▲ 636
■ 700
◐ 764
⊙ 840
◇ 940
◆ 1008
CUMULATIVE PERCENT
100
90
80
70
60
50
40
30
20
10
DIAMETER (MICRONS)
10
20
30
40
50
60
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80
90
100
110
120
130
140
150

Figure 4

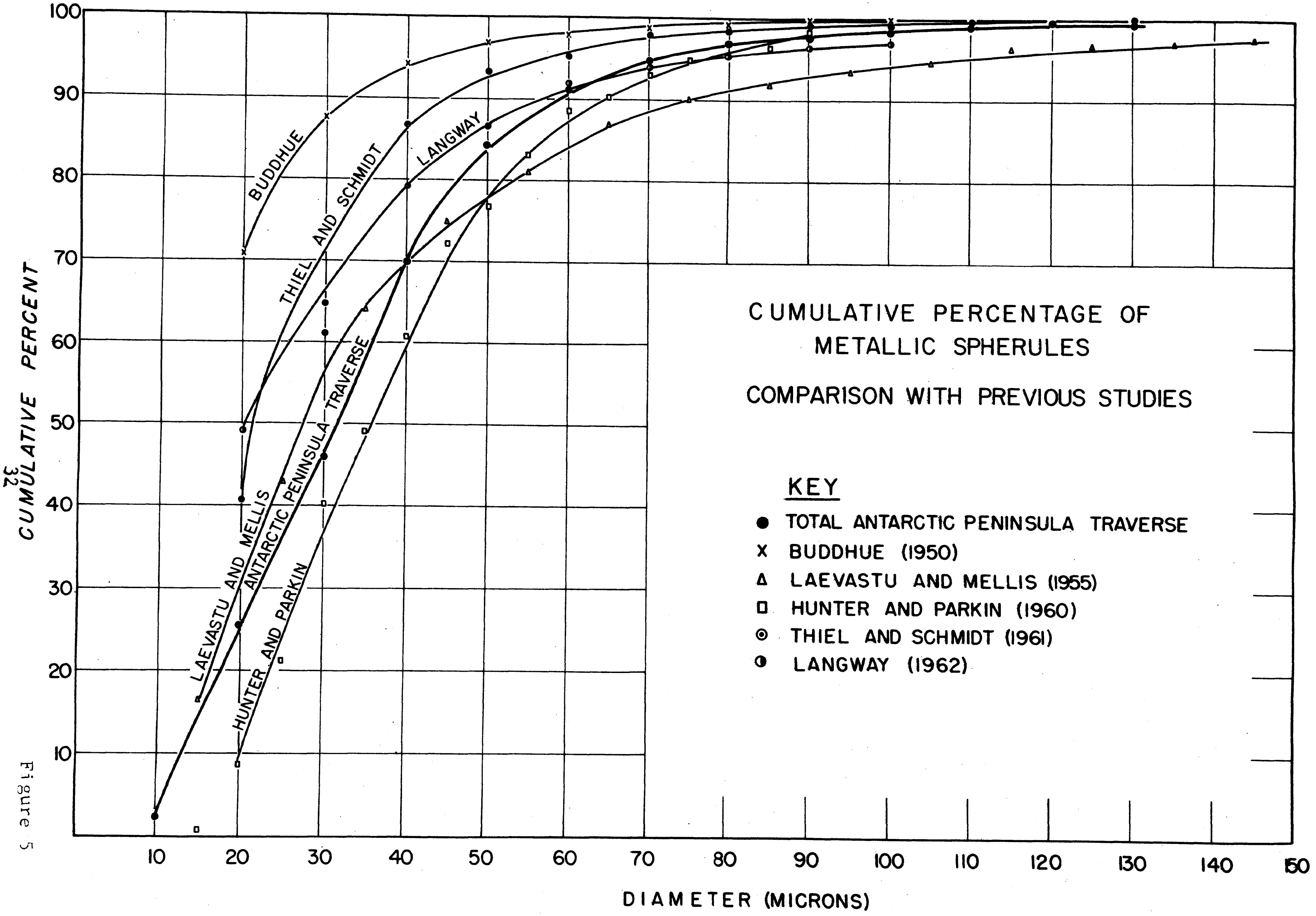
CUMULATIVE PERCENTAGE OF
METALLIC SPHERULES
COMPARISON WITH PREVIOUS STUDIES
KEY
● TOTAL ANTARCTIC PENINSULA TRAVERSE
X BUDDHUE (1950)
Δ LAEVASTU AND MELLIS (1955)
□ HUNTER AND PARKIN (1960)
⊙ THIEL AND SCHMIDT (1961)
◑ LANGWAY (1962)
BUDDHUE
THIEL AND SCHMIDT
LANGWAY
LAEVASTU AND MELLIS
ANTARCTIC PENINSULA TRAVERSE
HUNTER AND PARKIN
CUMULATIVE PERCENT
DIAMETER (MICRONS)
100
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

Figure 5

of the present work with that of other sites in Antarctica as reported by Thiel and Schmidt (1961) leads to an important conclusion: The size distribution of metallic spherules is not uniform over the Western Antarctic ice cap. Non-uniform occurrence of spherule size distribution is also shown by samples from each station on the Antarctic Peninsula Traverse, as suggested by the data in Table 4.

Glassy spherules were larger than their metallic counterparts, ranging from 20 microns to 300 microns in diameter as shown in the first column of Table 5. No station contained glassy spherules representing the extremes of particle size. Extremely large particles were rare, however, and at every station about 90% of all glassy spherules were less than 100 microns in diameter.

The wide ranges of size of glassy spherules probably result from the fact that fewer numbers of glassy spherules were recognized at each station. Only half as many glassy spherules as metallic spherules were identified, and the statistics for this more limited group were less reliable. Probably, an unknown number of glassy spherules have been overlooked. Buddhue (1950) mentioned the difficulty in locating these particles in the samples he examined. In addition, the identification procedures adopted for this study probably caused omission of several particles by restricting the shape to perfect spheres. This problem will be re-examined using a more liberal set of criteria during study of new samples.

Bearing in mind that the data for glassy spherules may be revised by this review, cumulative percentages of the particles in each diameter interval were computed. The values were given in Table 5 and have been plotted in Figure 6. The figure shows that most of the glassy spherules were small in size, with the mean diameter (67 microns) occurring at the 65% level. However, the lower slope of this curve indicates poorer sorting. Comparison with Buddhue's curve for similar material indicated that the glassy spherules from the Antarctic Peninsula Traverse were considerably larger than those he studied. While data from station 224 closely approximated Buddhue's curve, interpretation of this apparent relation is clouded because of the absence of supporting information and its significance is obscure. It is safe to say, however, that glassy spherules larger than those collected by Buddhue were found in the region of the Antarctic Peninsula Traverse.

Physical Properties

As an important complement to the detailed descriptions of particles given earlier, optical properties were studied and density determinations were made on representative samples of metallic and glassy spherules. Optical properties were examined using essentially standard techniques of microscopy (metallic spherules) and petrology (glassy spherules). Most metallic spherules were studied directly on the filter papers, but some were mounted in balsam and plastic for polishing. Glassy spherules were examined immersed in a pool of refractive index liquid, which was contained in a shallow depression on the surface of a glass slide. This

TABLE 5

Size Distribution of Glassy Spherules from Antarctic Peninsula Traverse, 1961-1962

Diameter (microns)	Totals			Sta. 224			Sta. 320			Sta. 464			Sta. 496			Sta. 572		
	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %
10	--	---	---	--	---	---	--	---	---	--	---	---	--	---	---	--	---	---
20	27	8.5	8.5	25	35.2	35.2	2	11.1	11.1	--	---	---	--	---	---	--	---	---
30	27	8.5	17.0	17	23.9	59.1	3	16.7	27.8	--	---	---	1	7.7	7.7	2	4.8	4.8
40	40	12.8	29.8	13	18.3	77.4	3	16.7	44.5	2	11.8	11.8	4	30.8	38.5	4	9.8	14.6
50	49	15.4	45.2	9	12.7	90.1	4	22.2	66.7	4	23.5	35.3	4	30.8	69.3	14	34.1	48.7
60	29	9.0	54.2	1	1.4	91.5	2	11.1	77.8	2	11.8	47.1	2	15.4	84.7	3	7.3	56.0
70	36	11.3	65.5	4	5.6	97.1	3	16.7	94.5	1	5.9	53.0	1	7.7	91.4	4	9.8	65.8
80	33	10.4	75.9							4	23.5	76.5	1	7.7	99.1	4	9.8	75.6
90	13	4.0	79.9							2	11.8	88.3						
100	34	10.7	90.6	1	1.4	98.5	1	5.5	100.0	1	5.9	44.2				7	17.0	92.6
110	7	2.2	92.8	1	1.4	99.9												
120	8	2.5	95.3							1	5.9	100.1						
130	1	0.3	95.6															
140	2	0.6	96.2															
150	5	1.6	97.8													2	4.8	97.4
160																		
170	2	0.6	98.4															
180	2	0.6	99.0															
190																		
200																		
300	2	0.6	99.6													1	2.5	99.9
400	2	0.6	100.2															
TOTALS	319		100.2	71		99.9	18		100.0	17		100.1	13		99.1	41		99.9

TABLE 5 (con't)

Diameter (microns)	Sta. 636			Sta. 700			Sta. 764			Sta. 840			Sta. 940			Sta. 1008		
	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %	No	%	cum %
10																		
20																		
30	1	3.0	3.0	1	3.0	3.0	2	5.1	5.1									
40	2	6.1	9.1	3	9.1	12.1	7	17.9	23.0	2	6.3	6.3						
50	4	12.1	21.2	3	9.1	21.2	3	7.7	30.7	4	12.5	18.8						
60	6	18.2	39.4	5	15.2	36.4	4	10.3	41.0	3	9.4	28.2	1	8.3	8.3			
70	4	12.1	51.5	7	21.2	57.6	3	7.7	48.7	7	21.9	50.1	1	8.3	10.0	1	11.1	11.1
80	3	9.1	60.6	6	18.2	75.8	6	15.4	64.1	5	15.6	65.7	4	33.3	49.9	--	---	---
90	4	12.1	72.7	2	6.1	81.9	2	5.1	69.2	2	6.3	72.0	1	8.3	58.2	--	---	---
100	2	6.1	78.8	2	6.1	88.0	8	20.5	89.7	5	15.6	87.6	2	16.7	74.9	5	55.6	66.7
110	2	6.1	84.9	--	---	---	1	2.6	92.4	1	3.1	90.7	1	8.3	83.2	1	11.1	77.8
120	2	6.1	91.0	1	3.0	91.0	1	2.6	95.0	1	3.1	93.8	1	8.3	91.5	1	11.1	88.9
130				1	3.0	94.0												
140				1	3.0	97.0										1	11.1	100.0
150	1	3.0	94.0				1	2.6	97.6	1	3.1	96.9						
160																		
170	1	3.0	97.0										1	8.3	99.8			
180							1	2.6	100.2	1	3.1	100.0						
190																		
200																		
300				1	3.0	100.0												
400	1	3.0	100.0															
TOTALS	33		100.0	33		100.0	39		100.2	32			12		99.8	9		100.0

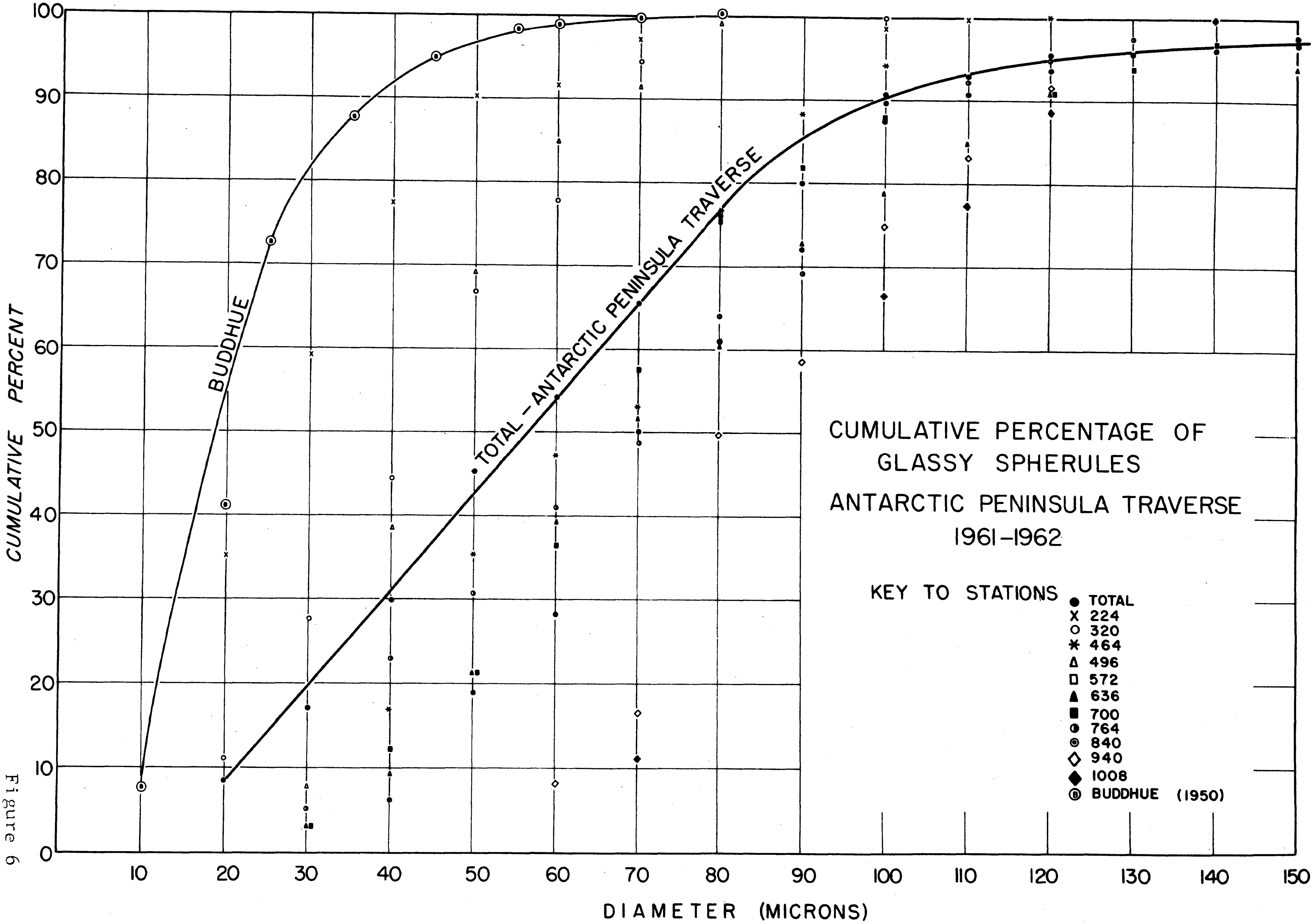
CUMULATIVE PERCENTAGE OF GLASSY SPHERULES
ANTARCTIC PENINSULA TRAVERSE 1961-1962
KEY TO STATIONS
● TOTAL
X 224
○ 320
✱ 464
△ 496
□ 572
▲ 636
■ 700
◐ 764
◎ 840
◇ 940
◆ 1008
Ⓑ BUDDHUE (1950)
BUDDHUE
TOTAL - ANTARCTIC PENINSULA TRAVERSE
CUMULATIVE PERCENT
DIAMETER (MICRONS)
0
10
20
30
40
50
60
70
80
90
100
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

Figure 6

procedure permitted recovery of the spherule for study in a different liquid. Refractive indices obtained in this way were reproduceable within 0.01, with comparable precision in measurement. Density determinations were made by observing the rate of spherule fall through a tube containing 1- methoxynapthelene and applying Stokes' law. Calibration tests using drops of mercury showed that this procedure was capable of yielding density values which were precise within 10 percent, an acceptable limit of error.

Data for twenty representative metallic spherules were listed in Table 6. Although the different surface types were present, similar optical properties were shown by each. Under reflected light, the spherules were found to be composed of several mineral species. The bulk of each spherule examined was comprised of a light pinkish gray, isotropic mineral of moderate to low reflectivity, which was identified as magnetite. This was confirmed through x-ray powder photographs. A pale, cream-colored mineral of higher reflectivity than magnetite was also present as thin lamellae, tiny blebs, and minute grains scattered throughout the magnetite host; this minor phase was tentatively identified as schreibersite. A third, purple-colored mineral of lower reflectivity than magnetite was also present as scattered blebs; this mineral has not yet been identified. The lamellae of both latter phases were found to be oriented in chevron patterns similar to that shown by the electron micrographs, and probably caused this surface feature. All the metallic spherules were at least moderately magnetic, being attracted readily to the tip of a magnetized needle. Density measurements clustered about 5 gm cm^{-3}, with a few in the region of 7 gm cm^{-3}. Taken together, these properties most closely resembled those of magnetite and/or metallic iron. This resemblance is entirely consistent with the long-proposed similarity of metallic spherules with microscopic metallic meteorites.

Data for eleven representative glassy spherules were listed in Table 7. Most of these spherules had smooth surfaces, although some showed conchoidal fractures and some were irregular and pitted. In transmitted light, shades of yellow were the most common colors of glassy spherules, although those examined represented the entire range from clear to olive brown. Some samples showed a few opaque inclusions. Most, with one exception, gave no hint of crystallographic features and were isotropic in optical character. The exception, glassy spherule number 9, showed a mottled internal structure and marked anisotropism with wavy extinction. Refractive indices for all samples ranged from about 1.48 to about 1.52, but most were within the narrow range from 1.50 to 1.52. Only a few density values were obtained because of the difficulty in observing the fall of glassy spherules; these were slightly greater than 2 gm cm^{-3}. Many properties of most glassy spherules were similar to those of lechatelierite, but their refractive indices and density were too high. Except for its weak anisotropism, the properties of leucite were very similar to those of the glassy spherules. However, a detailed petrographic study of the rocks sampled by the Antarctic Peninsula Traverse failed to disclose the presence of leucite in this area (Laudon, Behrendt, and Christensen, 1963). If the glassy spherules were leucite, they have come from outside the area of the traverse. The extremely unusual glassy spherule (number 9) matched the descriptions of

TABLE 6

Physical Properties of Metallic Spherules, Antarctic Peninsula Traverse

Spherule	Size (microns)	Color (shades of light gray)	Reflectivity	Surface	Optical Character	Internal Reflections	Rotation Properties	Apparent Crystallographic Features	Magnetism	Density
1	60	brownish-pink	moderate to low	ridged and furrowed	isotropic	none	n.o.*	intersecting lamellae	moderate	lost
2	40	brownish-pink	moderate to low	ridged, w/ pits	isotropic	none	n.o.	lamellae	moderate	4.7
3	30	pinkish	moderate	ridged, w/ pits	isotropic	none	n.o.	lamellae	moderate	lost
4	40	pinkish	moderate	ridged and furrowed	isotropic	none	n.o.	intersecting lamellae	moderate to strong	lost
5	50	brownish-pink	moderate to low	pitted	isotropic	none	n.o.	none	moderate	5.3
6	40	pinkish	moderate	pitted	isotropic	none	n.o.	none	moderate	4.8
7	40	pinkish-brown	moderate to low	pitted	isotropic	none	n.o.	none	moderate	5.1
8	60	purplish	moderate to high	smooth	isotropic	none	n.o.	none	strong	4.7
9	50	pinkish	moderate	pitted	isotropic	none	n.o.	none	moderate	lost
10	40	pinkish-purple	low	pitted	isotropic	none	n.o.	none	moderate	5.0
11	40	pinkish	moderate to high	ridged and furrowed	isotropic	none	n.o.	intersecting lamellae	moderate	lost
12	30	pinkish	moderate	ridged and furrowed	isotropic	none	n.o.	intersecting lamellae	moderate	7.1
13	100	pinkish-cream	moderate	pitted	isotropic	none	n.o.	none	moderate to strong	4.9
14	60	pinkish	moderate to high	ridged, w/ pits	isotropic	none	n.o.	lamellae	moderate	4.7
15	40	purplish	moderate	smooth	isotropic	none	n.o.	none	moderate to strong	lost
16	50	pinkish	moderate to low	ridged, w/ pits	isotropic	none	n.o.	lamellae	moderate	lost
17	30	pinkish	moderate	ridged, w/ pits	isotropic	none	n.o.	----	moderate	5.0
18	40	pinkish	moderate to high	smooth, w/ pits	isotropic	none	n.o.	none	moderate	lost
19	40	pinkish	moderate to low	ridged, w/ pits	isotropic	none	n.o.	----	moderate	lost
20	40	pinkish	moderate	ridged, w/ pits	isotropic	none	n.o.	----	moderate	5.2
										5.1 = MEAN
COMPARISON										
Iron		white	high	----	isotropic	none	----	granular texture	high	7.85
Magnetite		brownish-pink	low	----	isotropic	none	----	----	high	5.18
Chromite		brownish	low	----	isotropic	brown	----	granular	moderate	4.6
Ilmenite		cream	low	----	anisotropic	brown	----	----	moderate	4.7

*NOTE: n.o. = not observable

TABLE 7

Physical Properties of Glassy Spherules, Antarctic Peninsula Traverse

Spherule	Size (microns)	Color	Pleochroism	Surface	Crystallographic Features	Inclusions	Optical Character	Birefringence	Refractive Index	Density (gm cm^{-3})	
1	60	yellow to clear	none	smooth, w/ conchoidal fracture	none	opaque liquid (?)	isotropic	none	$1.48 < n < 1.52$	lost	
2	70	yellow	none	smooth	none	opaque	isotropic	none	$1.48 < n < 1.52$	lost	
3	100	yellow-orange	none	smooth	none	none	isotropic	none	1.52	2.3	
4	50	clear yellow	none	smooth	none	none	isotropic	none	1.50	lost	
5	40	clear	none	pitted	none	opaque	isotropic	none	$1.50 < n < 1.52$	lost	
6	80	yellow	none	smooth	none	none	isotropic	none	$1.50 < n < 1.52$	2.5	
7	120	clear	none	smooth, w/ conchoidal fracture	none	opaque	pseudo isotropic	yellow rim (strain feature?)	1.50	2.4	
8	60	yellow	none	smooth	none	none	isotropic	none	$1.50 < n < 1.52$	lost	
9	50	olive brown	faint	irregular	mottled internal structure	none	anisotropic, wavy extinction	cream-yellow-tan	$1.50 < n < 1.52$	lost	
10	70	clear	none	smooth	none	none	isotropic	none	1.50	1.9	
11	50	clear	none	smooth	none	none	isotropic	none	$1.50 < n < 1.52$	lost	
										2.3 = MEAN	
Comparison											
Lechatelierite		clear	none	irregular curves	none	bubbles	isotropic	none	1.458	2.19	(Winchell and Winchell, 1951)
Leucite		colorless, white, gray	none	----	pseudo-isometric form	---	anisotropic to pseudo isotropic	weak	$n_e 1.508$ $n_o 1.509$	2.47	(Winchell and Winchell, 1951)
Quartz		variable	weak	----	twinning	---	anisotropic	weak	$n_e 1.553$ $n_o 1.544$	2.65	(Winchell and Winchell, 1951)
Australite		brown-green	?	curved	flow marks	transparent	anisotropic	none	1.509	2.4	(Barnes, 1939)

australites published by Barnes (1939, 1961). Unfortunately, this spherule was lost during density determinations. A search for others of similar character yielded six additional olive-green, mottled spherules, which have been dispatched for analysis as reported in the next section. The search will continue on new samples from Antarctica to investigate fully the possibility that such glassy spherules may represent microtektites of recent age.

Chemical Composition

A total of 437 representative spherules were selected for microchemical analyses by the electron probe micro-analyzer technique. Co-operation with investigators at several institutions was arranged to handle this large number of samples, and most of these spherules were dispatched for study. These analyses are still in progress, and only the first, preliminary results are available now, as listed in Table 8. The values reported are accurate to within 10% of the elemental amount present.

Analyses of ten metallic spherules showed them to contain slightly more than 70% iron, with traces of titanium, manganese, and silica. Nickel was not detected in these first spherules; it was either present in small amounts which could not be detected, or was absent in these samples. Many previous workers have argued that spherules must contain nickel if an extraterrestrial origin is to be considered likely (Fredriksson, 1961). However, in view of the physical character of the spherules and the nature of their occurrence, it is difficult to reasonably postulate possible sites of terrestrial or industrial origin. Perhaps the presence of absence of nickel in these analyses should not, by itself, be regarded as an entirely reliable criterion for judging particle origin.

Only two analyses of glassy spherules are currently available. These were siliceous, and had traces of iron. The composition of spherule 9D13 was similar to those reported for tektites (Krinov, 1960). Preliminary chemical data, refractive indices, densities, and internal structures of glassy spherules were thus compatible with those for tektites.

Although the analyses of the few spherules presented in Table 8 were considered preliminary, their internal consistency was noteworthy. These spherules were selected at random from residues representing several stations. However, in all respects they appeared identical to the remainder of spherules recovered in this work.

The values obtained may be revised slightly by data of additional analyses, but the writer regards the preliminary results as representative of the composition of these types of particles.

Occurrence

An important objective of the present research was to study the areal occurrence and temporal distribution of microscopic extraterrestrial particles in the area of the Antarctic Peninsula Traverse. This was part of

TABLE 8

Chemical Composition of Spherules
(in weight percent)

Spherule	Diameter (microns)	Fluorescence	Fe	Mn	Ti	Si	Al	K	Ca	Others
METALLIC										
8D14	22	orange	65-70	1-2						
8D19	40	orange	75-80	1-2	<0.5	<0.5				
8D20	20	none	70-75			<0.5				
9D1	25	orange	55-60	<0.5						
9D10	30	orange	55-60	0.5						
9D12	20	orange	50-55	<0.5						
9D14	20	orange	55-60		<0.5					
9D15	50	none	65-70	1						
9D16	30	orange	65-70	0.5						
9D21	25	none	65-70	1		1-2				
GLASSY										
8D18	40	none	<0.5			?				light elements
9D13	30	orange	2-3		1	50-55	10-15	1	1	light elements

Analysis conducted by Advanced Metals Research Corp., Summerville, Massachusetts through the cooperation of Dr. Frances W. Wright, Smithsonian Astrophysical Observatory.

a larger, continuing effort to determine the occurrence of such particles over the entire Antarctic ice cap, and eventually over the entire surface of the earth.

The ages of the snow core samples were estimated to permit study of the temporal distribution of particles. Both glaciological studies (Shimizu, personal communication, 1962) and seismic determinations (Behrendt, personal communication, 1963) of snow accumulation were employed in this task. These values were listed in Table 9. Although Shimizu cautioned that accumulation values he obtained from glaciological pits could be in error by as much as 50%, agreement with values from seismic data suggests that the actual error was much less. Furthermore, the accumulation values adopted were consistent with those suggested for this area by Rubin and Giovinetto (1962) on the basis of meteorological factors and topographical influences. It appears likely, therefore, that Shimizu's estimate of possible errors in mean snow accumulation was very conservative.

Two lines of evidence suggested an apparent relation of spherule occurrence with mean snow accumulation at the stations sampled. First, the size distributions of metallic spherules were not uniform among the several stations (Table 4). To investigate this further, mean diameters were computed for each station, and plotted versus accumulation in Figure 7. Although considerable scatter was present, this graph suggests an approximate, inverse relation of spherule size to snow accumulation. Smaller particles were more common at stations where accumulation was greatest, and vice versa. The standard deviation of points from the line was about 10%. Glassy spherules showed even more scatter because fewer were identified, but suggested a similar relation. Second, the total numbers of metallic spherules at each station varied inconsistently. It was discovered that the frequency of spherule occurrence was apparently related directly to snow accumulation, as shown in Figure 8. The frequency of spherule occurrence was clearly greater at stations with higher accumulation. Again, the data revealed a standard deviation of about 10%. These results suggested that meteorological factors were in some way intimately intertwined with spherule occurrence.

This important conclusion raised an intriguing question: did the influx of spherules produce snowfall, or did the falling snow "capture" spherules as they descended through the atmosphere? In a hypothesis which he was later to describe wryly as "well-known but widely ignored," Bowen (1956) postulated that dust particles from meteor swarms served as condensation nuclei for precipitation. Noting that periods of heavy rainfall occurred about 30 days after principal meteor swarms, he suggested that the particles required this amount of time to fall to the level where they could influence precipitation. However, calculations of the length of time required for metallic, spherules to fall through a stagnant, standard atmosphere yielded values at least one order of magnitude less than Bowen's estimate (Thiel and Schmidt, 1961, Figure 2). These calculations, of course, represented an ideal case where there was no atmospheric turbulance to slow the rate of particle fall. However, collections of particles related to periods of meteor activity were made by Parkin and Hunter (1962). They found that only 3 to 4 days were required for such particles to reach the surface of the earth. Calculated and observed rates of particle fall thus do not support Bowen's hypothesis.

TABLE 9

Annual Snow Accumulation

	Mean Annual Accumulation (cm of water)		
Station	Glaciology (1)	Seismic (2)	Adopted Value
224	----	52	52
320	60.0+	42	42
464	----	27	27
496	26.5	39*	27
572	----	20	20
636	33.8	41*	34
700	44.8	47	46
764	33.1	50*	33
840	27.6	28	28
940	20.3	20	20
1008	35.1	35	35

(1) Shimizu, personal communication, 1962
(2) Behrendt, personal communication, 1963

+Value based on only one year's deposit--not adopted.
*Values derived from imperfect records--not adopted.

Another deficiency exists. While Bowen cited the conventional view of meteor particles (a few organized streams of particles plus a background of sporadic, independently travelling particles) the work of Gallagher and Eshelman (1960) showed that most of the background activity was concentrated into numerous showers. The number of shower events they discovered was so great that it would be "impossible" to predict the occurrence of particular showers which could be related to specific periods of heavy rainfall. Finally, as Fletcher (1961) pointed out, meteoric particles have low activity as condensation nuclei. At least, it would appear unlikely that spherule influx produced snowfall in this area.

To the contrary, the data shown in Figures 7 and 8 suggest to the writer that spherule occurrence was controlled by snow accumulation. Where snow accumulation was high, larger frequencies of spherule occurrence were found and greater proportions of smaller particles were present. This suggests that the spherules were "captured" by the heavy precipitation and deposited at these sites. Smaller spherules would be particularly sensitive indicators of this process; because of their lower mass, they would fall more slowly. Atmospheric winds could transport them away in the absence of an active depositional influence such as heavy snows. Stations with low snow accumulation had smaller frequencies of spherule occurrence, and lower proportions of small particles, which is consistent with this hypothesis.

For purposes of this study, the mean rates of snow accumulation were assumed to be constant with time so that the ages of snows at depth could be estimated and the numbers of spherules in each annual layer could be determined. Unfortunately, this assumption introduces a possible source of error to such ages. While mean accumulation values are useful in representing the general pattern of snow deposition at a station over a period of many years, they do not allow for the variability in deposit from one year to the next. No direct measurements of variability had been made in this area up to the time of writing, and it was not possible to apply corrections to the estimated ages. However, a tentative variability of about 25% has been suggested for this area, based on considerations of snow accumulation for Antarctica as a whole (Giovinetto, personal communication, 1963).

The numbers of metallic spherules occurring in estimated yearly layers were listed in Table 10. The numbers of spherules deposited in a years' time at any given station varied widely, but these can be almost entirely accounted for by applying the suggested variability factor to the estimated ages. It would appear, therefore, that the occurrences of metallic spherules at these stations were roughly similar over the time spans represented. Finally, no correlation among numbers of spherules in yearly layers was apparent among adjacent stations, even when variability in accumulation was taken into account. This can be attributed to the spacing of stations (about 100 km apart).

Following the work of Langway (1963), the average numbers of metallic spherules per liter (ANL) of meltwater were calculated in an attempt to provide a more uniform basis for comparison among stations. These values were listed in Table 10 and plotted in Figure 9. Considering variability in accumulation, the ANL values varied only slightly at any given station. Unfortunately, however, no obvious correlation of spherule

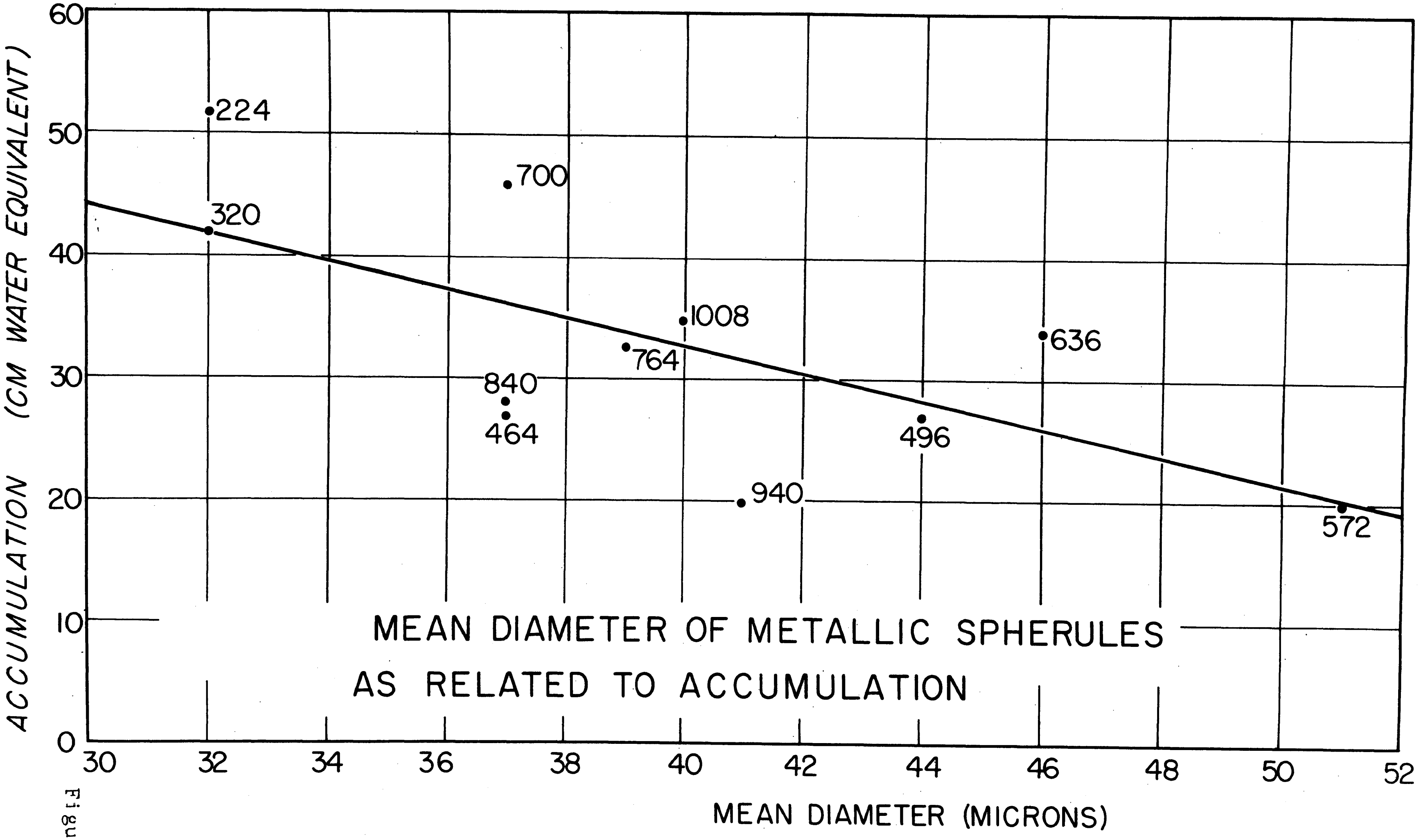
MEAN DIAMETER OF METALLIC SPHERULES
AS RELATED TO ACCUMULATION
ACCUMULATION (CM WATER EQUIVALENT)
MEAN DIAMETER (MICRONS)
0
10
20
30
40
50
60
30
32
34
36
38
40
42
44
46
48
50
52
224
700
320
1008
636
764
840
464
496
940
572

Figure 7

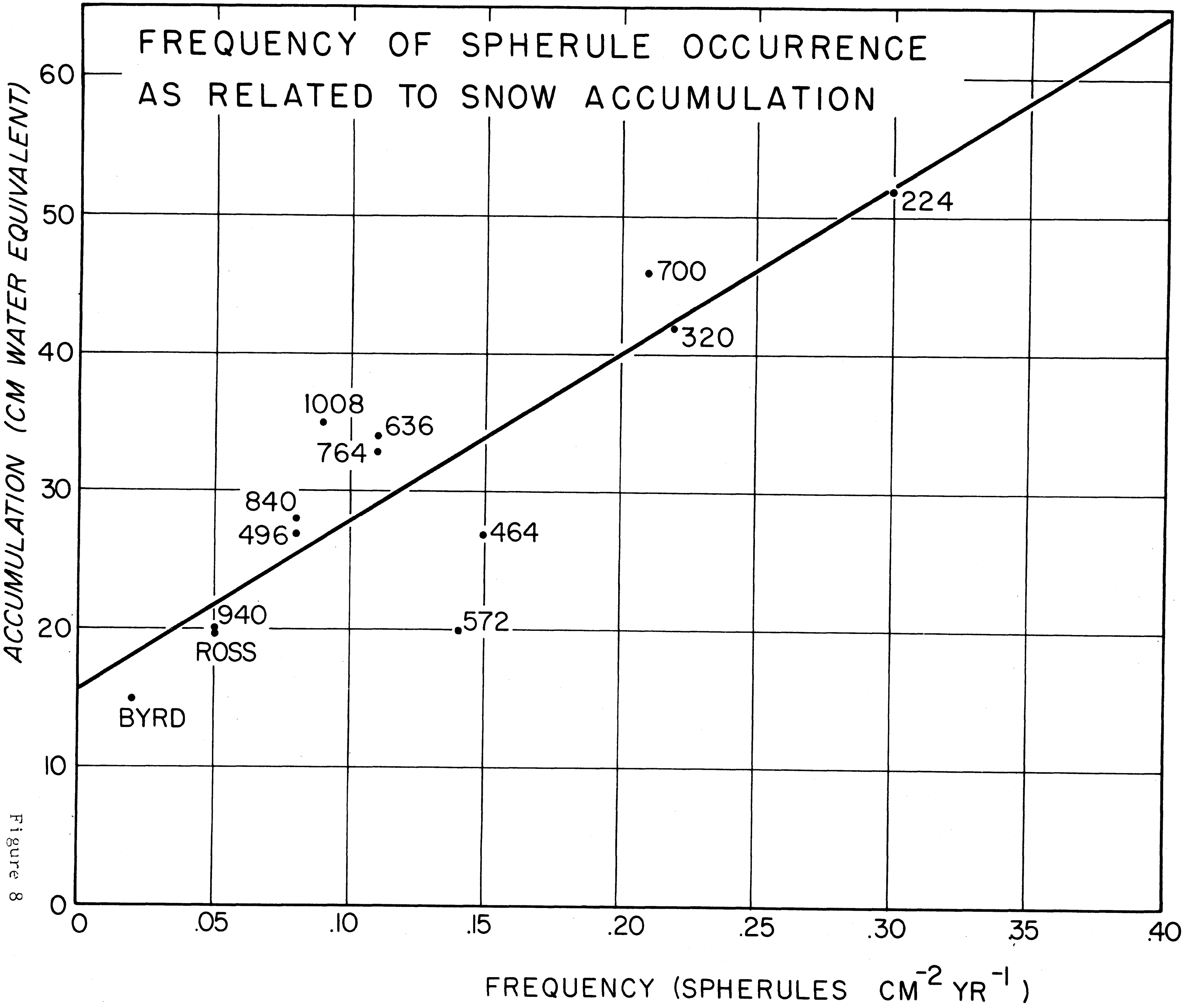
FREQUENCY OF SPHERULE OCCURRENCE
AS RELATED TO SNOW ACCUMULATION
ACCUMULATION (CM WATER EQUIVALENT)
FREQUENCY (SPHERULES CM^{-2} YR^{-1})
0
10
20
30
40
50
60
0
.05
.10
.15
.20
.25
.30
.35
.40
224
700
320
1008
636
764
840
496
464
1940
ROSS
572
BYRD

Figure 8

TABLE 10

Annual Occurrence of Metallic Spherules, Antarctic Peninsula Traverse, 1961-1962

(N.B.: "ANL" column indicates Average Number of spherules per Liter of meltwater)

Age	All Stations			Sta. 224		Sta. 320		Sta. 464		Sta. 496		Sta. 572		Sta. 636		Sta. 700		Sta. 764		Sta. 840		Sta. 900		Sta. 1008	
(years)	Total No.	Avg. No.	Avg. ANL	No.	ANL	No.	ANL	No.	ANL	No.	ANL	No.	ANL	No.	ANL	No.	ANL	No.	ANL	No.	ANL	No.	ANL	No.	ANL
0-1	61	6	4	11	5	14	7			6	6	5	5	2	2	7	4	4	3	4	3	1	1	7	4
1-2	45	5	4	10	5	1	1			6	5	8	10	7	6	4	2	3	2	5	6	1	2	0	0
2-3	65	6	5	13	6	7	4	6	7	3	3	7	7	5	5	8	4	4	3	6	5	4	6	2	1
3-4	47	4	3	10	5	7	4	7	6	3	3	2	2	5	3	4	2	5	4	0	1	1	2	3	3
4-5	34	3	3	6	2	3	2	3	3	2	3	6	8	2	2	1	1	2	1	3	3	2	2	4	2
5-6	70	6	5	10	4	6	3	4	4	4	4	5	7	6	6	11	8	3	3	1	1	6	9	2	1
6-7	39	4	2	7	3	8	3	2	2	1	1	4	4	4	5	8	4	2	1	1	1	2	3	0	0
7-8	45	4	3	10	4	9	5	4	4	3	2	5	5	1	2	3	2	1	1	4	4	2	3	3	1
8-9	47	4	4	4	2	7	3	2	2	4	2	10	15	6	5	8	3	1	1	3	2	1	2	1	1
9-10	41	4	3	6	2	9	5	2	2	4	2	6	8	3	4	5	3	4	4	1	1	0	0	1	1
10-11	33	3	3	3	4	7	6	3	2	4	4	4	3	1	1	5	3	2	1	1	2	1	1	2	1
11-12	25	3	2			10	6	2	2	2	2	2	2	1	1	3	2	1	1	1	1	0	0	3	1
12-13	26	3	2			7	3	2	2	1	1	2	2	1	2			6	5	2	2	0	0	5	2
13-14	36	4	4			2	4	2	2	5	4	10	14	7	5			2	2	4	5	2	1	2	1
14-15	24	3	2					2	2	1	1	0	0	13	6			4	4	2	2	1	2	1	1
15-16	11	1	2					2	3	2	2	0	0	2	3			2	1	2	2	1	1		
16-17	18	3	2					3	3	4	2	6	6	1	2			2	2	1	1	1	1		
17-18	11	3	3					2	2	2	4	2	2							4	5	1	2		
18-19	13	3	3					3	2	4	4	1	1							4	6	1	1		
19-20	5	2	2							1	1	4	5									0	0		
20-21	2	1	1									0	0									2	2		
21-22	5	3	3									4	4									1	2		
22-23	11	6	5									7	5									4	4		
23-24	2	1	1									1	1									1	1		
24-25	1	1	1									1	1									0	0		
25-26	2	2	2									2	3									0	0		
26-27	2	2	2									2	2												

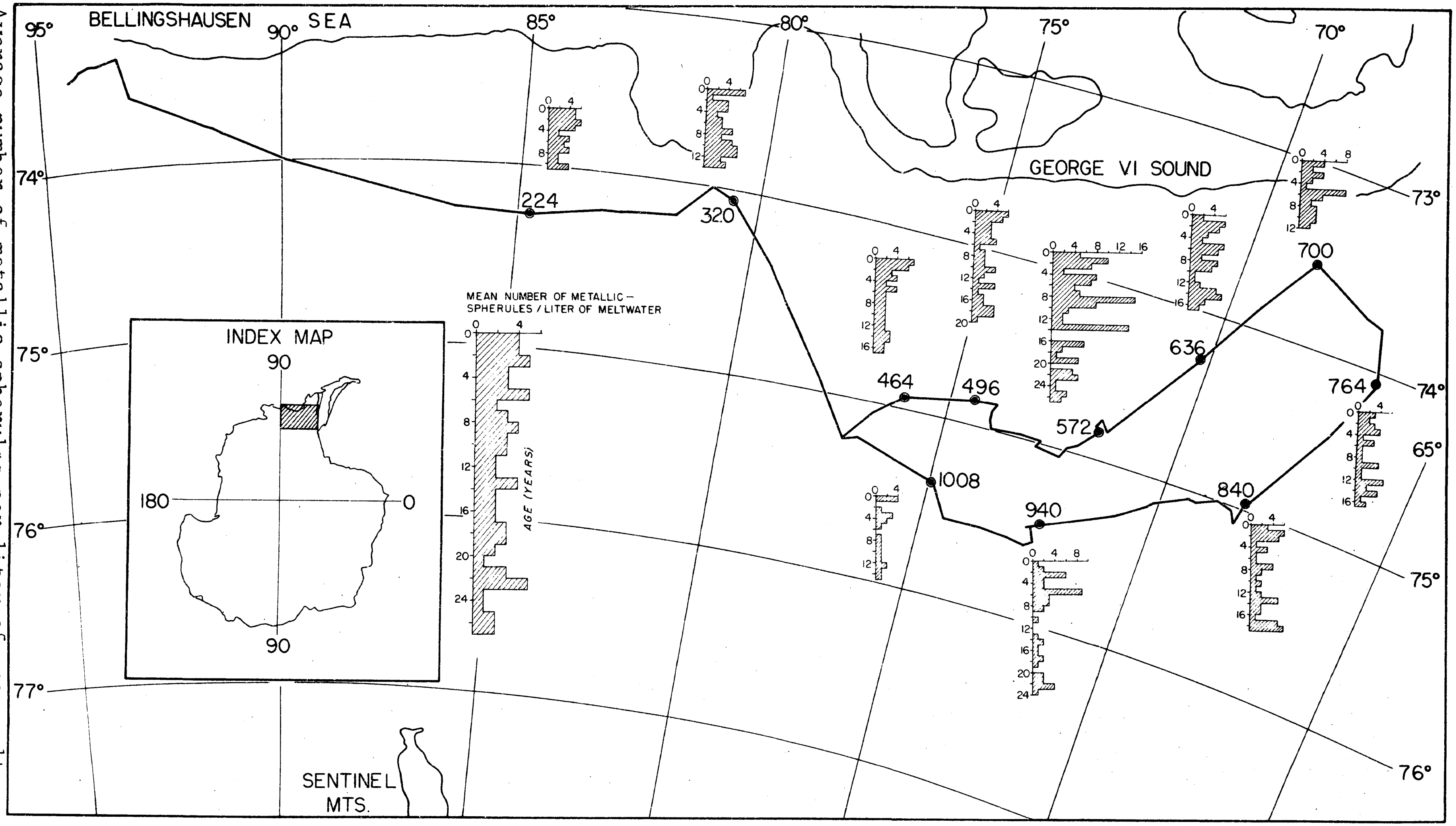

Figure 9. Average number of metallic spherules per liter of snow melt-water.

occurrence as indicated by these data was demonstrated among the stations. In addition, the ANL values for Antarctic Peninsula sites were from 10 to 50 times less than those reported by Langway (1963) for Greenland samples. At the present state of spherule studies, this enormous discrepancy should not be considered discouraging. Little is known about the character of spherule deposit at any point on the earth's surface during a period of several years. The oft-made assumption that the particles were uniformly deposited on the entire earth may be erroneous, and this apparent disagreement may be the first clue to such an important discovery.

A natural cause for variations in spherule occurence may be related to the earth's magnetic field, as suggested by Parkin and Hunter (1962). Langway's Greenland site was at a much higher geomagnetic latitude than the region covered by the Antarctic Peninsula Traverse.

Alternatively, however, it could have been possible that some of the particles in Langway's samples might have been of terrestrial origin. Langway's (1963) description of the spherules he recovered from Greenland snows mentioned that many were hollow, and that they yielded density values of about 4.5 gm cm^{-3}. Fredriksson (1961) recovered similar, hollow spherules from a collecting station in Hawaii, and attributed them to a volcanic origin. However, no modern, active volcanoes are known in the Greenland area. Langway also noted that electron probe analyses of at least one group of these spherules failed to disclose the presence of nickel, considered to be characteristic of metallic meteorites. As noted earlier, this may not be a primary criterion for resolving questions of particle origin. Perhaps some particles could be produced by industrial means. However, it remains to be determined whether patterns of atmospheric circulation exist which could carry industrial particles to Greenland from the manufacturing centers of the United States and Canada. Unless and until such a process is proved, the writer joins with Langway in regarding these particles as extraterrestrial matter.

The lack of correlation of spherule occurrence among the stations in the limited area of the Antarctic Peninsula Traverse probably reflected the influence of an additional factor, the character of the snow surface. Rapid changes in snow surface were observed over a short period of time. Reconnaissance flights discovered a hard snow surface marked by many sastrugi along part of the traverse route, but when the field party reached that area only three weeks later it encountered instead a featureless plain of soft, powdery snow (Behrendt, personal communication, 1963). Furthermore, sastrugi directions indicated wide fluctuations in surface wind directions (Shimizu, personal communication, 1963), which might be expected for this narrow isthmus between the Bellingshausen and Weddell Seas. It appears likely, therefore, that parts of each year's deposit have been affected by the action of surface winds, and that such effects have neither been uniform nor related in a simple manner throughout the area. The result of such wind-produced modifications in snow surface has been to seriously hamper correlation of snow layers and their contained particulate matter among the stations. This represents a major drawback to Marshall's (1959, 1963) suggestion that particulate matter can be used as a quantitative stratigraphic parameter for correlation of glaciological measurements over broad areas of a polar ice cap.

Finally, the occurrence of spherules at each station of the Antarctic Peninsula Traverse was compared to other local parameters to discover whether some correlation with these effects may perhaps be present. Table 11 lists these data. Unfortunately, no systematic relation of these values with spherule occurrence was revealed. Probably, topographic effects, station elevation, local winds and storms were complexly related to accumulation, and in this way only had a regular relationship to spherule occurrence. Both gravity values and magnetic field measurements were too nearly constant throughout the area of the traverse to greatly influence spherule occurrence. In addition, surface meteorological influences would mask their contributions. Gravity and magnetic effects upon the spherules were probably more significant when the particles were approaching the earth from space.

Annual Deposit

The annual deposit of metallic spherules was determined for each station using the mean annual snow accumulation and the total mass of spherules occurring in yearly snow layers. The mass of each spherule was computed from its measured diameter and the mean density value. Assuming that the spherules fell to earth during deposition of the snow layer in which they were found, the sum of the masses of individual particles occurring in annual layers gave the total mass of spherules for each year. These values were listed in Table 12. Mean values were computed to represent the ranges obtained for each station. Again, no correlation of yearly layers from station to station was apparent.

To permit comparison of data of the present study with previous works, estimates of the annual deposit of spherules over the earth were prepared by extrapolation. It was assumed here, as in the earlier estimates, that the spherules had been uniformly deposited over the entire surface of our planet. This assumption was adopted in lieu of knowledge about the character of spherule occurrence over regional areas of the earth's surface. Probably, however, it represents an ideal case which nature approaches but has not achieved.

Separate estimates of annual spherule deposition for the earth were prepared from data of each station (Table 13). The values covered a considerable range, from 0.4×10^5 metric tons per year (Station 940) to 2.4×10^5 metric tons per year (Station 572). This range can be explained by local features. Figure 10 showed that an apparent direct relation existed among mean snow accumulation and annual spherule deposit at seven of the eleven stations (Stations 224, 320, 700, 764, 840, 940, and 1008). These stations were located in widely separated parts of the region, had markedly different elevations, and showed greatly deviating surface wind directions (Table 11). In considering these factors together, it was

TABLE 11

Comparison of Data for Metallic Spherules, Antarctic Peninsula Traverse, 1961-1962

Item	Sta. 224	Sta. 320	Sta. 464	Sta. 496	Sta. 572	Sta. 636	Sta. 700	Sta. 764	Sta. 840	Sta. 940	Sta. 1008
Number	90	97	51	62	106	67	67	48	49	36	36
Avg. diameter	32	32	37	44	51	46	37	39	37	41	40
ANL	4	4	3	3	5	4	2	2	3	2	1
Avg. mass/yr ($x10^{-9}$ gm)	1342	1077	911	1020	1994	1483	1309	778	475	302	577
Annual accumulation ($x10^5$ metric tons)	1.6	1.2	1.1	1.2	2.4	1.8	1.5	0.9	0.6	0.4	0.8
Frequency (spherules cm^{-2} yr^{-1})	.30	.22	.15	.08	.14	.11	.21	.11	.08	.05	.09
Annual snow accumulation (cm water equivalent)	52	42	27	27	20	34	46	33	28	20	35
Station elevation (meters)	1055	857	715	1041	1443	1434	1045	2120	1721	777	520
Surface winds	SE	SE	NE	NE	NE	NE	N	N	E	E	E
Observed magnetic field strength (gammas)	53,595	52,755	52,455	52,195	51,830	51,335	50,840	50,600	51,520	52,080	52,555
Observed gravity (gals)	982.5588	982.5752	982.7205	982.6299	982.4674	982.3823	982.5243	982.2603	982.4345	982.6333	982.7530

TABLE 12

Mean Annual Mass Deposit of Metallic Spherules: Antarctic Peninsula Traverse, 1961-1962
(N.B. Values for annual mass deposit of spherules should be multiplied by 10^{-9} gm)

Age (years)	Sta. 224	Sta. 370	Sta. 464	Sta. 496	Sta. 572	Sta. 636	Sta. 700	Sta. 764	Sta. 840	Sta. 940	Sta. 1008
0-1	2075	1298	--	3040	3438	1277	1188	776	726	132	2954
1-2	1817	74	--	2080	4740	1313	607	982	708	826	0
2-3	1393	2884	441	977	1985	654	820	2985	640	446	791
3-4	832	833	185	458	4439	717	434	575	62	588	854
4-5	703	251	530	140	1466	859	288	773	273	93	179
5-6	3487	752	373	3149	943	1135	5895	3174	44	1641	125
6-7	714	922	206	1006	3224	1052	1270	214	177	454	990
7-8	1172	2634	257	506	1905	1718	1554	263	1051	19	342
8-9	210	318	322	381	4606	2085	1017	15	895	14	225
9-10	506	1197	764	689	1002	737	1482	371	669	119	113
10-11	1854	1279	734	1000	1044	15	904	127	687	0	590
11-12		1318	162	622	838	175	247	67	121	0	357
12-13		242	1061	1476	425	262		453	265	247	319
13-14			585	61	3900	1110		522	1056	419	244
14-15			341	785	0	11419		795	619	181	
15-16			232	355	0	487		358	286	92	
16-17			540	1380	3388	198			52	676	
17-18			8416	311	555				215	165	
18-19			328		617					0	
19-20					775					222	
20-21					93					105	
21-22					2363					635	
22-23					11339					166	
23-24					0					0	
24-25					426						
25-26					238						
26-27					90						
AVERAGE	1342	1077	911	1020	1994	1483	1309	778	475	302	577

TABLE 13

Annual Deposit of Metallic Spherules on the Earth's Surface

Station	Annual Deposit ($\times 10^5$ metric tons Earth $^{-1}$yr^{-1})
224	1.6
320	1.2
464	1.1
496	1.2
572	2.4
636	1.8
700	1.5
764	0.9
840	0.6
940	0.4
1008	0.9
Mean, Antarctic Peninsula Traverse	1.2

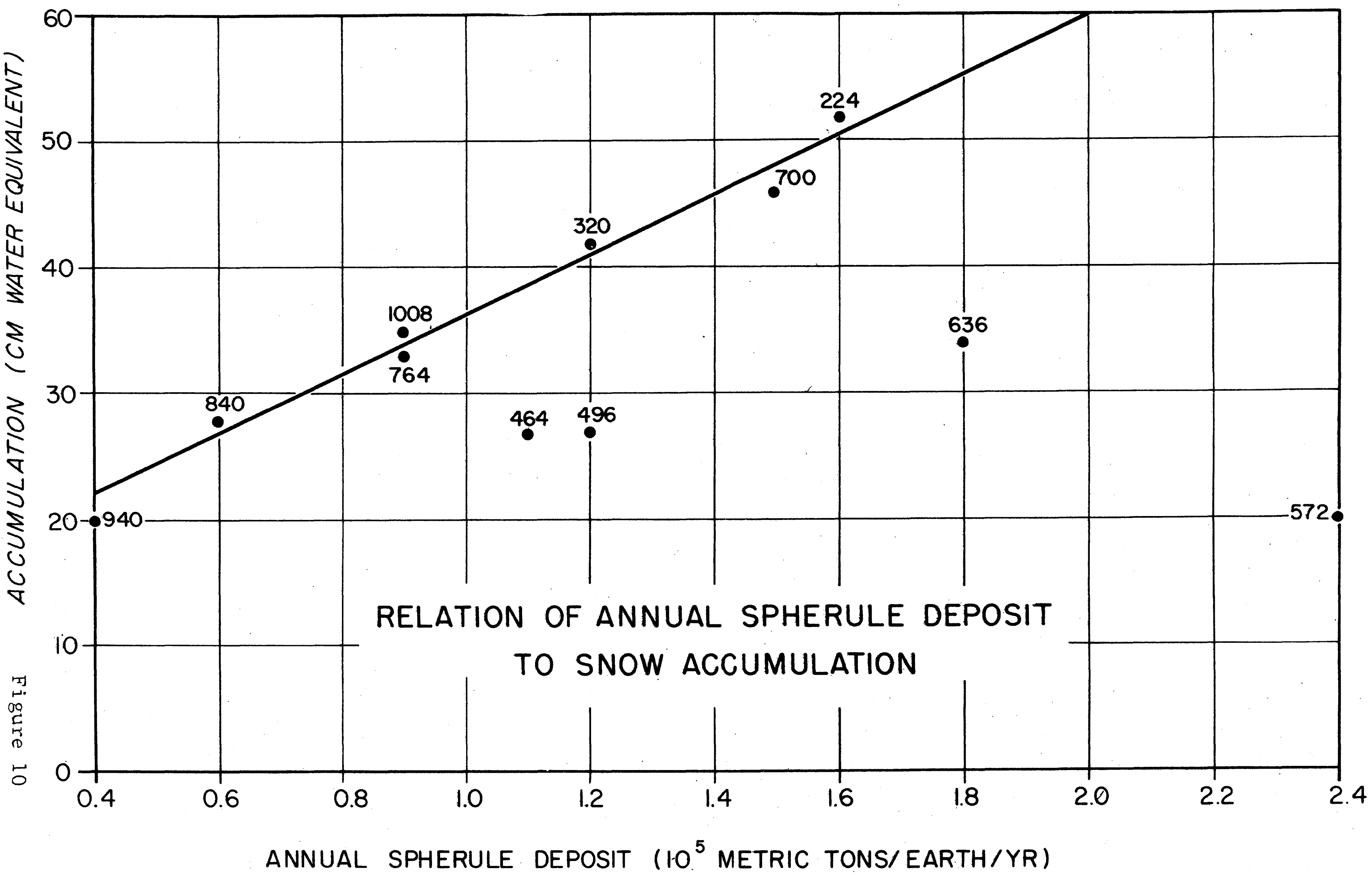
RELATION OF ANNUAL SPHERULE DEPOSIT TO SNOW ACCUMULATION

Figure 10

found that greatest snow accumulation occurred at low elevations near the Robert English Coast, with smaller amounts being deposited in the lee of the east-west surface ridge just north of Eights Station (Fig. 11). This suggests that major deposition of snow occurred when moisture-laden air from the Bellingshausen Sea moved southward and was forced to rise upon encountering the surface of the ice cap. As suggested earlier, the accumulating snow apparently captured the spherules, producing the observed relations with annual particle deposit.

Exceptions to this general relation were shown by Stations 464, 496, 572, and 636. While these stations had lower snow accumulation, they indicated high annual spherule deposits. This was caused by the high proportion of larger spherules recovered from these stations; more than 22% of all spherules from each site were greater than 60 microns in diameter. These stations had many other features in common. Each was established in the vicinity of local nunataks, which probably locally altered the general pattern of snow accumulation. Furthermore, Stations 464, 496, and 572 were located in the immediate shadow of the regional surface ridge (Fig. 11). Although Station 636 was on the windward side of this ridge, it was situated on a broad flat bench just above a steep slope. Finally, these stations were the only ones in the area at which a north-easterly surface wind direction was discovered (Table 11: Shimizu, personal communication, 1963). Moreover, these stations were directly across the "track of sea level depressions" shown for this area by Alt et al. (1959). These relations suggested to the writer that the anomalous annual deposit values at these stations were caused by large particles carried in by storm systems. Deposition of the particles probably occurred through a combination of the effects of local and regional topography upon the carrying power of the storm winds. This is best shown by Station 572, which is most shadowed by the surface ridge and which had the greatest percentage of large particles. Stations 464 and 496, opposite a small saddle in the regional ridge through which the storm winds could move more easily (Fig. 11), showed the smallest departure from the general relationship indicated by the majority of stations. Station 636 was intermediate between these extremes, probably because of its location.

Figure 12 shows cumulative rates of spherule deposition for the sites sampled. Values obtained were consistent among the stations, with differences among them attributable to local snow accumulation and topography. The total rate of deposition shown by the present samples was slightly less than that obtained in the preliminary study (Thiel and Schmidt, 1961), suggesting that spherules were deposited at a slower rate in this area. Stations sampled in the earlier study were located much closer to the magnetic pole, and magnetic field effects might have contributed to the different rates. However, the difference is slight and the data are too few to justify further speculation. New samples from the South Polar Plateau will be examined to investigate this area in greater detail.

Results of similar studies at other places on the earth are of interest in this context. The mean annual deposit of metallic spherules,

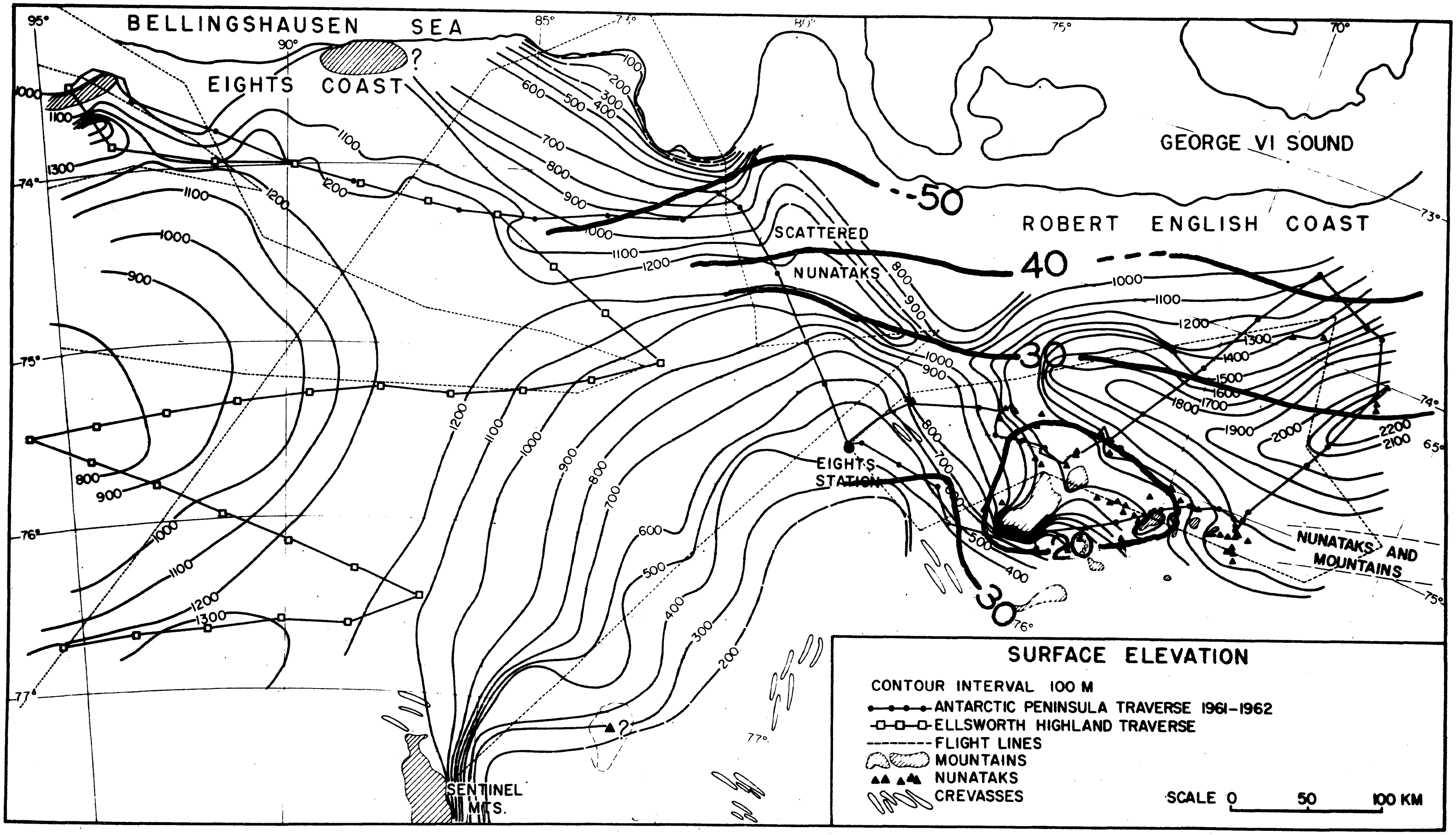

Figure 11. Contours of surface elevation (light lines) and snow accumulation (heavy lines), (After Behrendt, 1963).

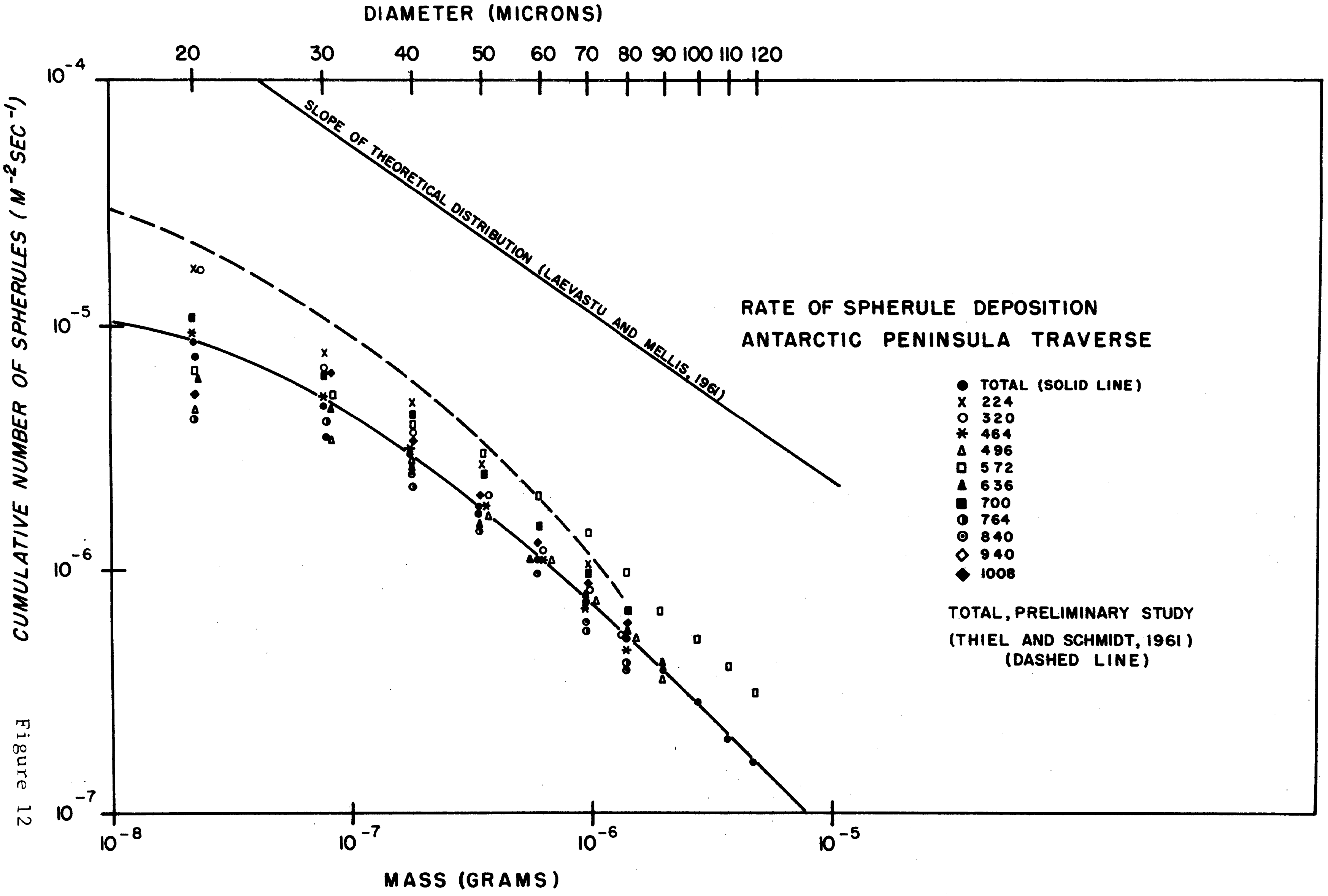
DIAMETER (MICRONS)
20
30
40
50
60
70
80
90
100
110
120
10^{-4}
10^{-5}
10^{-6}
10^{-7}
CUMULATIVE NUMBER OF SPHERULES ($M^{-2}SEC^{-1}$)
SLOPE OF THEORETICAL DISTRIBUTION (LAEVASTU AND MELLIS, 1961)
RATE OF SPHERULE DEPOSITION
ANTARCTIC PENINSULA TRAVERSE
● TOTAL (SOLID LINE)
X 224
○ 320
✱ 464
△ 496
□ 572
▲ 636
■ 700
◐ 764
◎ 840
◇ 940
◆ 1008
TOTAL, PRELIMINARY STUDY
(THIEL AND SCHMIDT, 1961)
(DASHED LINE)
10^{-8}
10^{-7}
10^{-6}
10^{-5}
MASS (GRAMS)

Figure 12

suggested for the entire earth by samples collected from the Antarctic Peninsula Traverse region, was 1.2 x 10^5 metric tons. This contrasted with those for similar sized particles at low magnetic latitudes (Crozier, 1962; 0.5 x 10^5 metric tons) and higher magnetic latitudes (Langway, 1963; 9 x 10^5 metric tons). These limited data suggest that the earth's magnetic field might exert an important influence upon spherule occurrence over regional areas of the globe.

Discussion

The writer regards the particles recovered in this work as extraterrestrial in origin. It is unlikely that the physical properties and chemical compositions of the spherules, which so closely approached those of macroscopic meteorites, could have been produced through industrial means or terrestrial events. Rocks in the traverse area were not found to contain any mineral species similar to these particles. Furthermore, it seems unlikely that particles of this composition and character could be produced by volcanic action. The nearest known active volcano is Mt. Erebus, located in McMurdo Sound, about 2500 km away from the traverse area. Glasstone's (1962) fallout calculations show that it would be impossible for particles of the size collected to be transported such distances. Even if the particles could be produced artificially, it seems hardly possible that they could have been transported enormous distances to Antarctica, where there is little evidence for the widespread industrial contamination this hypothesis requires. The systematic relationships of spherule size, frequency of occurrence, and annual deposit with snow accumulation could scarcely be attributed to contamination during shipping and handling of snow samples and filtrates. Too large to be considered cosmic dust, not apparently related to cometary meteors as meteoric dust, and situated far from known meteorite falls, the evidence thus suggests that most of the particles discovered were micrometeorites as defined by Krinov (see Schmidt, 1963).

The micrometeorites studied in the present research were probably directly related to the dust cloud discovered by rocket, satellite, and space probe measurements in the space near the earth. High altitude particle collections (Soberman, et al., 1962) have recovered metallic spherules from the fringe of space, and it is reasonable to postulate that such particles exist as a myriad of natural earth satellites beyond the practical limits of the atmosphere. Dole (1962) has shown that these particles could be concentrated into a dust cloud entirely by the gravitational attraction of the earth, providing their velocities were sufficiently low. Spherule data suggest that magnetic field effects may influence particle deposition on earth. Probably, a steady state exists in the dust cloud, with slowly travelling particles being constantly added from space to take the place of those accreted by the earth. Fast moving particles on divergent trajectories from the earth would not be appreciably affected by the earth's pull, and would fly past the earth into space.

The surface appearances of most metallic spherical micrometeorites were consistent with a presence in the dust cloud, their pockmarked textures probably being caused by the impacts of even smaller particles comprising the dust cloud in space. This suggests that these spherules travelled with low velocities, and that they entered the earth's atmosphere at low angles of incidence, preventing the occurrence of surface melting and preserving the fine details of the spherule surfaces (Öpik, 1956). The work of O'Keefe (1961) has shown that the decaying orbit of a natural earth satellite would result in a low angle of incidence with the atmosphere, supporting the proposed means of preserving spherule surface features. On the other hand, spherules with highly polished surfaces apparently entered the atmosphere at high velocities and/or high angles of incidence. Becoming molten as a result of frictional effects, all traces of surface texture would be destroyed on those spherules. It would appear that the polished spherules were travelling too fast to have spent much time, if any, in the earth's dust cloud, and they may represent samples of matter more directly from space.

Data for glassy spherules are less complete, although it appears likely that a similar explanation may be applied to them as well. The surface features of the mottled, olive brown glassy spherules (microtektites?) may also be explained in this way, but further work is required to prove this tentative conclusion.

The compositional, mineralogical, and physical similarity of micrometeorites to larger meteorites suggests that they may have been formed through similar processes. Current thinking on the origin of meteorites assigns an important role to bodies of at least asteroidal dimensions, probably situated in the asteroid belt between the orbits of Mars and Jupiter. Meteorites could have been produced in this area by planetary breakup (Ringwood, 1961; Parkin and Hunter, 1962), by destruction of primary and secondary objects (Urey and Craig, 1953) or by collisions between asteroids (Anders and Goles, 1961). Each of these hypotheses appears capable of producing material similar to that described here, and in amounts compatible with observed rates of deposition.

Comets and cometary meteors probably contribute significant amounts of particles to the earth's dust cloud by evaporation of comet nuclei. Freed to space during comet passage, solid particles and flakes could be gravitationally attracted to the region about the earth as discussed earlier. Perhaps angular flakes from this source achieve rounded or spherical forms during their encounters with increasingly more dense portions of the atmosphere. Alternatively, it is possible that spherules exist in comets themselves.

The lunar surface could possibly contribute other particles to the earth's dust cloud. Dislodged from the moon by impacting meteorites, such material could have been ejected into space where particle capture by the earth's gravity field might have been possible (Gault, 1963). Observations of the moon's surface suggest that it is covered with finely divided material, lending support to this view. Of course, this explanation is best applicable to glassy particles (microtektites and tektites???) because of the siliceous character of the moon. However, it is conceivable that metallic particles could have been produced from explosion of the meteorites which impacted on the moon and that some of these particles populated the earth's dust cloud. It should be possible to examine these suggestions first hand before long.

The total observed rate of microparticle deposition on the earth raises interesting questions of planetary origin. The most often mentioned hypothesis for the origin of our solar system suggests that formation of the planets took place through gravitational accretion of dust particles (Kuiper, 1956). Under the principle of uniformitarianism, the present deposition of micrometeorites may be considered as a modern analog to the primeval process by which the earth developed. Of course, the present rate of particle deposition is much reduced from that which prevailed during the birth of the solar system. Extrapolating present rates of particle deposit unchanged throughout geological time, about 10^{14} metric tons would have accumulated; this is less than the mass of the earth by a factor of 10^7. Clearly enormous numbers of particles and much greater deposition rates early in the history of planet formation would be required for development of the earth, as stipulated by most proponents of the accretion hypothesis. The particles collected today may thus be akin to the building blocks of our solar system, and in fact, we may be observing a continuation of the process responsible for the origin of the world we live in.

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