Institute of Polar Studies
Report No. 14

Glaciological Investigations on Sukkertoppen Ice Cap, Southwest Greenland, Summer 1964

by

Arthur S. Rundle
Institute of Polar Studies

February, 1965

The Ohio State University
Research Foundation
Columbus, Ohio 43212

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ABSTRACT

Glaciological studies were made on the Sukkertoppen Ice Cap, southwest Greenland, during August, 1964. Temperatures at depth indicate that much of the ice cap is temperate. Zonation according to Benson's facies concept is complex and there is probably overlapping of facies. Accumulation across the ice cap appears to be fairly uniform and any differences from one locality to another are small. Snow pit and core analysis show significant variation in accumulation from year to year, in some cases as much as 100 per cent. Along the traverse route the mean net annual accumulation is 31 cm of water. Some processes involved in firn densification in the soaked facies of Benson's classification are discussed.

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1 Map of Sukkertoppen Ice Cap, route, and study sites.

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3 Accumulation at four main sites

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INTRODUCTION

The Sukkertoppen Ice Cap in southwest Greenland lies between Søndre Strømfjord and Evigshedfjord and has an area of approximately 2000 km^2 (Fig. 1). It has a varied topography but generally its surface elevations are between 1200 and 1700 meters.

The ice cap has many features which make it an ideal area for glaciological study. Its boundaries are so easily and concisely defined that it can be considered as a distinct geographical unit. Geophysically little is known about the ice cap or any other similar-sized body of ice at this latitude and in this type of environment. Furthermore, the ice cap is situated in a region of particular interest in the fields of biology, geology, and meteorology, so an understanding of its nature, behavior, and possible effects on adjacent areas assumes special importance.

Before 1962, glaciological investigations of a general nature had been carried out by five expeditions, four from Oxford University and the other from Cambridge University (Mott, 1937; Sugden and Mott, 1940; Etienne, 1940; Hayward, 1956; and Holland, 1961). Though brief journeys were made onto the ice cap by these expeditions, most of their work was confined to the peripheral areas.

In 1962 a three-man group from The Ohio State University made a two-way crossing of the ice cap, man-hauling their supplies and equipment on a small fiberglass sled. Gravity measurements were made at 19 stations on the ice cap from which details of the subglacial topography were derived (Bull, 1962).

On July 31, 1964, a two-man glaciological team from The Ohio State University (A. S. Rundle, glaciologist, and R. A. Spahn, Jr., assistant glaciologist) established its first camp on the western side of the ice cap at approximately 66°20'N, 52°27'W.

The purpose of the 1964 glaciological program was to extend the work of Bull by making an assessment of snow accumulation across the cap, measuring temperature within the ice in order to determine its physical nature, and by studying the densification of snow in an area of other than dry snow.

A crossing was made from east to west closely following the route taken by Bull (Fig. 1). Supplies and equipment were man-hauled on an akhio equipped with a pair of skis (Fig. 2). This modification reduced considerably the frictional drag normally experienced with this type of sled and allowed two men to pull an initial load of 580 lb with relative ease.

During the crossing, four two-meter pits were dug. Stratigraphy, grain size, hardness, and density of the firn were recorded. Using a standard SIPRE coring auger, an eight- to ten-meter core was retrieved

through the floor of each of the pits to provide firn samples from a total depth below the surface of twelve meters and fourteen meters, respectively. The cores were examined for stratigraphy, grain size, hardness, and density. Temperature values were obtained from the snow pit walls and from the bore holes.

Twenty-six accumulation markers were placed along the route (Table 1). Each marker consisted of a bamboo pole, 12 feet long and one inch in diameter, to which was attached a large red flag. Each pole was marked with a knife cut two meters above the snow surface. None of the markers left by Bull in 1962 were seen by the 1964 party.

TABLE 1. ACCUMULATION MARKERS PLACED ON SUKKERTOPPEN ICE CAP, AUGUST, 1964

Approximate Miles East from Station 1 at 66°20'N 52°27'W	Flag No.	Station	Date
1.50	1		August 8
3.00	2		August 8
4.25	3		August 8
5.00	4	2	August 8
5.50	5		August 12
6.50	6		August 12
7.50	7		August 12
8.25	8		August 12
10.00	9		August 12
10.50	10	3	August 12
11.50	11		August 15
12.50	12		August 15
14.50	13	4	August 15
15.50	14		August 19
16.50	15		August 19
17.25	16		August 19
18.00	17	5	August 19
18.33	18		August 26
18.67	19		August 26
19.00	20		August 26
19.50	21		August 26
20.00	22		August 26
20.50	23		August 26
21.00	24	6	August 29

Two supplementary markers were placed to the south of Camp No. 6 on August 29

ACCUMULATION

Introduction

According to the classical interpretation of stratigraphy, annual horizons in a firn section may be tentatively identified by observing certain specific features in the firn. Depth hoar, and significant changes in grain size, hardness, and density, are valuable indicators. These, when used in conjunction with records from accumulation markers set in the snow, allow a very reasonable measure of annual accumulation.

Conditions on Sukkertoppen Ice Cap

The firn sections observed on the Sukkertoppen Ice Cap in 1964 do not lend themselves to a simple analysis for the determination of snow accumulation. High summer temperatures, the presence of free water, and percolation have led to considerable metamorphism of the firn. Consequently, the classical indicators have been partially or wholly obliterated.

A series of changes in the upper layers of the firn was observed taking place during August. High temperatures caused melting in the top 15 to 20 cm, thus allowing complete soaking of this layer. This resulted in an extremely incoherent granular layer which contained many small ice glands and wafer-thin ice layers and lenses. A sudden drop in temperature caused this entire layer to freeze and become hard, coherent firn and firn-ice. To a certain extent this occurred each night, with a reversal during the heat of the following day. Fresh, fine-grained drift, deposited during a storm, quickly changed and became part of this melt surface.

In the interpretation of the profiles, these frozen melt surfaces have been sought and used in conjunction with observed, significant changes in grain size, hardness, and density. These layers will later be thickened and developed by further soaking and percolation. Fine-grained, relatively ice-free, winter snow lies above them, and softer, coarse-grained, low-density snow (depth hoar) lies below them. This is seen particularly well at a depth of two meters in three of the pits.

The degree of depth hoar formation will be influenced by local meteorological conditions at the time of its formation. Essentially, the steeper the temperature gradient and the longer it is maintained, the greater the development of depth hoar. Though the actual temperatures recorded at Søndrestrøm Air Base do not indicate an exceptionally severe winter in 1961-62, they do show that the winter cold did last longer than in previous years. Such an extended cold period would allow the greater development of depth hoar now seen at approximately two meters.

Accumulation values interpreted from these profiles are shown in Table 2 and in Fig. 3. The values in Table 2 are similar to values determined near Mt. Atter in the southwest part of the cap, where the mean for the period 1930-38 was 33.9 g cm^{-2} (Etienne, 1940) and 34.3 g cm^{-2} for the period 1948-56 (Holland, 1961). However, they do not correspond with Bull's figures of 17.6 g cm^{-2} near Site 2, 14.9 g cm^{-2} near Site 3, and 16.0 g cm^{-2} near Site 4 (Bull, 1962).

TABLE 2. TABLE OF ACCUMULATION VALUES
Grams/sq cm

Year	Site 1	Site 2	Site 3	Site 4
1963-64	28.3	32.2	34.7	24.1
1962-63	31.5	39.0	34.1	26.3
1961-62	30.4	30.4	31.4	20.8
1960-61	21.8	23.9	25.3	27.5
1959-60	32.3	34.2	33.5	32.7
1958-59	31.9	30.9	33.5	39.7
1957-58	34.5	36.5	35.6	35.8
1956-57	31.1	40.1	26.7	40.0
1955-56	25.6	31.9	--	31.6
1954-55	22.2	28.6	--	25.0
1953-54	29.4	27.7	--	39.0
1952-53	35.3	--	--	--
Mean 1953-63	29.5	32.3	32.2	31.1

ICE TEMPERATURES

Using a thermometer, reading to 0.2°C, temperatures were recorded at five-centimeter intervals in the snow pit walls. After each section of the core was removed from the bore hole, the temperature was recorded at the bottom of the hole, i.e., at approximately one-meter intervals. The results are shown in Fig. 4 and in the profile diagrams.

These curves show, in varying degree, the effects of the winter cold wave. The minimum temperatures at Sites 1, 2, and 3 occur (in August) at a depth of about six meters.

At Site 4 the minimum temperature in August was -3.7°C, at a depth of five meters. From this it may be calculated (see, for example, Cameron and Bull, 1962) that the mean temperature in the coldest month should be about -30°C. Since the mean temperature at Søndrestrøm for the coldest month is -14°C, this value (-30°C) at 1600 meters appears reasonable.

The temperature at a 12-meter depth is about -1°C at each site. However, this does not represent mean annual air temperature because of the transfer of heat energy by percolating meltwater.

FIRN Ddensification

Introduction

As snow accumulates compaction or densification occurs in response to the increased load. In Greenland, Sorge in 1930-31 (revised by Bader, 1954) pointed out that in areas where there is no melting in the summer, the density of snow at a given depth does not change with time, provided the conditions of accumulation remain constant. Kojima (1964) considers this process as "a kind of viscous flow caused by the overlying snow."

If the known rate of accumulation remains constant, a depth at which ice or firn of a given density might occur can be computed. However, this case remains true if only the overlying load is considered the causal factor. Other factors, such as wind packing, melting, percolation, and sublimation, will invalidate a simple expression of the process of densification. These complex conditions exist on the Sukkertoppen Ice Cap.

Conditions on Sukkertoppen Ice Cap

The core profiles taken in 1964 show several interesting features (Fig. 5).

(1) Each section has a considerable amount of ice.

(2) There is a remarkable alternation of pure, very bubbly ice and milky "granular" ice, in which the individual grains are no longer visible but where the intergranular air bubbles have not been closed off.

(3) In many cases the boundary between these two types is remarkably distinct and abrupt (Fig. 6).

The "wetness" of each site was noted in the field, though it was not measured quantitatively. Site 2 (approximately 1510 m) was the wettest site. Wetness decreased from west to east from Site 1 (1650 m) to Site 3 (1520 m) and Site 4 (1520 m). Site 2 lies on the periphery of the ablation basin of a large glacier at the foot of a high dome. Local meteorological conditions, a foehn wind effect in particular, are believed to be responsible for the wetness of Site 2. Examination of the profiles reveals that the degree of iciness accords with the degree of wetness.

The depth at which the milky ice first occurs is also remarkably constant, at about six meters; at Site 2 this depth is slightly less. In the depth-density profiles for Sites 1, 2, and 3 there is a distinct break occurring at or close to six meters depth.

Five-point running means of the density values were plotted for each site (Fig. 7) in an effort to bring out this break more clearly. The curves show that the firn above the point of minimum temperature, five to six meters, has a density less than 0.550, whereas below this point the firn is more dense. The value of 0.550 is approximately the density that is expected, by Sorge's Law, in dry snow at a depth of 12 meters with an annual accumulation of 31 g cm^{-2}. Sorge's density values at this depth were:

Recorded:	0.537
Calculated:	0.534 (Bader, 1954)

Site 4 has the same accumulation as Sorge's Eismitte but the density of 0.550 is reached at a depth of just over five meters.

Conclusions

In an area soaked with meltwater, as on the Sukkertoppen Ice Cap, the formation of ice from snow is a process in two parts. Down to a depth of about six meters, the overburden causes compaction and an increase in the density of the firn. Surface melt percolates to about six meters so that in the summer the firn is isothermal, at 0°C, to this depth.

Ice layers are built up and the firn increases in iciness, especially at six meters where further percolation is not possible due to lower temperature. At this depth ice is rapidly built up.

Any firn layers which are not completely iced or incorporated into ice layers before they reach a depth of six meters will not increase in density by this refreezing process. The densification below six meters will be governed by the load. An interpretation of this kind explains, in some measure, why there is a sudden alternation of milky ice and bubbly ice, and especially why the boundaries between them are so abrupt.

This situation is recorded by Schytt (1955) at low altitudes on the Thule Ramp, northeast Greenland, and is an expected conditon between the firn line and saturation line of a glacial body (Bader, 1954). However, the zonation on Sukkertoppen Ice Cap cannot be simply and concisely described with current terminology. Müller (1962) describes similar problems on Axel Heiberg Island, where he found it necessary to subdivide Benson's facies. Wagner (1963) also noted a complex condition on Kaskawulsh Glacier in the Yukon and concluded that there is a considerable overlapping of zones.

The Sukkertoppen Ice Cap, up to an altitude of 1600 meters, lies in the soaked facies of Benson's classification. However, there is probably a broad overlap of the soaked facies and superimposed ice facies.

ABLATION AND SUPERIMPOSED ICE ZONES

Conditions on the Western Edge of the Ice Cap

In August, 1964, pit and core studies at 12 sites approximately 100 meters apart revealed that along a line from its edge to a distance one km onto the cap, the depth of snow ranged from 45 to 90 cm. Below this snow was solid bubbly ice, some of which was overlain by a readily recognizable cryoconite surface, in which the original cryoconite holes were five to six cm deep. An excessively dirty layer characterized the upper part of the bubbly ice (Fig. 8).

Evidently this area has not always been covered by snow. The cryoconite surface encountered at some of the sites is indicative of direct radiation on a dirty ice surface. The considerable concentration of dirt in the upper part of the ice must be the result of prolonged exposure when there was little or no snow cover. All the snow was completely saturated and melting. Excavations revealed meltwater seeping away, downslope at the snow-ice interface.

At one site, about 0.5 km inland from the snow edge, densities as well as stratigraphy were recorded. The results are summarized below:

Depth cm	Grain Size mm	Description	Depth	Density
0- 6.0	1.0	Soft fresh snow, lightly packed and wet	5.5	0.280
6.0-15.0	up to 4.0	Hard, coarse grains, banded together, icy in bottom	8.5	0.385
			12.0	0.394
15.0-19.0	--	Ice layer	14.0	0.417
19.0-24.0	1-2	Medium hard	17.0	0.533
24.0-25.0	--	Large ice lens	20.0	0.495
25.0-39.0	1-2	Medium hard, with small ice lenses	24.0	0.412
39.0-41.0	--	Ice layer	27.0	0.397
41.0-54.0	1-2	Medium hard	32.0	0.451
54.0-60.0	up to 5	Soft coarse grain. Crystal forms evident in places overlain by ice	34.5	0.440
			44.0	0.392
60.0-75.0	1-2	Soft at top getting harder downward	46.0	0.416
75.0-79.0	3	Very soft, very coarse	51.0	0.420
79.0		Dirty ice "pavement"	55.0	0.334
			59.5	0.420
			64.0	0.357
			71.0	0.382
			73.5	0.354

Assuming that the very low density recorded at 55.0 cm and the soft crystalline layer recorded between 54.0 and 60.0 cm represents a summer surface (i.e., 1963), it follows that all of the 1962-63 accumulation, plus a little from the previous year, remains. The accumulation between summer 1963 and summer 1964 totals 23.9 g cm^{-2} in this section.

At this same site a short core (85 cm) was taken from the old ice surface, described as follows:

0 - 3 cm	Fairly clean bubbly ice
3.0- 5.0 cm	Very dirty ice
5.0- 7.0 cm	Fairly clean ice
7.0 cm	Black band of dirt about 0.5 cm thick (Fig. 9)
7.5-13.0 cm	Fairly clear ice with a few large (0.5 cm) pockets of dirt
13.0-46.0 cm	Clean ice with many bubbles
46.0-64.0 cm	Almost clear ice, but a few tiny specks of dirt
64.0 cm	A sudden boundary. Ice below this has several pockets (0.5 cm) of dirt.
64.0-78.0 cm	Dirty ice. Specks getting smaller.
78.0-85.0 cm	Quite clean ice, with many bubbles.

Schytt (1955) describes a similar situation on the Thule Ramp in Greenland. There he found several distinct dirt horizons in what he considered to be superimposed ice. He concluded that the heavy dirt bands were representative of old cryoconite surfaces, and that the clearer intervening ice represented superimposed ice, laid down from meltwater, refreezing below a thin snow cover.

Using his arguments, it follows that in the core examined the dirty ice between 3.0 and 7.0 cm represents an old cryoconite surface which was last exposed, possibly in 1963 (the exact year, however, is not clear), and that the clean ice between 13.0 and 46.0 cm or even down to 64 cm is superimposed ice, laid down on an older cryoconite surface at 64.0 cm depth. The clean ice from 0 to 3.0 cm and 78.0 to 85.0 cm would also be superimposed ice.

Conditions on the Eastern Edge of the Ice Cap

An initial pit, dug about 2 km from the eastern edge of the cap, upslope from the head of Tasersiaq Tongue, revealed 110 cm of wet snow overlying darker ice.

Five other sites were studied from pit and core samples along a line beginning 2.5 km above the head of Tasersiaq Tongue and extending 4.5 km upslope onto the cap. The depth of snow overlying solid ice along this line was:

Site A	140 cm
Site B - 1 km upslope from A	131 cm
Site C - 1 km upslope from B	373 cm
Site D - 1 km upslope from C	more than five meters
Site E - 1 km upslope from D	more than five meters

From the examination of the stratigraphy at Site B (a pit), the 131 cm of snow cover is estimated to represent the remains of 2.5 years of accumulation. All of the snow cover at these sites was completely saturated, so much so that it was difficult to recover the cores. The hole at Site A partially filled with water.

At Sites A, B, and C where solid ice was encountered, the top few centimeters were of a granular nature and milky in appearance. This is regarded as newly-formed superimposed ice. Nothing recognizable as a cryoconite surface was seen on this side of the ice cap. Generally then, this area should be regarded as part of the superimposed ice zone. The true ablation zone lies further downslope at the head of Tasersiaq Tongue.

However, faint dust and dirt particles were seen in some of the ice samples. At Site B granular (newly-formed superimposed) ice was found between 131 and 169 cm depth. From 169 to 225 cm there was clear, bubbly ice, dark in appearance and extremely hard and brittle. There was a

tendency for the bubbles in this section to be layered, giving the whole core a "banded" appearance. Between 69 and 78 cm were five specks of dust and dirt less than 0.5 mm in size.

At Site C, ice occurred at a depth of 373 cm. A core 69 cm long taken from this ice showed:

0-11 cm	Granular milky ice
11-69 cm	Darker clearer ice, but faint milky bands evident

Between 98 and 104 cm was a faint dust layer. Again, the particles were less than 0.5 mm in size.

Conclusions

It seems, then, that climatic conditions in the area on the western edge vary from year to year. In some years all the winter snow plus any remaining snow from previous years melts completely and exposes a true ablation ice surface in which cryoconite holes develop. In other years the snow does not melt completely and partial melt of the overlying snow cover allows the development of superimposed ice. The "line of net ablation" (Schytt, 1955) is therefore quite mobile in this area.

It is possible that the snow cover from the area on the eastern edge is completely removed by ablation during some years, revealing an ice ablation surface. This would be one explanation for the faint dust bands at 69 to 78 cm and 98 to 104 cm in two of the cores examined, the ice above then being superimposed ice, formed in later years. On the other hand, the very fine dust particles could merely have been washed through the overlying snow and incorporated into the superimposed ice. However, as on the western side of the cap, the line of net ablation here may be very mobile.

ACKNOWLEDGMENTS

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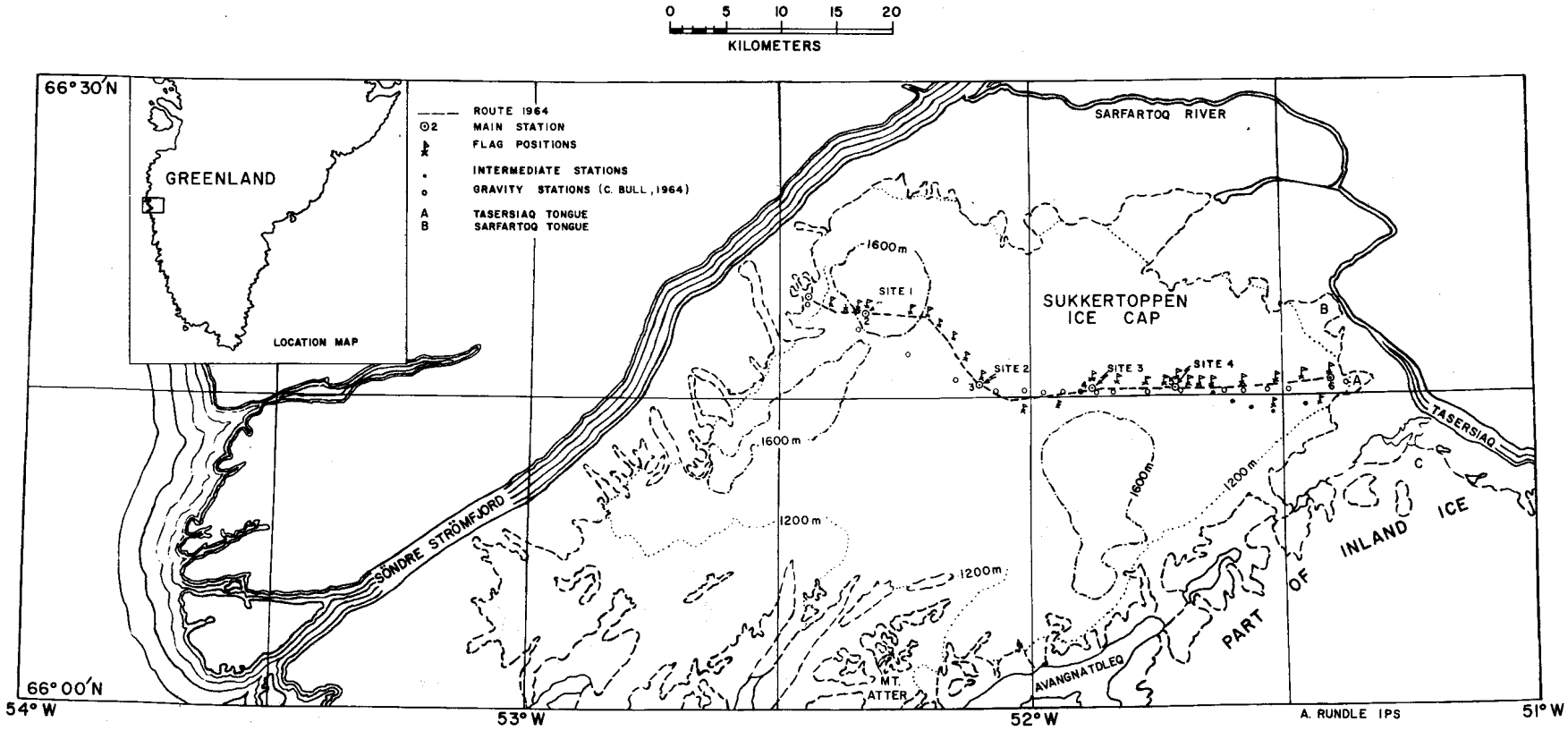


Fig. 1 - Sukkertoppen Ice Cap, 1964 traverse route and glaciological study sites, and 1962 gravity stations

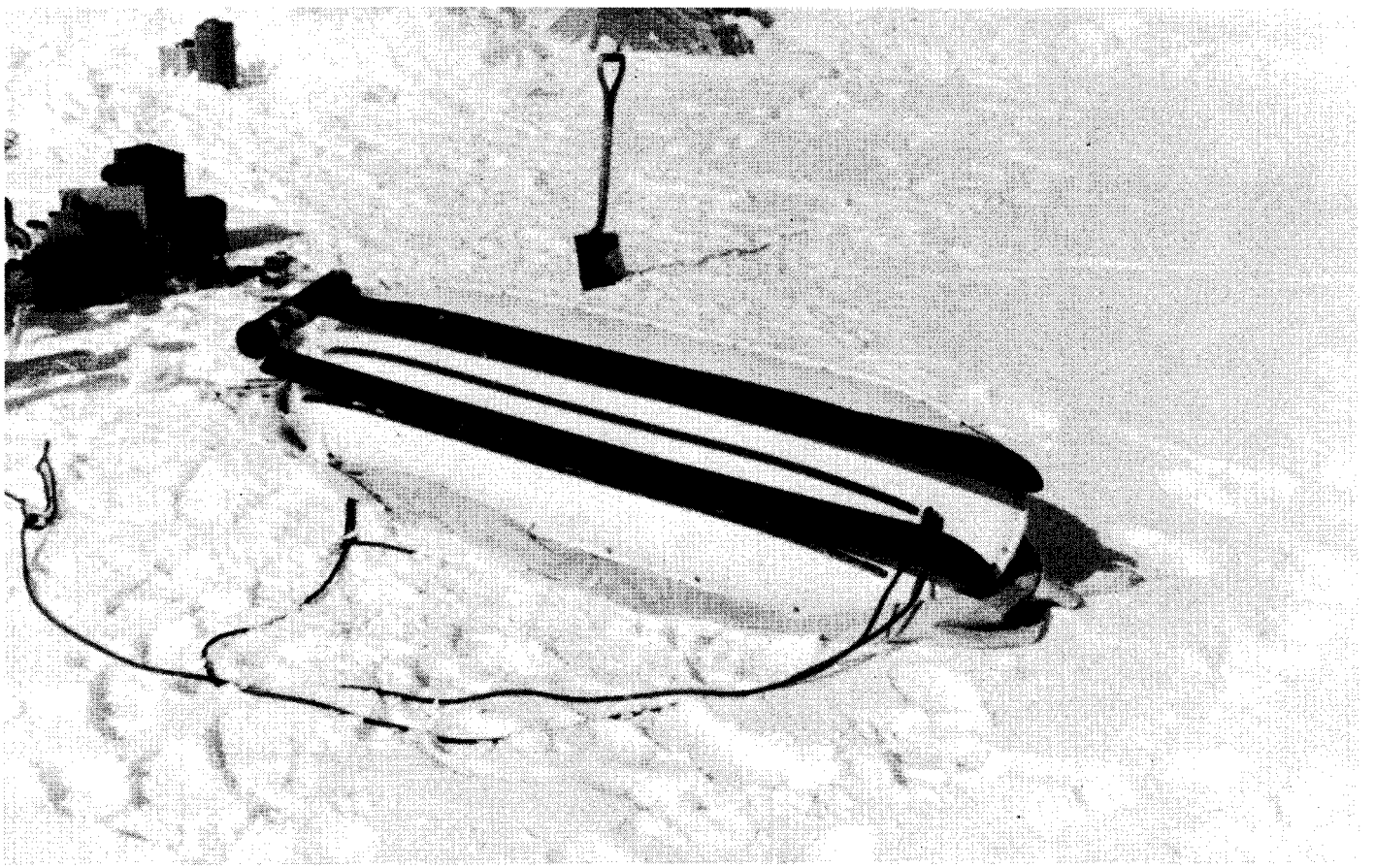


Fig. 2 - Fiberglass akhio sled with standard skis attached to the bottom. Each ski was securely fastened with four stout sheet metal screws.

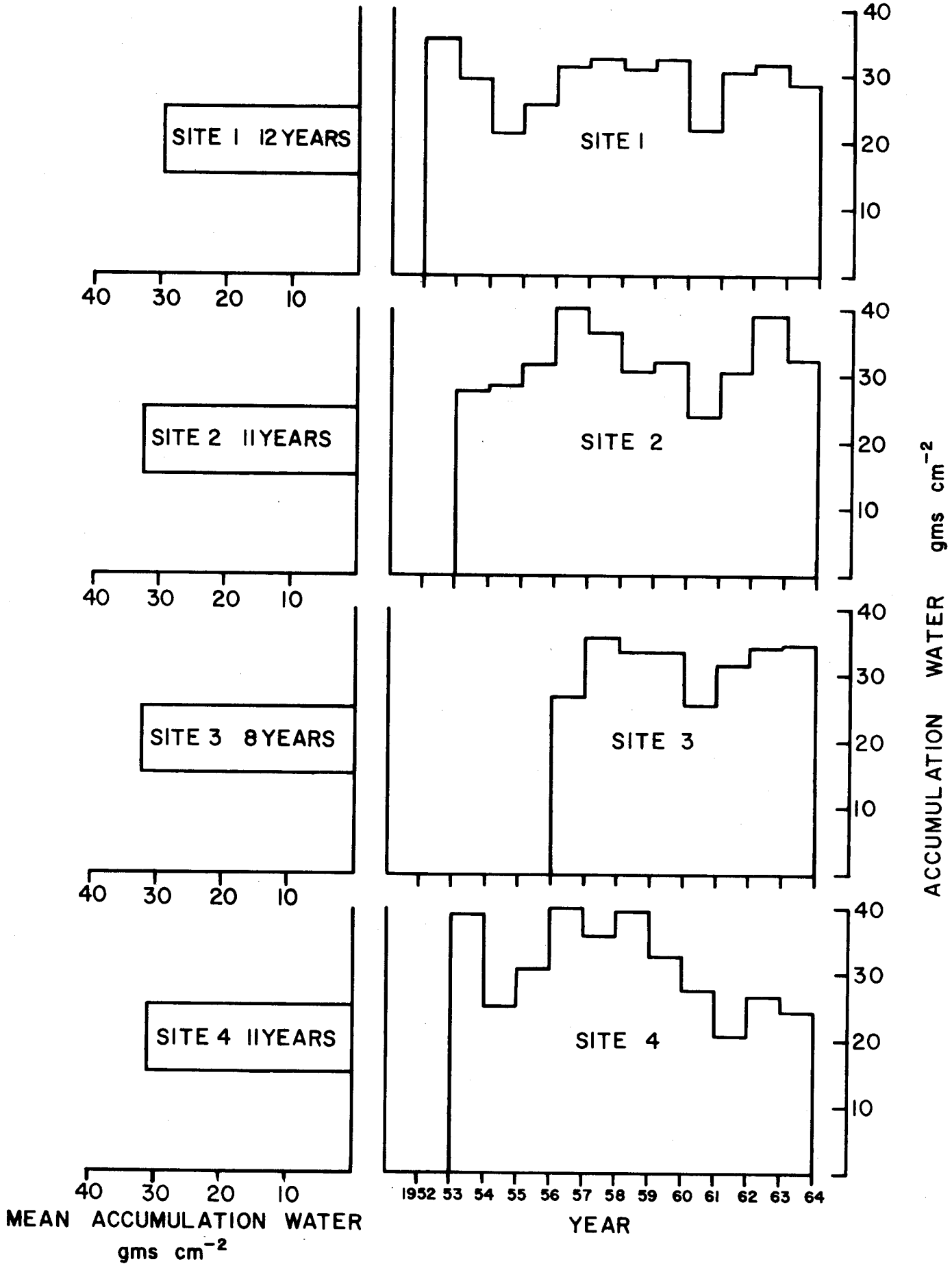


Fig. 3 - Accumulation interpreted from pit and core profiles at the four main sites on the 1964 Sukkertoppen Ice Cap traverse

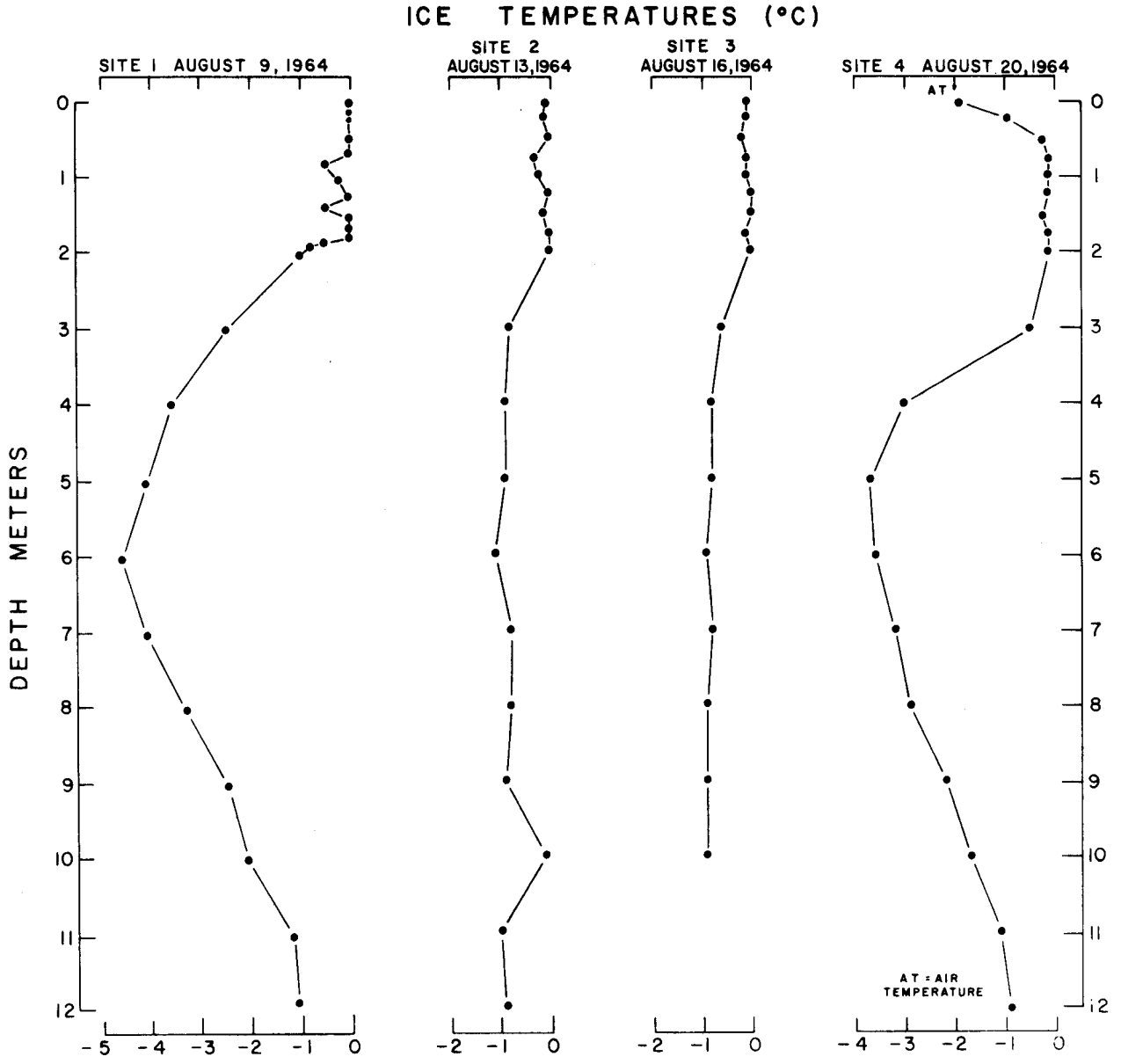


Fig. 4 - Ice temperatures at the four main sites on the 1964 Sukkertoppen Ice Cap traverse

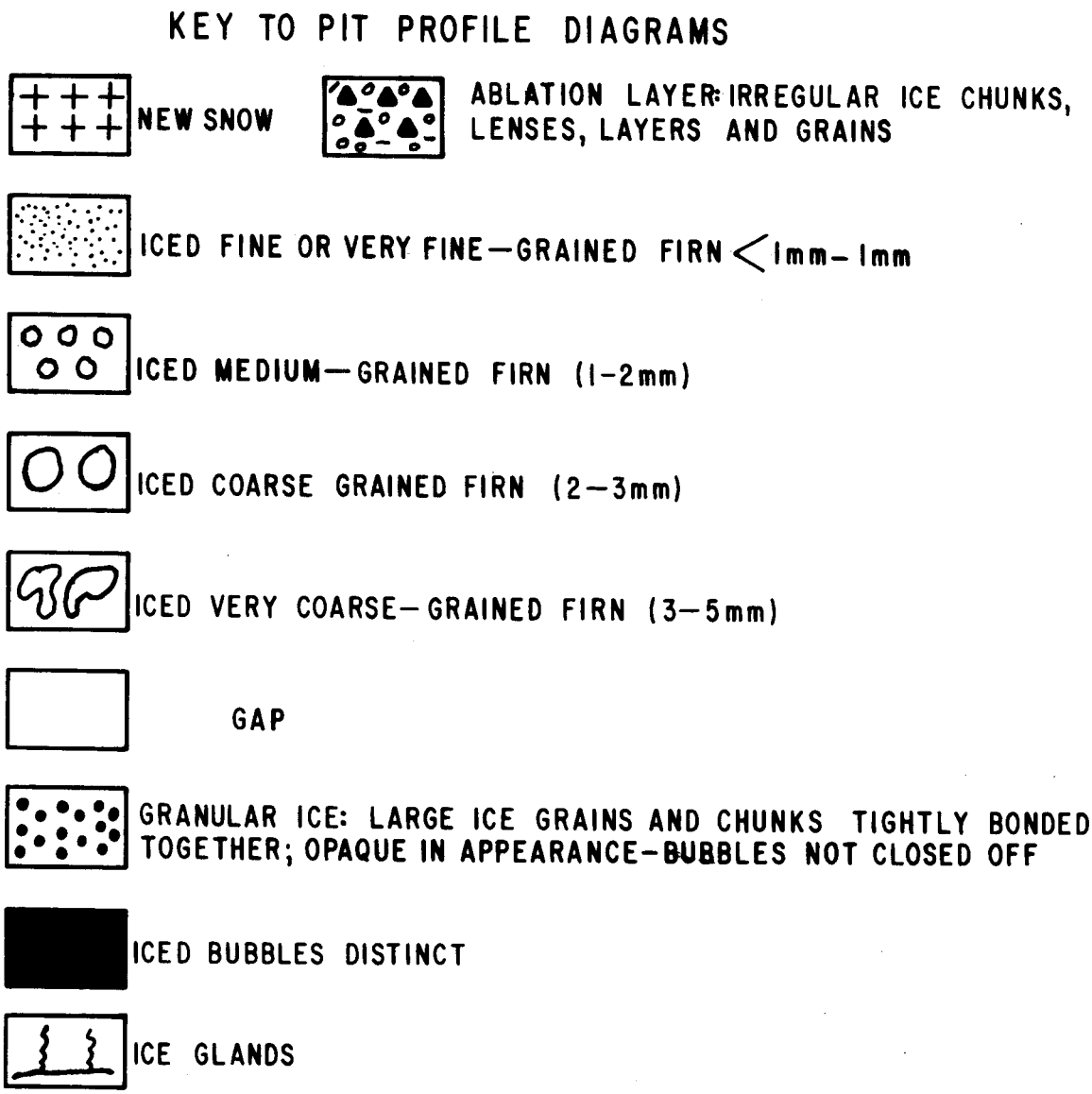
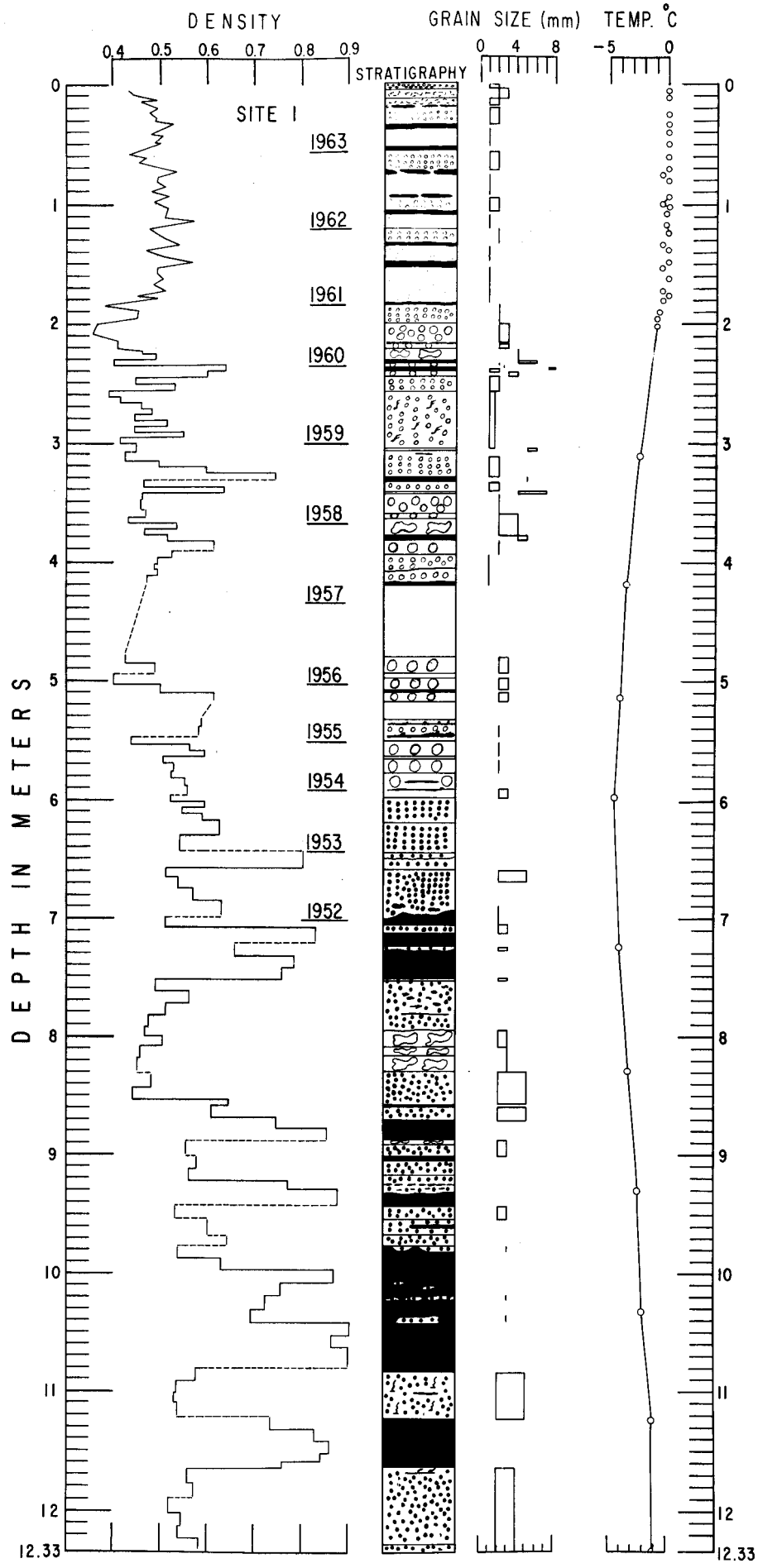


Fig. 5 - Density, stratigraphy, grain size, and temperature at the four main sites on the 1964 Sukkertoppen Ice Cap traverse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0.4
0.5
0.6
0.7
0.8
0.9
GRAIN SIZE (mm)
0
4
8
TEMP. °C
-5
0
STRATIGRAPHY
SITE I
1963
1962
1961
1960
1959
1958
1957
1956
1955
1954
1953
1952
DEPTH IN METERS
0
1
2
3
4
5
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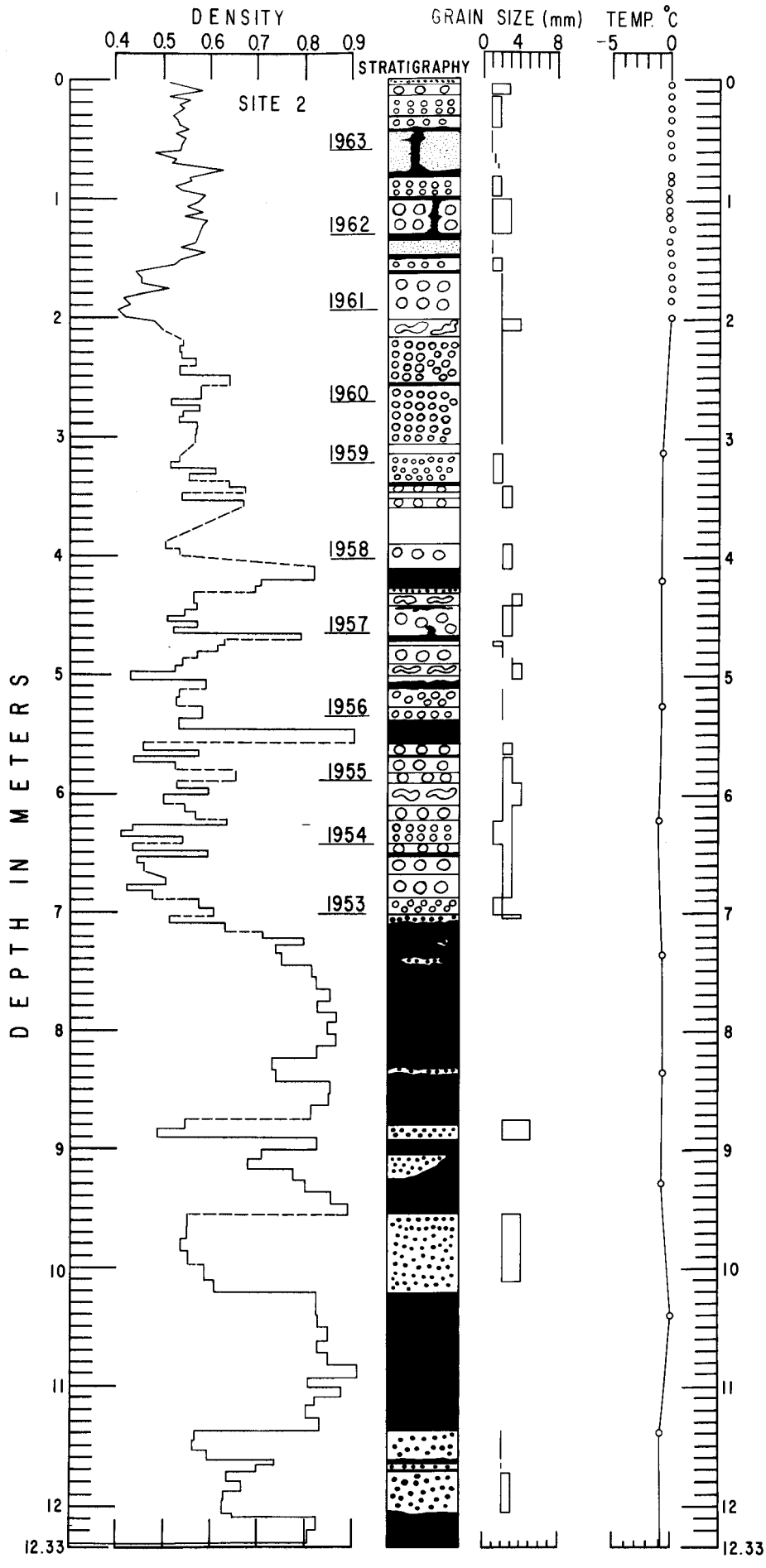
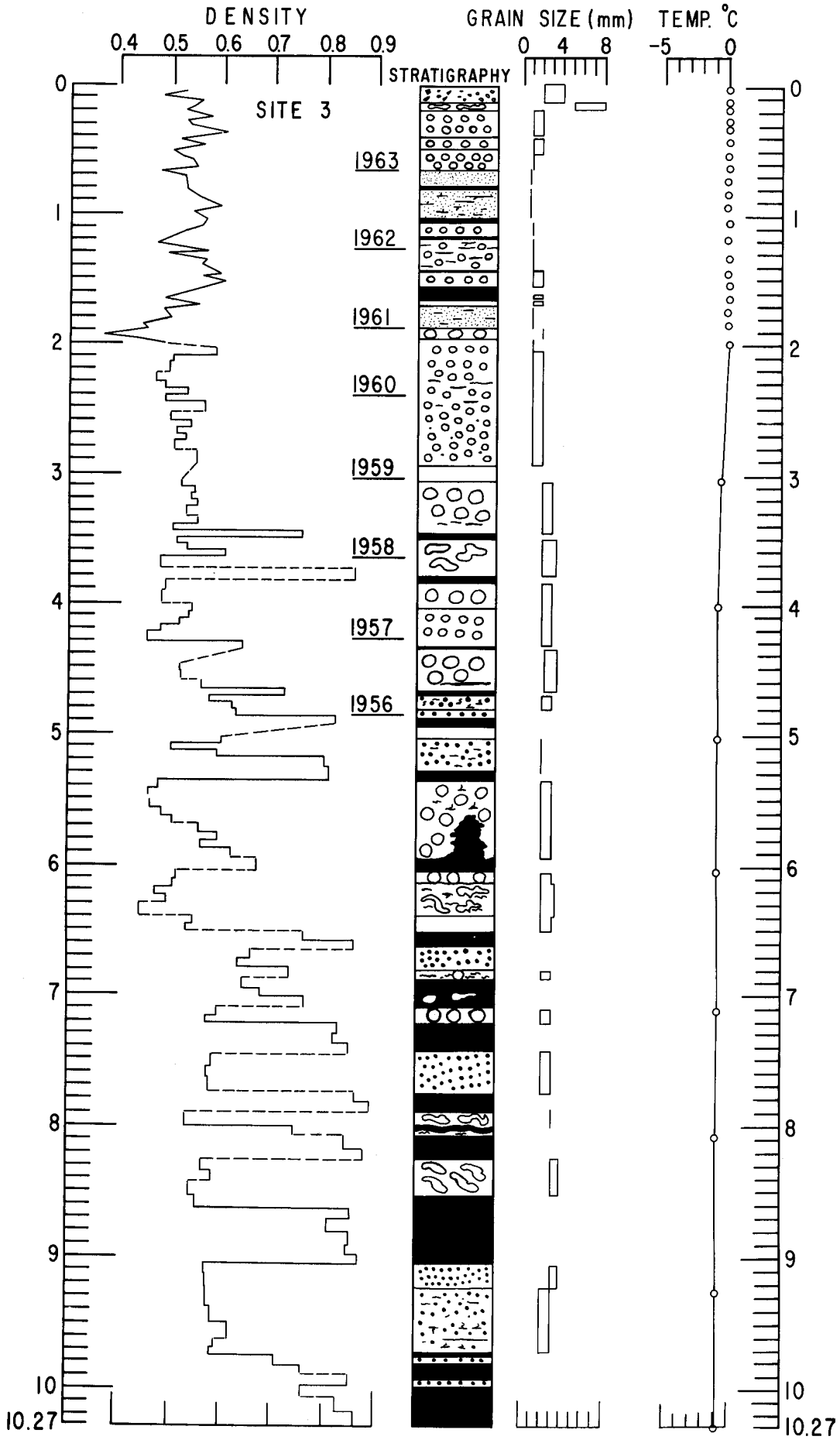
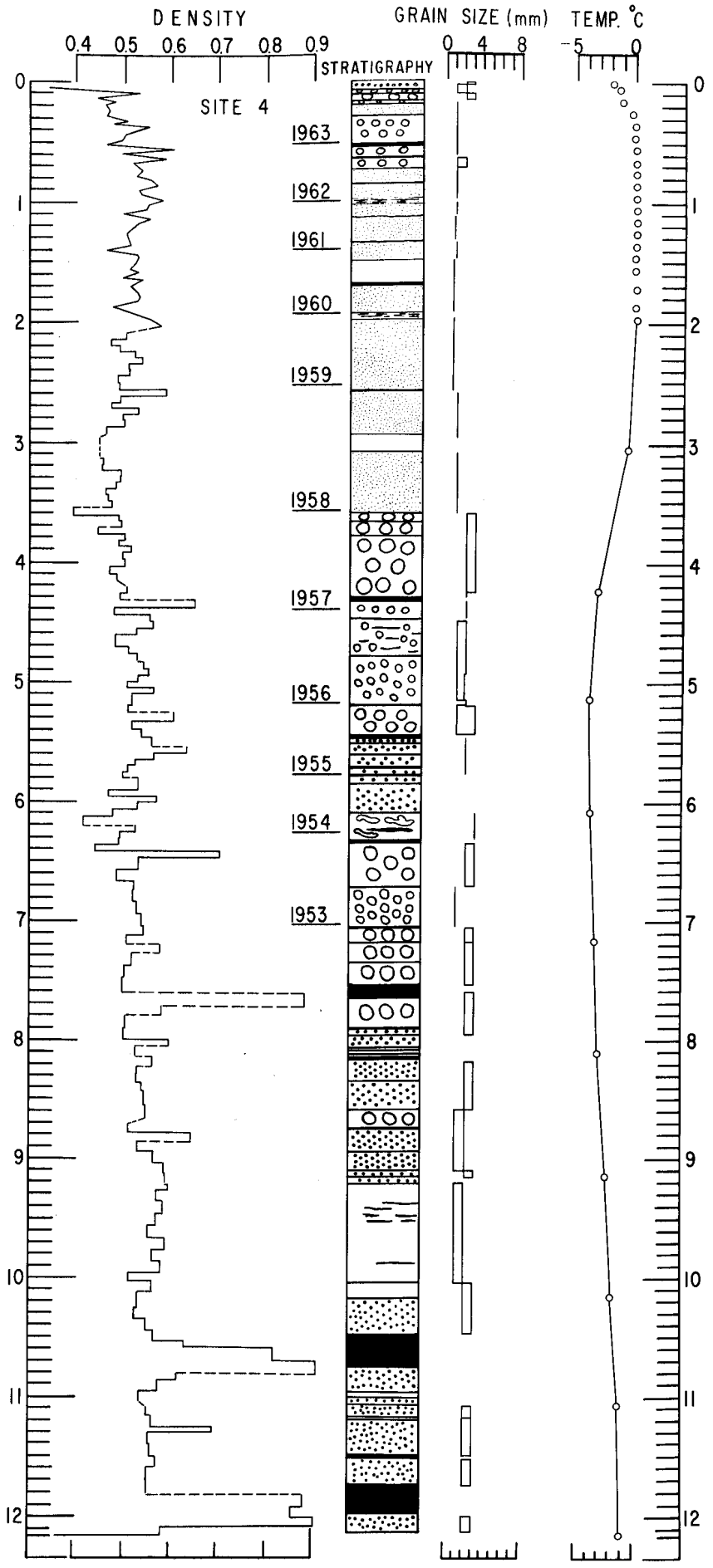
11
12
12.33


DENSITY
0.4 0.5 0.6 0.7 0.8 0.9
GRAIN SIZE (mm)
0 4 8
TEMP. °C
-5 0
STRATIGRAPHY
SITE 2
1963
1962
1961
1960
1959
1958
1957
1956
1955
1954
1953
DEPTH IN METERS
0 1 2 3 4 5 6 7 8 9 10 11 12 12.33


DENSITY
0.4 0.5 0.6 0.7 0.8 0.9
GRAIN SIZE (mm)
0 4 8
TEMP. °C
-5 0
STRATIGRAPHY
SITE 3
1963
1962
1961
1960
1959
1958
1957
1956
0
1
2
3
4
5
6
7
8
9
10
10.27


DENSITY
0.4 0.5 0.6 0.7 0.8 0.9
STRATIGRAPHY
GRAIN SIZE (mm)
0 4 8
TEMP. °C
-5 0
SITE 4
1963
1962
1961
1960
1959
1958
1957
1956
1955
1954
1953
0
1
2
3
4
5
6
7
8
9
10
11
12

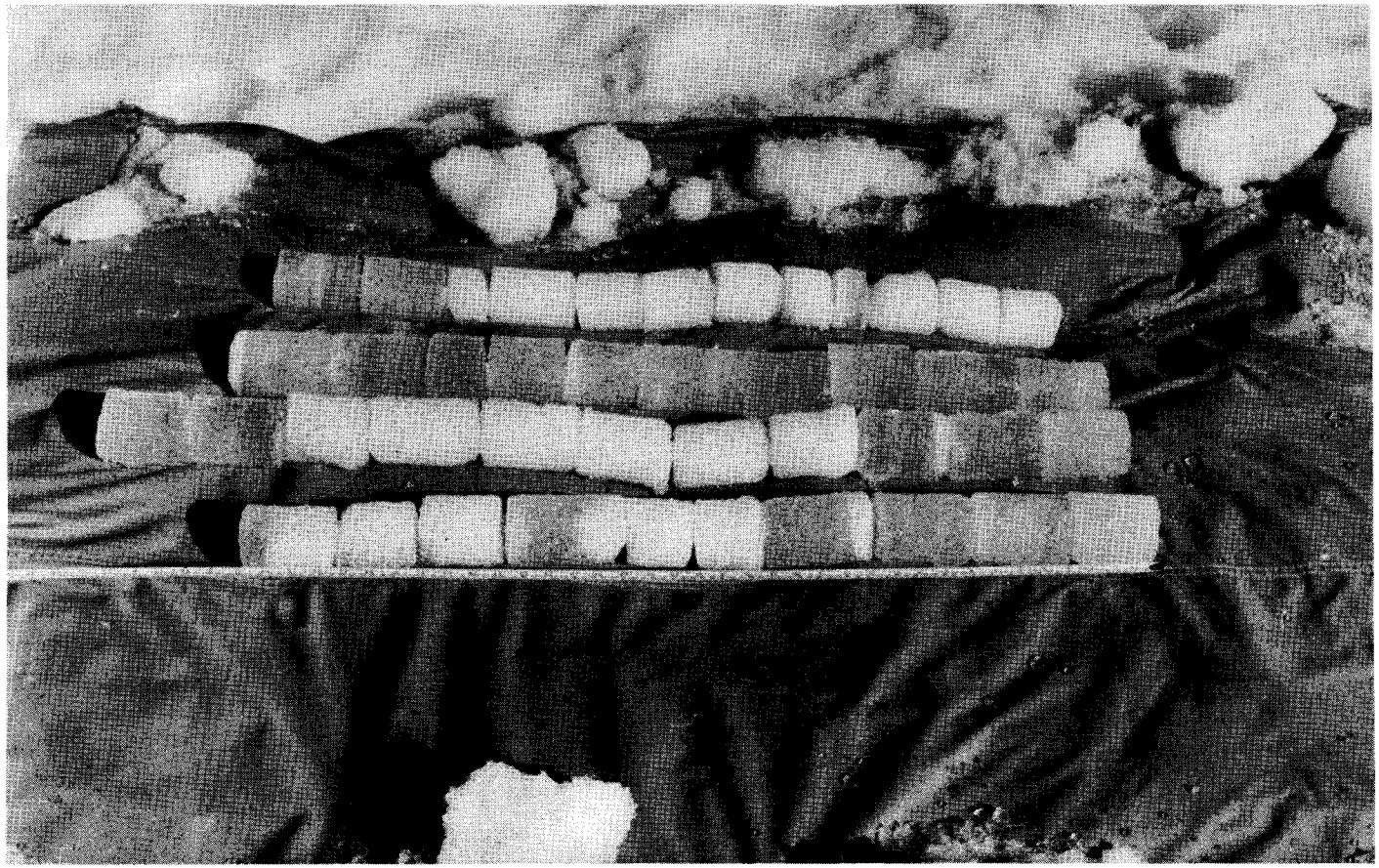


Fig. 6 - Core from Site 2 showing alternation of pure ice and milky ice. Top of each section of core is at right. Depths from surface for each row of core (top row to bottom row) are:

1216-1123 cm	1028-915 cm
1123-1028 cm	915-818 cm

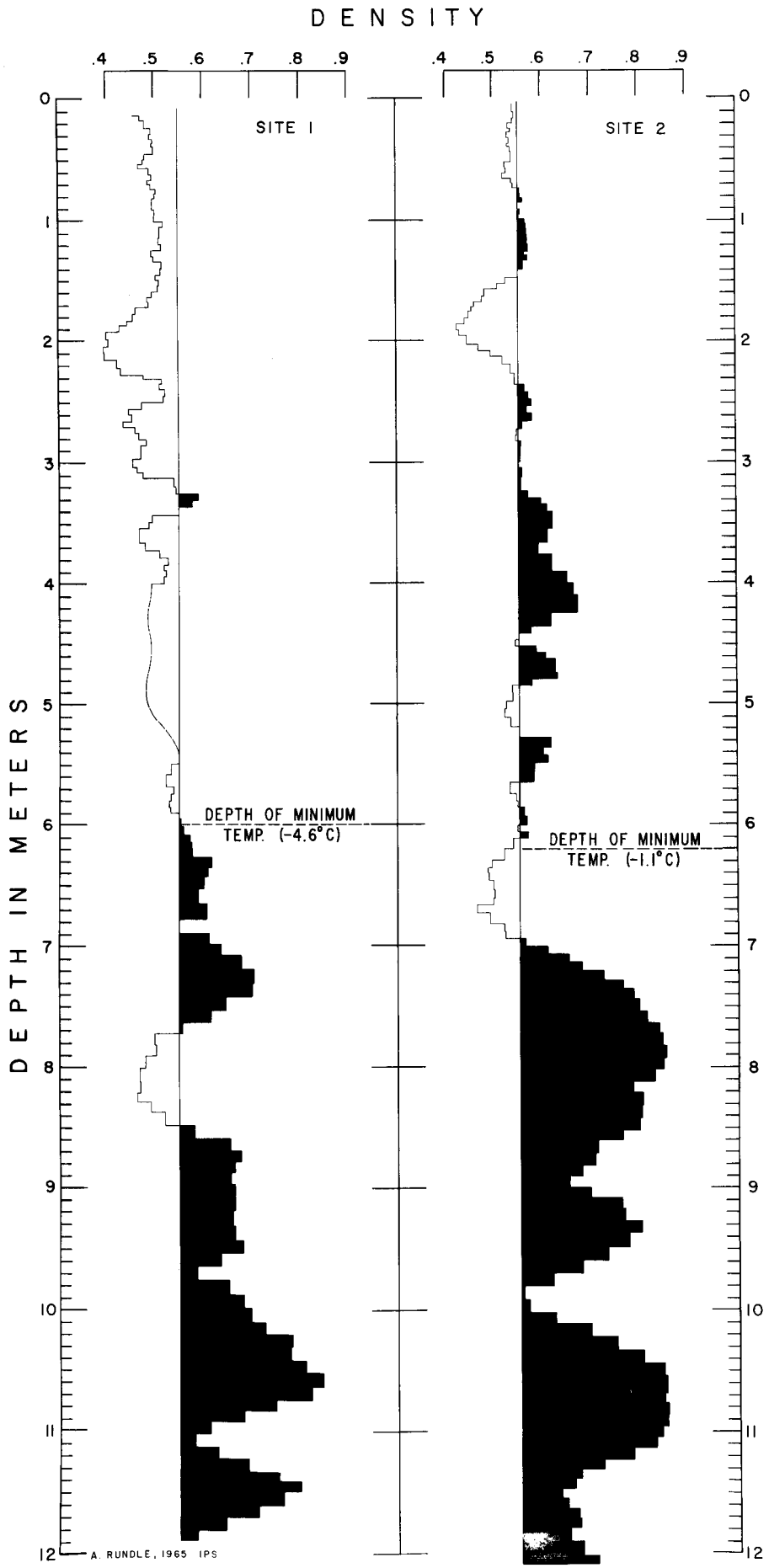
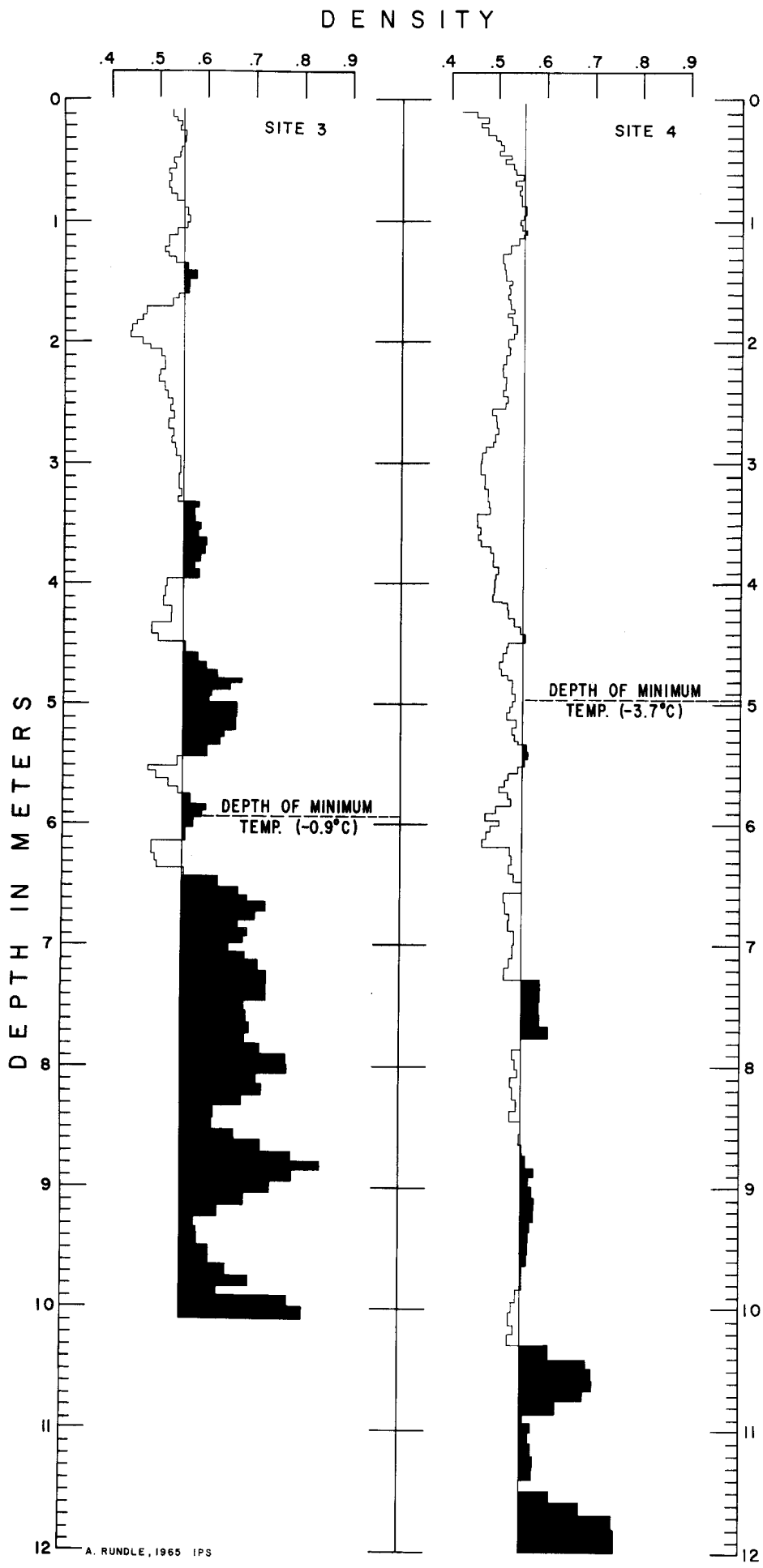


Fig. 7 - Variation of density with depth at the four main sites on the 1964 Sukkertoppen Ice Cap traverse. The plotted value at each depth is the five-point running mean.


DENSITY
.4 .5 .6 .7 .8 .9
SITE 3
SITE 4
DEPTH IN METERS
0 1 2 3 4 5 6 7 8 9 10 11 12
DEPTH OF MINIMUM TEMP. (-0.9°C)
DEPTH OF MINIMUM TEMP. (-3.7°C)
A. RUNDLE, 1965 IPS

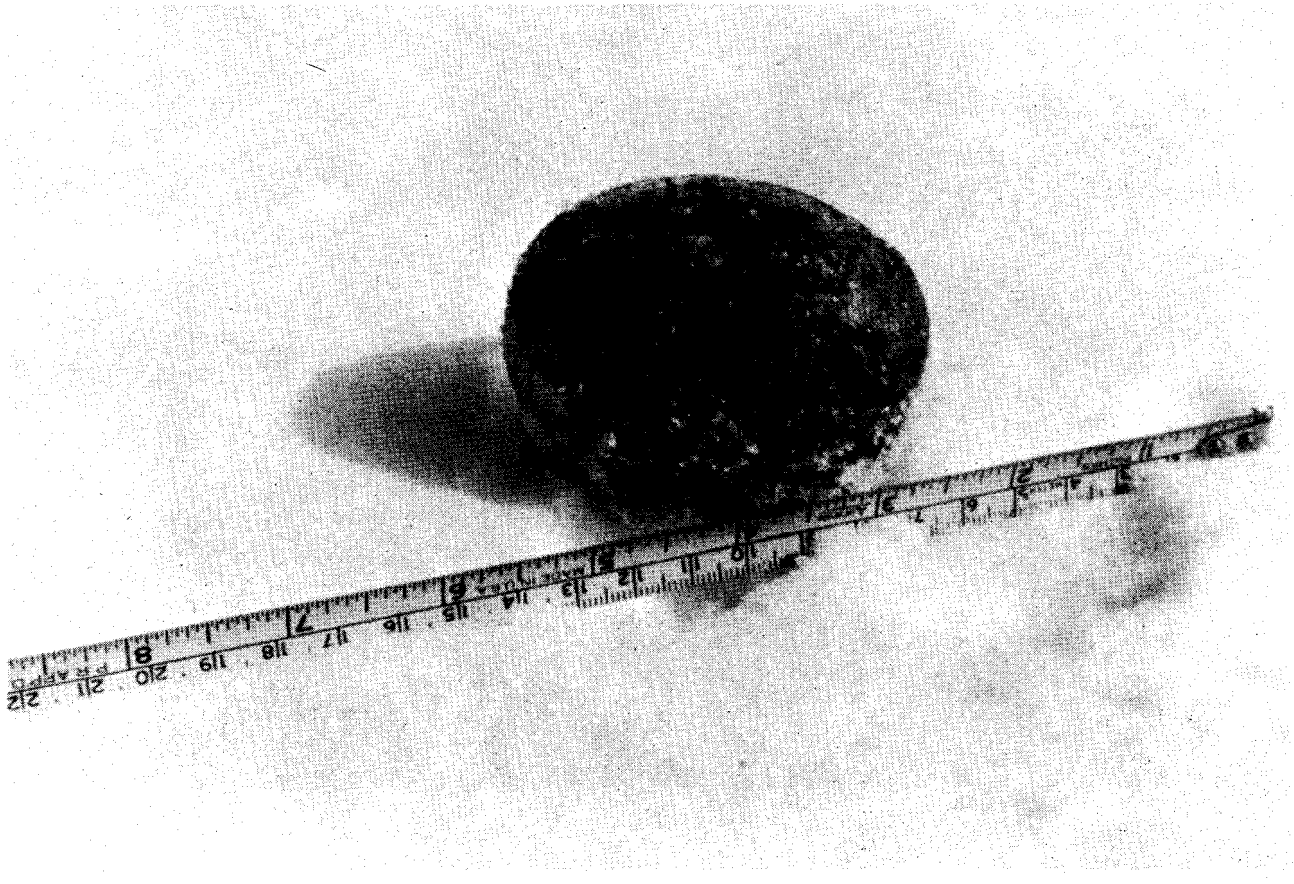


Fig. 8 - Part of core taken on western edge of Sukkertoppen Ice Cap showing dirty ice lying immediately below the snow cover

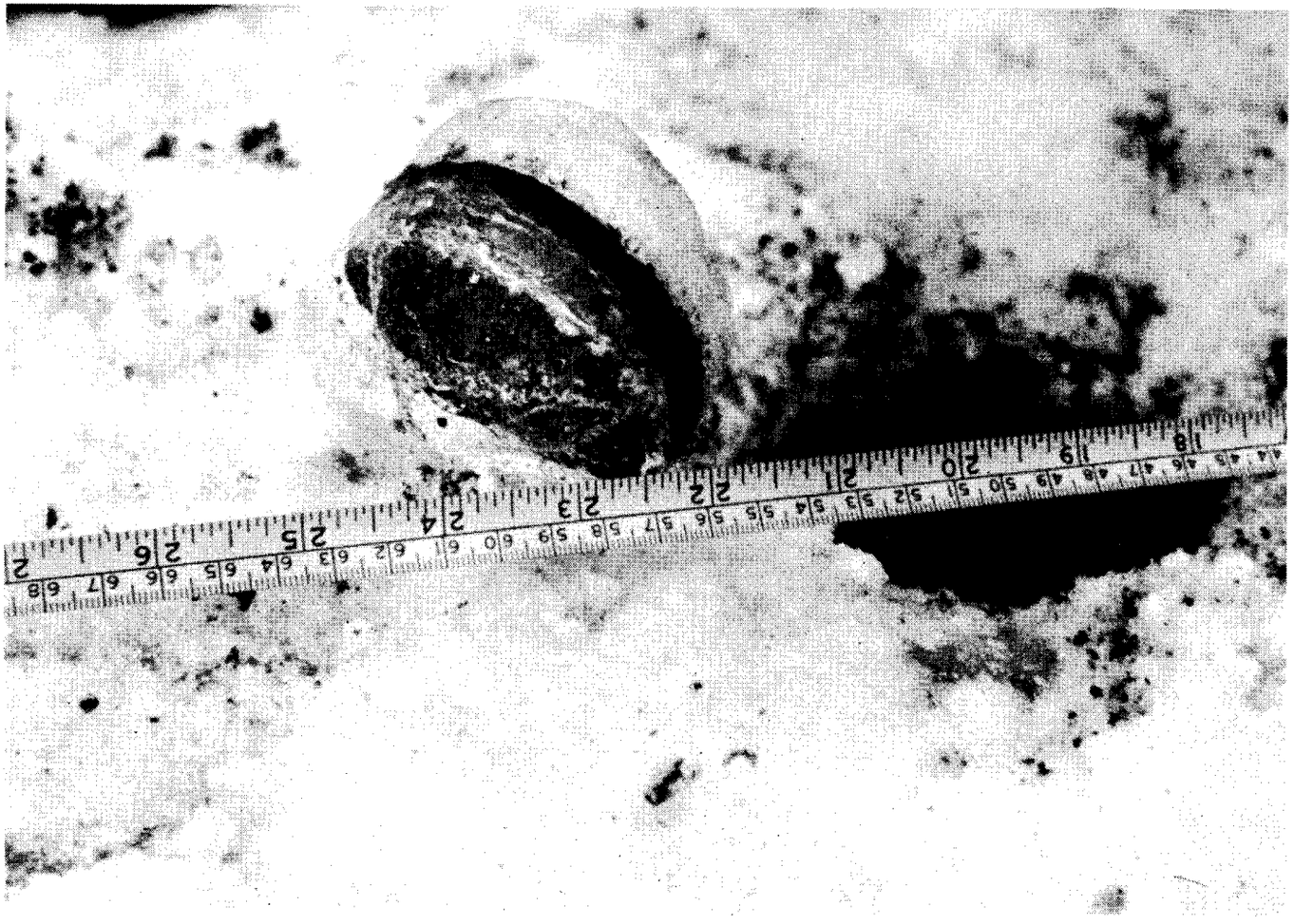


Fig. 9 - Thick lense of dirt at 7.0 cm depth in ice on western edge of Sukkertoppen Ice Cap