Studies on naledi (icings) in West Spitsbergen

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Naledi (icings) have been studied on the west coast of Spitsbergen between 1972 and 1979. The study area contains several naledi of different types which are documented by air photographs taken during the last 50 years. Additional studies based upon field observations and air-photo interpretation have been undertaken in other parts of Spitsbergen. Sixty-three different naled sites are described, terminology is discussed, and a classification of different types of naledi is proposed. The forms of the naledi related to their genesis, their hydrological characteristics, and their position in the terrain are described. Details of surface morphology, hydrology, salt precipitation, and the naled as a geomorphological agent are discussed. A study was made to find out if naledi might be used as indicators of short-term climatic variation. Good correlations were found between the length of the freezing period and the ice volume at the end of the winter. It was also found that variations in the summer air temperature can be correlated with either variations in ice volume loss or the remaining surface area of naledi with acceptable accuracy and, that under certain conditions, naledi may be used as indirect indicators of short-term climatic variations.

De 1972 à 1979, des nalédi (ou aufeis) ont été étudiés sur la côte ouest du Spitsberg. La région étudiée contient plusieurs nalédi de types différents, qui sont documentés par des photographies aériennes prises depuis 50 ans. Dans d'autres parties du Spitsberg, a été entreprise une autre série d'études basées sur des observations *in situ* et l'interprétation de photos aériennes. Dans cet article, sont décrits 63 différents sites où l'on rencontre des nalédi; on commente la terminologie, et l'on propose une classification des différents types de nalédi. On y décrit aussi les formes de ces structures du point de vue de leur génèse, de leurs caractéristiques hydrologiques et de leur situation. On examine en détail la morphologie superficielle, l'hydrologie, la précipitation des sels, et le caractère des nalédi en tant qu'éléments d'évolution géomorphologique. On a effectué une étude pour savoir si l'on pouvait utiliser les nalédi comme indicateurs de variations climatiques à court terme. On a constaté qu'il existait une bonne corrélation entre la longueur de la période d'englacement et le volume de glace accumulé à la fin de l'hiver. On a aussi découvert que l'on pouvait corréler avec une précision acceptable les variations de la température de l'air estivale et les variations de la réduction du volume de glace ou la superficie résiduelle des nalédi, et que dans certaines conditions, ceux-ci pouvaient servir d'indicateurs indirects des variations climatiques à court terme.

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Introduction

Extrusive ice is one of the main groups in the classification of ground ice (Embleton and King 1975, p. 34; Washburn 1979). The most important form of extrusive ice is the *naled* (plural *naledi*) also called *icing* or *aufeis*. The terminology is still somewhat confusing. In spite of the fact that the term aufeis appeared first in scientific literature (von Middendorf 1859) it is more likely that the term naled is the original one (aufeis is only the German translation of the Russian word naled). Further the word naled is a natural word in the Russian language (Dahl 1881), used both in common and scientific Russian covering all varieties of the matter. As it is the most specific term and easiest to distinguish from other terms concerning ice, it can be regarded as the most appropriate term and is proposed by the author for common use. From the literature and from field observations in Spitsbergen it is evident that naledi occur in many different situations with water emanating from various sources.

Earlier observations of naledi in Spitsbergen

One of the earliest observations and "interpretations" of naledi in Spitsbergen was made by Holtedahl (1913, p. 89) who commented on two large naledi on a photo taken by A. Staxrud in July 1912, "the white areas in the foreground are snow". Similar mistakes are numerous in the early literature but quite understandable as these features were not considered of any interest and thus were not discussed during early exploration of Spitsbergen. Three authors have since observed and discussed the occurrence of naledi on Spitsbergen more systematically (Åkerman 1980; Liestøl 1977; Orvin 1944). Orvin used the occurrence of sheets of ice in association with springs as an indicator of spring activity in winter. Although he did not use the term naled, aufeis, or icing, he presented a large number of sites with winter-active springs and also described the occurrence and properties of the "ice sheets" formed by spring water during the cold season. He also indicated the occurrence of naledi in front of glaciers (Orvin 1944, p. 3).

The use of air photos in the study of springs, pingos, and, indirectly thereby, naledi was adopted by Liestøl (1977). In a comprehensive inventory of pingos and springs in Spitsbergen, he stressed the occurrence of icings in association with pingos as being fundamental in the discussion about the genetic classification of pingos in Spitsbergen.

Methods and Aims of This Study

The occurrence of well-developed naledi around Kapp Linné focused the author's interest upon the naled as a periglacial geomorphological feature and also as a form-producing agent. Studies of air photos and visits to other parts of Spitsbergen, as well as naledi shown in old photographs in literature, show that they are common, but neglected, periglacial features in Spitsbergen.

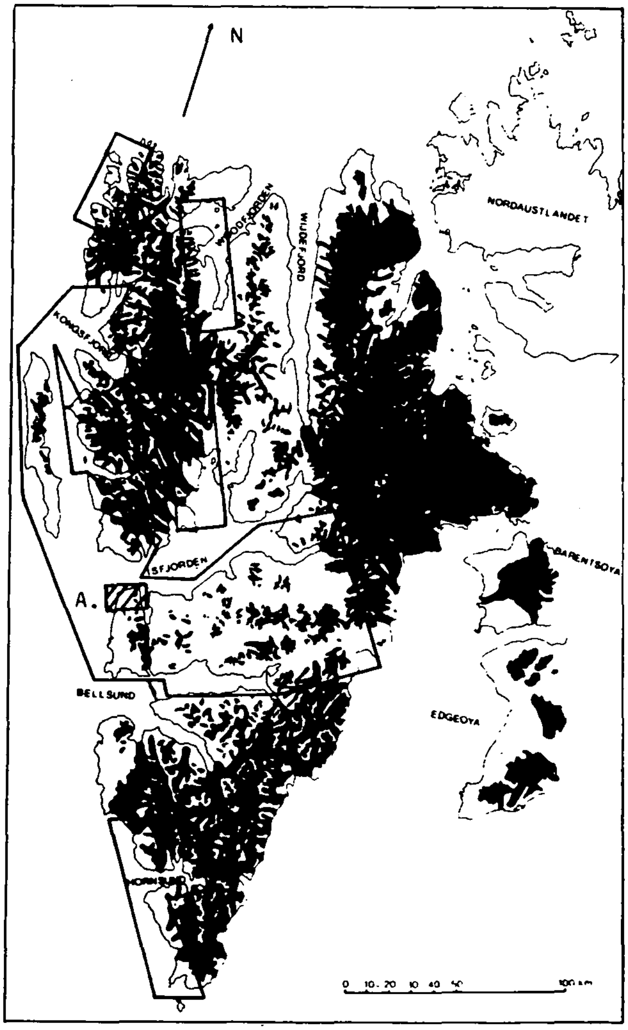

FIGURE 1. West Spitsbergen, the main island of the Svalbard region showing the field area (A) and areas covered in the air-photo inventory of naledi (solid black lines). The glacial cover (black) is according to Norwegian Polar Institute Topographic Map (scale 1:2M).

The occurrence of naledi in front of glaciers gives information about the thermal regime and status of a glacier and its bed. In this respect, the occurrence of naledi in association with, for example, surging glaciers is most interesting. They also give us information about unfrozen intra- or sub-permafrost waters.

This paper is a review of observations made in a field area on the western part of the southern shore of the Isfjorden (Figure 1). Detailed descriptions of the geological, geomorphological, hydrological, and climatological characteristics of the area are given in Åkerman (1980).

This study describes the occurrence and distribution of naledi in Spitsbergen. An attempt at classification of the different types of naledi found, and a description of their general characteristics, are provided. As the field work covers the period 1972 to 1979 it was possible to study the naled complex between the Kongressvatnet and Linnévatnet lakes during a succession of years and to get correlations with climatic parameters.

Classification of Naledi in Spitsbergen

An inventory of naledi was made for selected parts of Spitsbergen on the basis of field studies, descriptions in the literature, and from air photos (*see* Figure 1). The inventory is not complete, but it may serve as the first step towards a complete inventory. The areas not included in this survey are mainly covered with glaciers and are therefore less important.

The regional distribution of naledi in Spitsbergen will not be discussed until more information has been collected.

The large number of observations of naledi of different origin and types in the field area (Figure 2) makes it possible to classify them into major groups based upon the "genetic" background of their source of water. The following classification is proposed for naledi in Spitsbergen:

1. Naledi associated with groundwater springs;
   A. Ordinary groundwater springs (*spring naled*);
   B. Thermal groundwater springs (*thermal spring naled*);
2. Naledi associated with pingos (*pingo naled*);
3. Naledi associated with rivers and streams (*river or stream naled*); and
4. Naledi associated with glaciers (*glacier naled*).

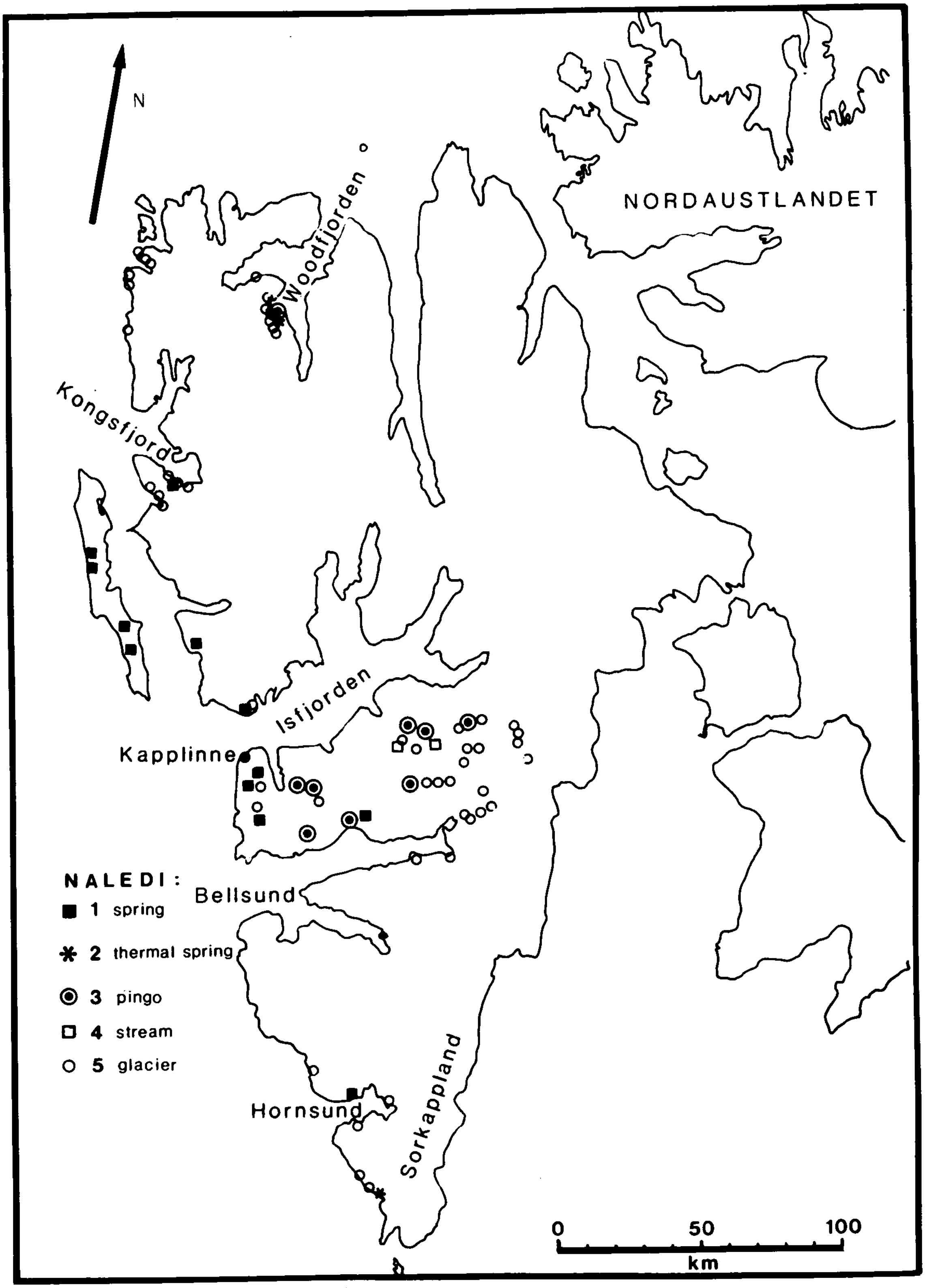

FIGURE 2. Distribution of naledi in West Spitsbergen.

Spring naledi (Type 1A) include those formed from water discharged by groundwater springs in bedrock as well as from the soil cover. The springs may originate from water-bearing strata below the permafrost as well as from intrapermafrost taliks. They vary greatly in size from very small features to large perennial, or semiperennial, naledi. The larger ones are often striking features which are locally of great geomorphological importance.

Thermal-spring naledi (Type 1B) are rare in Spitsbergen and are only known from the thermal springs of Woodfjorden and from Sörkapp Land north of the Oslokbreen glacier. Typical of this type of naled is that they are normally found at some distance from the source as it takes a longer time to cool the water to the freezing point.

Pingo naledi (Type 2) are quite common and are represented by smaller naledi that are formed on, and around, pingos. Most of the pingos in Spitsbergen are interpreted as being of the "open-system" type because they are producing water during the cold season and therefore naledi are formed in their surroundings. In an inventory of pingos (Liestøl 1977) the occurrence of water and/or ice is stressed and several examples of naledi are shown in pictures. The naledi assocated with pingos are, in most cases, small but as the water is often comparatively cold (0.2 to 1.5°C) the thickness may be great and the ice often remains for a considerable part of the summer.

River or stream naledi (Type 3) are numerous in the valleys of Spitsbergen. They often cover large areas of the floodplains of braided streams. They do not last very long in summer as the early flow of water, together with the fact that they are thin and very often dissected by several stream channels, makes them melt away even before the thin snow cover in the surroundings. In most cases, therefore, they are not observable on air photos, most of which are taken in late summer. This may explain why only two examples of this type are indicated in Figure 2.

Glacier naledi (Type 4) are the most common type in the region (Figure 3). The subpolar glaciers that dominate the region normally discharge water also during the cold season and therefore many of them have naledi in their terminal areas. The glaciers also cut unfrozen aquifers and insulate the ground so that no permafrost exists beneath them. Most of the naledi in front of the glaciers are not fed by water from the glacier itself, but rather from groundwater "released" by the direct or indirect action of the glaciers. Such glacier naledi are often of considerable size and are of great importance to

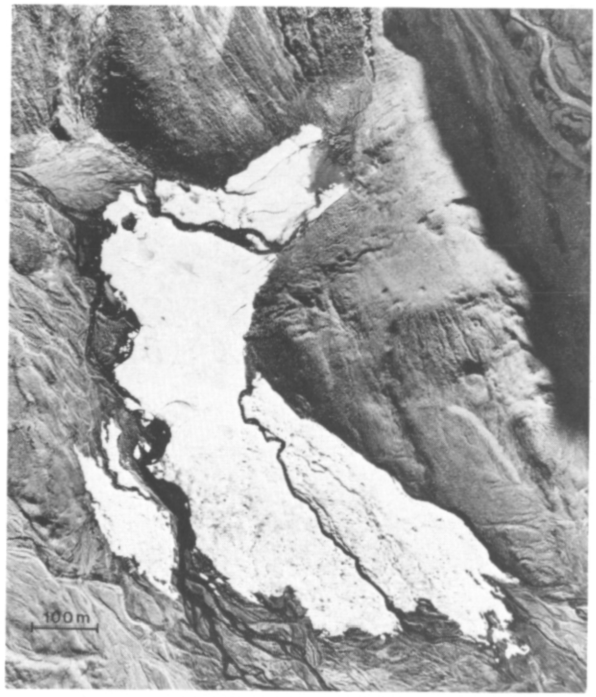

FIGURE 3. Naled in front of Pedersenbreen Glacier, Kongsfjorden (Part of N.P.I. Air Photo No. S71 7071, August 11, 1971).

geomorphological processes in front of glaciers. In many cases, however, they are not as long-lived as those formed by springs because the large quantities of meltwater during the summer season often cut through the naled and therefore speed up the melting process. The inventory, whilst it covers only part of the region, gives a fairly good view of the occurrence of naledi (Table 1). In some cases it was possible to follow a naled in photographs from many years and, in these cases, the results have been considered in the discussion about the naled as a climatic indicator.

Naled Morphology

General Characteristics

The areal extension and shape of a naled are mainly dependent on the topography as the paths of the flowing water determine the place where the ice body is formed. Naledi have many possible shapes but each different type of naled, as a result of their mode of formation, has a more or less typical form. The many observations in Spitsbergen make it possible to distinguish some characteristic forms.

Spring naledi formed by water with a low discharge rate are normally fan-like as the water in most cases has not created a well-defined stream

TABLE 1. Naledi of West Spitsbergen

Location/name	Naled type*	Air-photo No.	Description and remarks
Dalsendbreen	4	S70 4604/05	Small
Brentskardet	2	S61 2980/81	On the side of pingos
Drönbreen	4	S61 2981/82	Outside terminal moraine
Bergmesterbreen	4	S62 2984/85	Outside terminal moraine
Vegbreen	4	S61 2984/85	
E. Trollsedet	4	S61 2986/87	
Rieperbreen	4	S61 3300/01	Small, close to glacier
Bolterelva	3	S61 3300/01	Small
Foxbreelva	3	S61 3087/88	
Glottfjellbreelva	3	S61 3089/90	
Litledalsfjellet	1A	S60 7254/55	Small
Frodalen/Colesdalen	3	S60 7370/71	Upon alluvial fan
Rypfjellbreen	2	S60 7313/14	Three pingos
Tungebreen	4	S60 7296/97	On both sides of moraine
Såtebreen	4	S60 7047/48	
Lundströmsdalen	4(3)	S60 7047/48	
Kjellströmsdale	4	S60 7044/45	Four close to moraine
Lumpbreen	4	S70 4685/86	Large, retreating glacier
Elfelbeinbreen	4	S70 4683/84	
Hellebreen	4	S70 4683/84	Large, surging glacier
Marthabreen	4	S71 6051/52	Small
Skallfjellsbreen	4	S71 6051/52	Large
Skallfjellet	4	S71 6051/52	Large
Kokbreen	4	S71 6051/52	
Bergmojabreen	4	S71 6051/52	
Snöskruvbreen	4	S61 3076	
Ytterdalsgubben	1A	S61 3389/90	Small, on the slope
Jutunkilderne	1B	S66 4346/47	Small
Trollkilderne	1B	S66 4370/71	Large
Karlsbreen	2	S66 4370/71	Around pingo
Scheldrupbreen	1A(4)	S66 4370/71	Large complex
Nygardbreen	4	S66 4370/71	Large
Adolfbreen	1A(4)	S66 4369/70	Complex
Fredrichbreen	1A	S66 4345/46	Large complex
Petersenbreen	4	S66 4455/56	
Edithbreen	4	S66 4454	
Ulversbreen	4	S66 4455	
Steenbreen	4	S66 4479	
Magdalenafjord	4	S66 4621	
Magdalenafjord	4	S66 4622	
Gåsbreen	4	S61 3263	Outwash plain
Kvalfangarbreen	4	S61 3267/68	Small
Bungebreen	4	S61 3256/57	Small
Vikovskibreen	4	S61 3256/57	Small
Rabotbreen	4	S71 6068/69	Largest found
Forlandsletta	1A(3)	S66 4546/47	Several small
Persisvatna/elva	3	S66 4545/46	Small in canyon
Gordonpynten	4	S66 4548/49	On the beach
Pedersenbreen	4	S69 1395/96	
A. Lovenbreen	4	S69 1395/96	
Mindre Lovenbreen	4	S69 1395/96	
Kongresselva	3(1A)	S69 2482	Several smaller
Vasstakelva	3	S60 7388/89	
Dalfonna	4	S61 3387/88	
Orustdalen	1A	S69 2477	
Veteranbreen	4	Groundphoto	
Gangdalselva	3	S61 3295	
Daudmannen	1A	S66 4155/56	Large
Höganäsbreen	4	S71 6055/56	Small
Kjellströmelva	3(4)	S71 6063/64	Close to glacier
Linnévatnet	1A	S69 2482/83	Complex
Tunbäcken	3	S69 2431/32	Small

*Type 1A = spring naled, 1B = thermal spring naled, 2 = pingo naled, 3 = stream naled, and 4 = glacier naled.

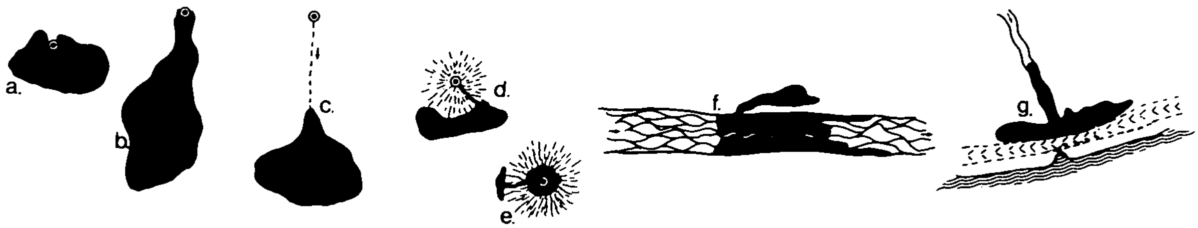

FIGURE 4. Schematic shapes of different types of naledi observed in Spitsbergen: **a** spring naled (low discharge rate); **b** spring naled (high discharge rate); **c** thermal spring naled; **d** pingo naled (high water temperature and discharge); **e** pingo naled (low water temperature and discharge); **f** river naled; **g** stream naled.

channel. Where the spring is situated on a slope, the naled may cover an alluvial fan. The ice body in these cases is thin and is often found close to the source. If the surface is more or less level, the ice body surrounds the source (Figure 4**a**).

Springs with a high discharge rate often have a well-defined stream channel to which the spring naled will be restricted (Figure 4**b**). If the channel is filled with ice, the shape of the naled will be more irregular because the overflowing water will follow the lowest parts of the surrounding terrain. However, the part of the ice body that will remain late in summer is generally restricted to the stream channel where the ice is thickest. The ice formed by the overflowing water is generally thin, not exceeding 0.5 m in thickness, and melts early in the summer.

Thermal spring naledi form far away from their source as it takes a long time for water to cool to the freezing point (Figure 4**c**). The shape of the ice is, in most cases, very irregular depending on the topography of the area where the water is freezing. The ice body is thin and often split up into smaller units. In many cases, this type of naled is formed upon lake or fjord ice as is the case with the naledi formed near the thermal springs in Woodfjorden, north Spitsbergen.

Pingo naledi normally do not have any specific shape as they may cover the entire pingo, or parts of it, as an ice armour (Liestøl 1977, pp. 20 and 21; Orvin 1944, p. 16). They may form a fan-like structure at the base of the pingo or they may be restricted to a stream channel leading from the pingo. The shape of the ice body will be dependent on the discharge rate of the water and on the water temperature. Thus, higher water temperature and high water discharge produce ice in the stream channel or in the flat surroundings of the pingo, Figure 4**d**; low water temperature and low discharge produce ice upon and close to the pingo, Figure 4**e**.

The naledi in front of glaciers also show a great variety of shapes as the topography in front of glaciers may vary considerably both with place and time. The ice body may be restricted to a stream channel and have a well-defined elongated shape or it may cover vast areas of the outwash plain with a less specific shape. The most common characteristic of this type is that the ice body is divided, very often already in early summer, into a chaotic pattern of ice sheets, ice blocks, and meltwater channels. This is a result of the large amount of meltwater from the glacier.

River naledi formed in braided rivers in wide valleys are, in most cases, restricted to the floodplain but, occasionally, large areas of the valley bottom may be flooded creating vast naledi (Figure 4**f**). These are generally thin, however, and do not last very long in summer. Several descriptions of this type of naledi are reported but, as they normally melt during the spring floods, only remnants are found on air photos. Documentation of naledi formed in larger stream channels are few from Spitsbergen. Stream naledi commonly form in stream channels when storm ridges block the outlets of rivers. During autumn, which is the period with the most frequent storms, the formation of large storm ridges, armoured with seaweed and ice, may become very effective and durable blocks to river outlets on exposed beaches. The river may flood the lower part of the stream channel and also the beach behind the storm ridge and thereby create naledi (Figure 4**g**).

Surface Morphology

The surface of a naled is normally without any striking topographic features. The gently undulating surface may be interrupted, however, by superficial drainage channels and by different types of mounds. These mounds or domes may vary in size from small humps, less than a metre high and a couple of metres in diameter, to large domes ten to twenty metres in diameter and up to three (in extreme cases more than five) metres high. Mounds as a characteristic feature for naledi were pointed out by several authors (van Autenboer 1963; Bird 1967; Liestøl 1977; Muller 1945; Porsild 1925; and others) and in some cases structures as high as ten to twenty metres were described (Bird 1967, p. 208).

Generally these structures are smaller in the naledi obserbed in Spitsbergen but they are, nevertheless, an important feature, because the mounds may help in separating naledi from glacier ice and snow fields on air photos. On the basis of field observations in Spitsbergen, the mounds on the surface of naledi can be separated into three groups with different morphological characteristics and origin. These three types of mounds are called "injection mounds", "cavity mounds", and "ridge mounds" and a description of their characteristics and genetic differences are given by Åkerman (1980, pp. 173–185).

Drainage

Flowing water, which is the main factor in the formation of naledi, also creates some typical morphological (mainly erosional) features on the surface of the naled. The drainage associated with a naled is either internal, marginal, or superficial. It is difficult to trace the internal drainage system in detail during most of the year. The internal drainage pattern can be studied in more detail only in connection with different mound structures, marginal outlets, and during the late summer when the ice body is disintegrating.

The marginal drainage often determines the size and form of the naled during the early stages of formation until stream channels are filled with ice. Thereafter, the superficial drainage, together with the internal drainage, is responsible for the continued formation of the naled (Table 2).

The superficial drainage is the most important with regard to surface structures on the ice. Especially during the summer, most of the drainage runs in channels melted into the surface of the ice. These drainage channels in the surface of the naled are characteristic features because they make it possible to distinguish naledi from snow patches on air photos.

The superficial drainage channels typically show perfectly developed meanders with a "wavelength" apparently depending upon the gradient (Figure 5).

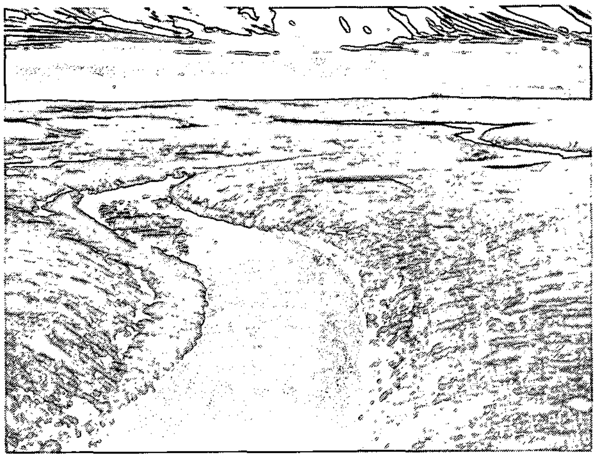

FIGURE 5. A wide superficial drainage channel on the largest naled of the complex near Kapp Linné, Spitsbergen, July 21, 1974.

Precipitation of Mineral Salts on/in Naledi

The occurrence of different types of mineral precipitation on the surface, or in the ice layers, of naledi has long been noticed and reported from different parts of the world. Early authors stated that precipitation of mineral salts was only characteristic for naledi formed by highly mineralized water, whereas others have associated mineral precipitation only with naledi formed in karst areas. Several investigations, especially in the Soviet Union, have shown that such mineral precipitation is a characteristic feature for almost all naledi, and that it occurs even in connection with naledi formed by water with very low mineral content (Shvetsov and Sedov 1941). Precipitation of salts on the surface of a naled or within the naled ice may be explained by (i) evaporation from the water flooding the ice surface, and (ii) by the increasing salt concentration in the water during the freezing process. Recent studies have shown that the latter process is the dominant one.

Observations of precipitation of mineral salts from naledi in Spitsbergen have so far not been found in the literature, in spite of the fact that it seems to be a rather common feature found in

TABLE 2. Types of drainage and their relative importance in naledi at different seasons

Drainage	Autumn	Winter		Spring	Summer	
		Early	Mid		Early	Mid
Internal	+	+	+ + +	+	+	+
Marginal	+ +	+ + +	+	+ +	+ +	+ + +
Superficial	+ + +	+ +	+ + +	+ +	+ + +	+ + +

Note: Observations on the naled complex between the Kongressvatnet and Linnévatnet lakes near Kapp Linné, Spitsbergen.
+ = *none or very low,* + + = *subordinate importance, and* + + + = *important or dominating.*

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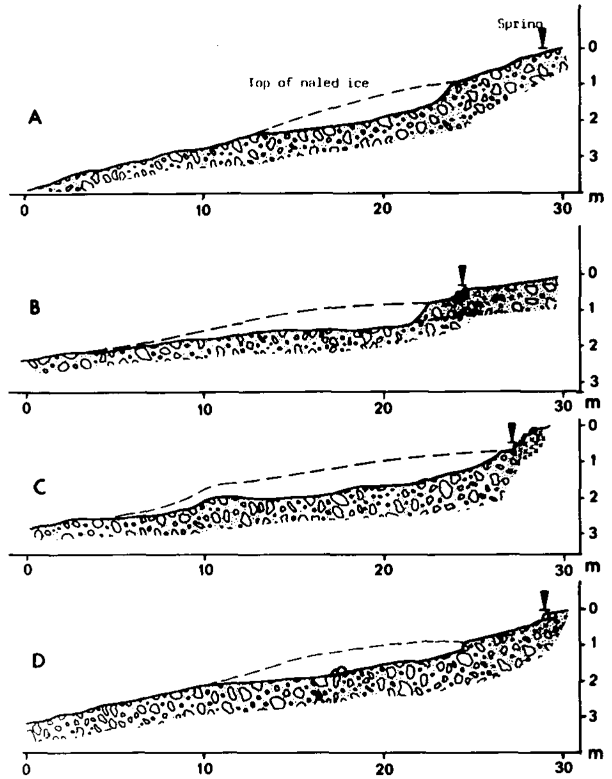

FIGURE 7. Slope profiles of four "naledi hollows" located near Kapp Linné, Spitsbergen.

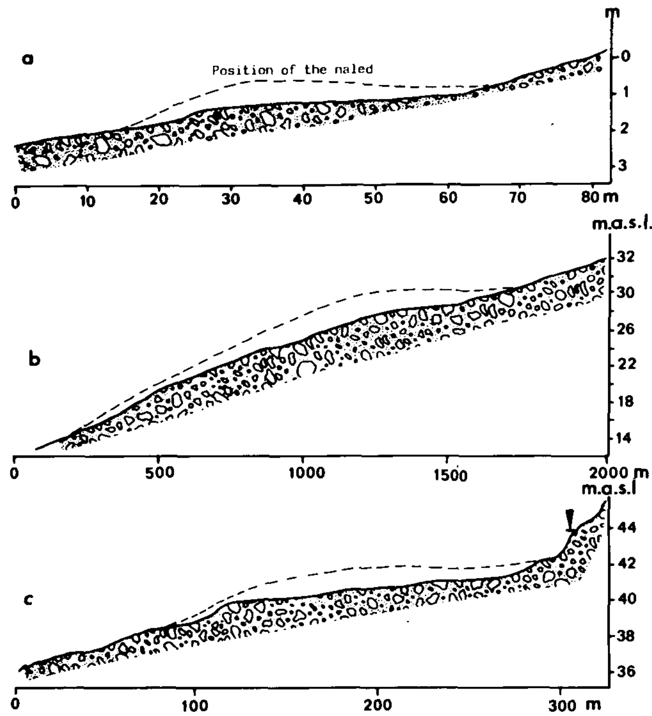

FIGURE 8. Slope profiles in which a step has formed as a result of protection by a naled. All are located near Kapp Linné, Spitsbergen.

naled than beneath a snowdrift. Several of the naledi observed in Spitsbergen show depressions in the terrain that are interpreted as being the result of this process.

The naledi hollows are generally shallow, of the same scale, and have the same profile as is characteristic of nivation hollows. Downhill profiles of four small naledi reveal underlying naledi hollows (Figure 7). All four are fed by springs with a low discharge situated close to the resulting naled.

Effects upon Stream Profiles

The occurrence of an ice body in a stream channel may protect the stream bed from fluvial erosion during the main discharge at spring flood. This protective effect is evidently of greater importance than the erosive effects of the nivation. In such a situation, the flow is channeled along the margins of the naled while the central part of the stream channel remains protected by the ice. This causes a change in the stream profile (at least in its central portion) and, in some cases, creates a profile with a step where the naled is located. Several examples of this type of stream profile have been found in association with naledi in small streams (Figure 8). The profiles were measured in the central part of the stream channels and the position of the naledi in early summer are indicated.

Effects upon Stream Patterns

The occurrence of a naled, annually or occasionally, may directly or indirectly change the course of streams and thus change the drainage pattern. This may occur both on a small scale close to a minor naled and also on a large scale when rivers are obstructed and forced to find new channels. Examples of this effect are found only on a small scale within the study area (Figure **9a**) where a stream is blocked by a storm ridge during autumn, but are more common in larger rivers in other parts of Spitsbergen.

A second fairly common situation is the presence of a braided section in a stream which normally has a more or less straight course. This type of drainage pattern is developed in small streams, the profiles of which are interrupted by a more level section where the water will flow relatively slowly. During fall it may freeze sooner than the water in the steeper sections, developing a small, thin naled. In spring, when the drainage starts, the naled will force the water to channel along the margins and later between the blocks of disintegrating ice forming a braided section or a section with flow over a swampy area (Figure 9**b**).

The naledi formed this way are very thin and disappear very early in spring. They are therefore generally overlooked. Still, this type of stream pattern and this type of very small naledi are so common that they may be considered as one of the most characteristic morphometric features of the small-scale drainage patterns on the strandflat areas of Spitsbergen.

Accumulative Forms

In the case of naledi formed in front of glaciers, accumulative features reveal the important role played by naledi as landform-producing agents. The most common situation is that the water creating a naled in front of a glacier does not emanate from the glacier itself but from unfrozen water-bearing strata beneath the glacier. Therefore the ice in the naled does not contain significantly more solid matter than other types of naledi, nor does it show any other specific differences in ice structure, morphology, etc. During periods when the glacier discharges large quantities of meltwater, however, this meltwater, with all that it carries, may flow out over the naled or it may follow the superficial or internal drainage channels of the naled. Under these conditions accumulative forms may be initiated and shaped by the presence of the naled; they may later be found preserved on the outwash plain when the naled has disappeared. Some forms owing their origin to the presence of the naled may incorrectly be interpreted as being of glacial or fluvioglacial origin.

The best examples of this are esker-like landforms that are common in front of many glaciers in Spitsbergen (Jewtuchowicz 1966). In many cases, these landforms are not of englacial or subglacial origin as first proposed, but have formed in the drainage channels of a naled. The sedimentation processes, stratification, and block orientation are more or less identical within a "naled esker" and the true eskers. A schematic picture of an "esker" formed within a naled is given in Figure 10, based on several observations in west Spitsbergen.

The naled eskers found frequently on the outwash plains of many glaciers in Spitsbergen are generally small features. They rarely exceed two metres in height but may be several tens of metres in length.

Kame-like structures, as well as other less specific features, formed on the outwash plains are also believed to have their origin in the effects of a naled. However, no details are available because no glacier with naledi is present within the study area at Kapp Linné. In spite of this, however, these landforms and processes are important and it should be kept in mind, when the glacial geomorphology in front of subpolar glaciers is investigated, that there always is a possibility that a naled and not the glacier itself is responsible for the observed landforms or form complex. This could affect interpretations concerning, for example, glacial morphology or glacial history.

The "Form-preventing Effect"

The most common and widespread geomorphological effect that naledi have on the ground surface is the "negative" effect of preventing or suppressing different landform-producing processes. Almost all naledi create a surface which to some

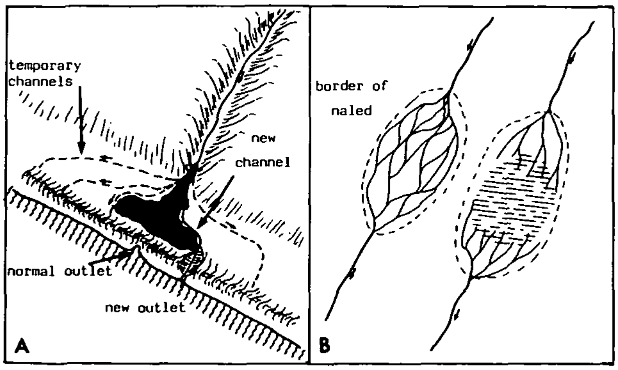

FIGURE 9. Diagrams of ways in which naledi may influence the drainage pattern of **A** minor- and **B** medium-scale streams.

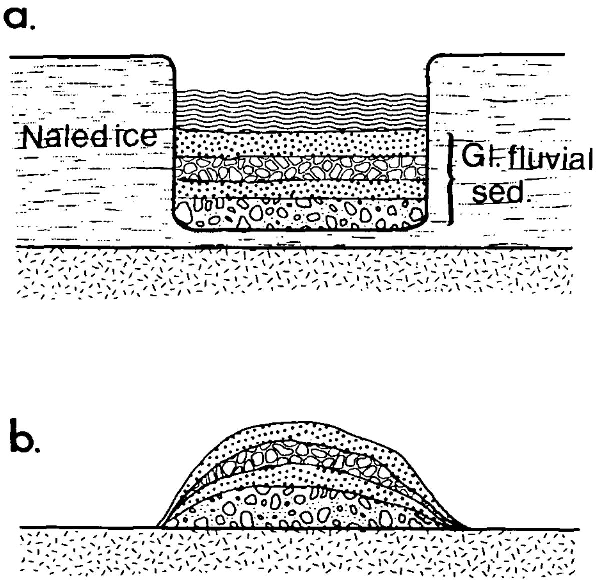

FIGURE 10. Diagram of the formation of "naled esker" within a superficial drainage channel: **a** during the existence of the naled; **b** after melting of the naled.

extent differs from the surroundings. Whether these differences are permanent, long-lived, or just incidental varies considerably according to the type of naled, the hydrology, and the climate.

The form-preventing effect shows up in a suppressed or totally absent vegetation cover. In the area studied, this effect on the distribution and occurrence of lichens is the most important one as these are the dominant vegetation. The vegetation has great importance for several patterned-ground features and processes, and thus for the surface morphology. Since, in this respect, the naledi do not differ very much from lingering snowdrifts, these criteria cannot always be used for identification of a naled site on air photos.

On the ground, however, this negative effect on the surface is more easily distinguished and can be used for the estimation of the maximum size of a naled as the border between the area covered with a naled and the surrounding area is, in most cases, fairly distinct.

Naledi as Indicators of Climate

The study of periglacial geomorphology always involves questions about the relations between geomorphological processes and climatological parameters. Good knowledge of climatological conditions is often essential for the understanding and interpretation of the processes and the development of landforms. Very often, however, the climatological data are insufficient or entirely lacking in areas with an active periglacial environment. Therefore it has become an important task to seek indirect methods and various climatic indicators which might be useful in studies of landform-developing processes (both active and inactive) in such areas, and in reconstructing past climatic conditions.

Glaciers have often been conceptualized as natural systems that integrate the multiple effects of climatic change. The nature of naledi makes it plausible that they respond to changes in climate in a similar way and could be used as climatic "indicators" or "tools" for the study of short-term climatic variations.

It has been possible to study some naledi during a succession of years and to make some simple investigations of their reactions to variations in the climatic conditions. However, with the exception of radiation balance data for a few recent years, the only factor for which sufficient data exists is the air temperature. As there normally is a relatively good correlation between air temperature and other climatic factors, air temperature may be used for rough estimations. Air temperature data were obtained from Isfjord Radio station, situated some 10 km north-west of the study area at Kapp Linné.

The surface area and volume of the naled complex investigated have been measured in the field during the years 1973 to 1977; for other years the surface areas have been measured on air photos (Figure 11). The calculations of ice volumes are based on direct measurements of the ice thickness in boreholes. In earlier observations, volume calculations are based on stereographic measurements. The latter figures are, of course, less accurate than the others.

Climatic Influences during the Period of Formation

The spring feeding the naled complex near Kapp Linné provides almost constant water discharge with a constant water temperature, so the main factor that determines the volume of the naled during the winter is the air temperature. If there is a comparatively low discharge of water, it can be assumed that when the air temperature is a few degrees below freezing point all the water from the source will freeze. This is the actual situation observed by the crew of Isfjord Radio. The formation of the naled starts soon after the first days of sub-zero air temperatures. In these conditions, the total volume of ice formed is determined by the length of the frost period only. The volume of the naled, measured on the first possible occasion in the spring, shows relationships both with the length of the frost period and the mean winter air temperature. Although the correlation between ice volume and the mean winter air temperature is poor (Figure 12**a**), the likely explanation is that the winter temperatures on the site are well below the "formation limit" below which all the water will freeze, even during comparatively mild winters, and that oscillations in the winter temperature do not have any vital importance for the ice volume. The length of the freezing period generally is the most important factor (Figure 12**b**). This is a logical result, provided that the rate of discharge from the spring is such that all water will be frozen.

Influences during the Melting Period

The most important factors acting upon the naled during the melting period are the air temperature and the radiation balance. From Ny Ålesund, situated in Kongsfjorden (*see* Figure 2) some 100 km north of the study area, radiation data was obtained for the period 1973 to 1977. Based on these data, which are reasonably representative also for the study area (Åkerman 1980, p. 219), it is possible to estimate the radiation balance for the naled surface during at least these years. In a comparison between

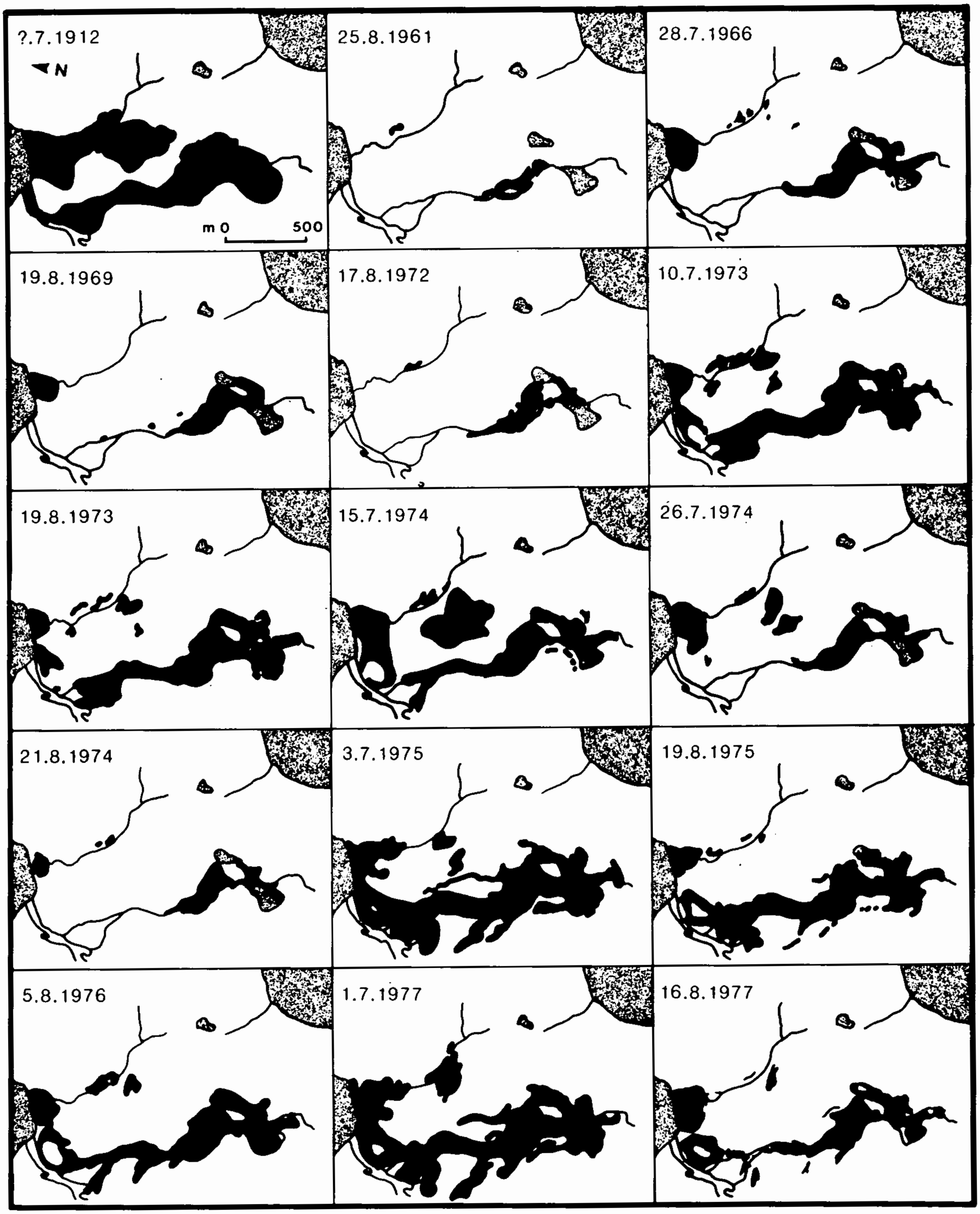

FIGURE 11. The size of the naled complex near Kapp Linné, Spitsbergen, drawn for different years from ground photos, air photos, and field measurements.

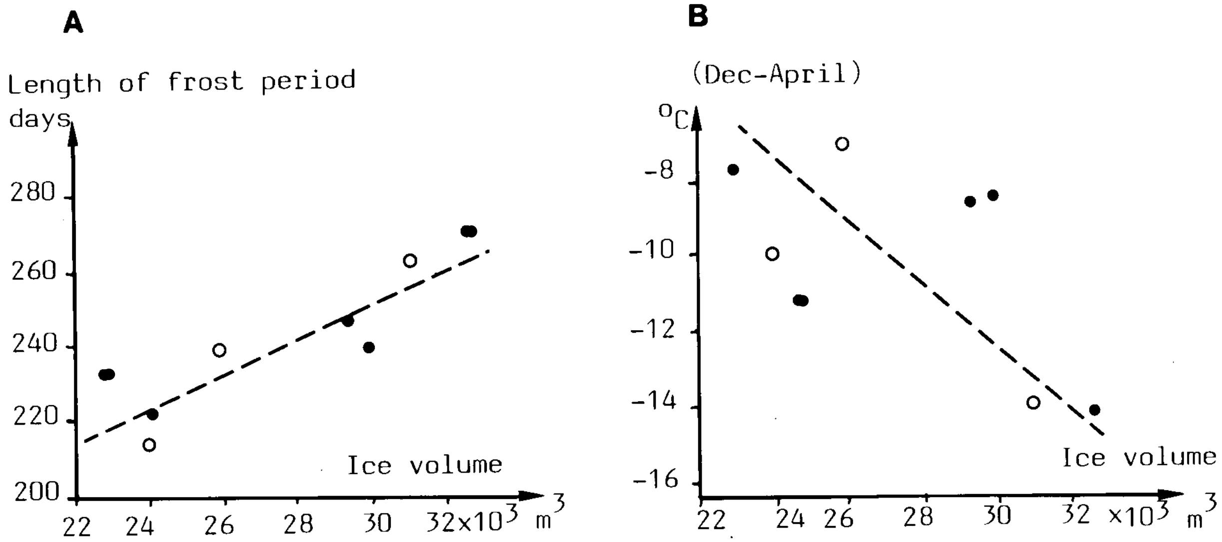

FIGURE 12. Correlation between the ice volume of the naled complex near Kapp Linné and **A** the length of the freezing period and **B** the winter air temperature at standard meteorological height at Isfjord Radio station. Filled dots are field-measured ice volume. Open dots are volumes estimated from air photos. (Dotted lines represent visual lines of best fit drawn by author. Ed.).

the observed volume loss of the naled and the energy available for melting, a fairly good correlation existed (Figure 13).

If the rate of melting of the naled reflects the variations in the temperature regime in the same way, or even better, this would be an advantage. Temperature data exist for a number of years but not radiation data and, as temperature is a factor easier to obtain and handle in order to use the naled as a climatic indicator, it is important to get an idea about the correlations between air temperature and the volume loss from the naled. When the measured loss in volume of the observed naled is compared with the air temperature in July during the years of observation, the correlation is found to be not as good as the one involving the radiation balance (Figure 14). Including May and June in the comparison (the main period of "warming up" and the first period of melting) does not change the result. Other factors are most likely of minor importance in comparison with air temperature and radiation balance and will not affect the result to any higher extent. Therefore it is reasonable to conclude that the radiation balance has the best correlation with the rate of ablation of the naled investigated. However, the correlation with the air temperature is reasonably good and, for most practical applications, or when radiation data are lacking, air temperatures

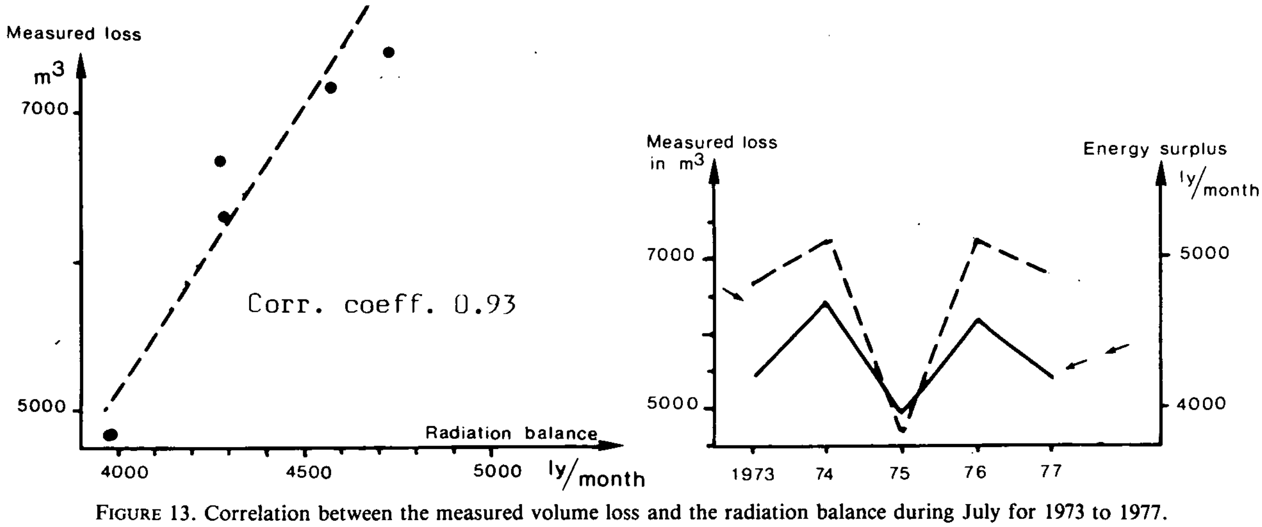

FIGURE 13. Correlation between the measured volume loss and the radiation balance during July for 1973 to 1977.

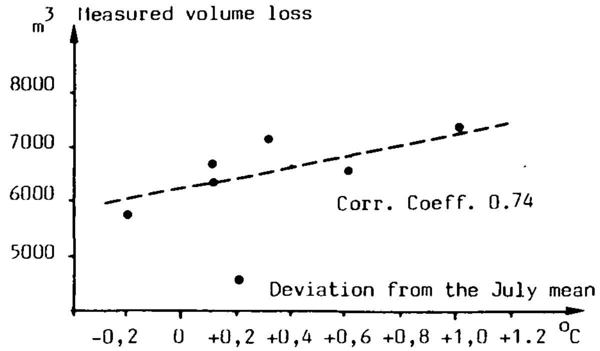

FIGURE 14. Correlation between the measured volume loss and the deviations from the long-term, mean monthly air temperature for July.

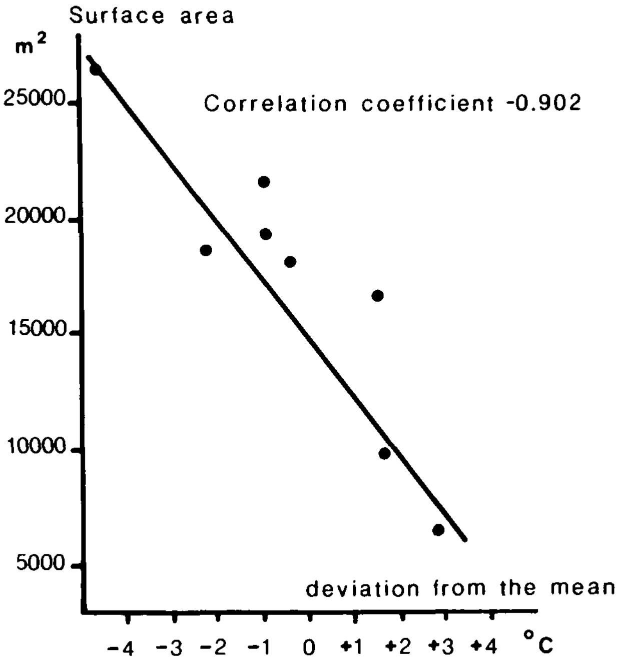

FIGURE 15. Comparison between the surface area of the investigated naled and the deviations of the mean annual air temperature at standard meteorological height at Kapp Linné during the period 1944 to 1977.

can be used with acceptable accuracy.

Generally, information about the surface area of a naled is more easily obtained than information on the volume. It would be an advantage, therefore, if there were also a correlation between the climatic factors and the ice surface area. As the naled normally has a variation in surface area which is far greater than changes in the thickness (volume) it is likely that such a correlation exists. A fairly good correlation exists between the surface area of the investigated naled complex, measured on as closely similar observation dates very year as possible, and the deviation of the annual mean temperature from the long-term mean for the period 1944 to 1977 (Figure 15).

It may be concluded therefore, that, if the highest accuracy is not required, the naled and its surface area alone can be used as a fairly representative indicator of changes in the temperature conditions during the summer season. The naled, and especially its changes in volume during summer, could be used as an indirect indicator of differences in the summer climate. However, all the prerequisite conditions that have been discussed must be taken into consideration and it is not possible, therefore, to use just any naled and its variations in areal extent and volume as an indicator of changes in the climatic conditions.

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