Marian PULINA

Institute of Geography, Silesian University Sosnowiec

The effects of cryochemical processes in the glaciers and the permafrost in Spitsbergen

ABSTRACT: This paper presents the results of investigations of the cryochemical processes in the glacial ice and the long-term permafrost in Spitsbergen, which have been confirmed by laboratory experiments. These investigations were performed on two glaciers: the Bertil Glacier, which lies in the central part of West Spitsbergen, and the Werenskiold Glacier, in the southern part of Spitsbergen. This paper also gives results for the unglaciated Fugleberget basin on the Hornsund Fiord in South Spitsbergen. It the autumn, winter and spring seasons distinct effects of cryochemical processes were found. They could be seen:
1) In the increased mineralization of the water circulating inside the glacier and the permafrost, which results from the freezing process (autumn and winter), and in the relatively high mineralization of the water in the early ablation period (spring); 2) in the precipitation of salts from the freezing water, both at the glacier front (winter naked ice), in the glacial caves and the unglaciated region. Sulphate salts (mainly gypsum) are most often precipitated. Carbonates (mainly calcites) were also found to precipitate. Calcites precipitate on the walls of limestone caves and even in the limestone rubble on talus cones. The experiments carried out at the Polish Station at Hornsund aimed at determination of the actual changes in the mineralization of Spitsbergen water caused by the processes of freezing and thawing.

Key words: Arctic, Spitsbergen, chemical processes, cryochemistry.

1. Introduction

Hydrological and hydrochemical investigations performed on several Spitsbergen glaciers (the Werenskiold and the Hans in the area of the Hornsund Fiord and the Bertil Glacier on the Bille Fiord) and in the unglaciated Fugleberget basin on the northern coast of the Hornsund Fiord showed a large increase in water mineralization in late autumn and in winter. Year-long investigations performed on the Werenskiold and the Bertil Glaciers in 1979–1980 showed that water mineralization increases

several times from summer to winter. For the Werenskiold Glacier this increase was from about $60 \, mg/dm^3$ to more than $370 \, mg/dm^3$ in winter and for the Bertil Glacier, from above $140 \, mg/dm^3$ to above $220 \, mg/dm^3$. Detailed hydrochemical investigations showed that the relatively highly mineralized water in late autumn and in winter result from a transformation of summer ablation and precipitation water. They are, however, not related to the increased leaching of the basal rocks or morainal debris which occurs in these seasons. This can be seen in Fig. 2 which shows a circular diagram of the ionic composition of the ablation water (1, 6) compared with the water circulating inside the Bertil Glacier in autumn and winter (2–5). In addition a diagram of the ionic composition of the summer water formed by the dissolution of the carbonate bedrock of the basin is shown (7, 8) for the Fugleberget basin. The ionic composition of this water is diametrically different from that of the precipitation or ablation water.

Analysis of the process which could cause such a "condensation" of the ionic composition of the precipitation water in autumn and winter season has shown that this may be the phenomenon of water freezing, since in the course of water crystallization foreign ions are expelled from the crystal lattice of the ice crystals forming. This causes an increase in the mineralization of the unfrozen solution.
This cryochemical process is well known to occur in highly mineralized sea water (Savelev 1971).

In order to prove the above hypothesis, a few dozens of experiments involving measurement and registration of the mineralization of water from glacial rivers, were carried out. These experiments were made in the hydrochemical laboratory of the Polish Polar Station at Hornsund in Spitsbergen in the course of the expedition of the Institute of Geophysics, Polish Academy of Sciences in the winter 1979/1980,

2. Cryochemical experiment

An aqueous solution which contains a given amount of salts in ionized state, increases its mineralization in the course of the freezing process. The ice crystals forming expel from the crystal lattice foreign ions, which pass to the unfrozen solution. As the salt concentration increases salts leave the supersaturated solution. The salt crystallization in the aqueous solution occurs when the saturation limit is exceeded. The order of crystallization depends on the value of this limit which is different for particular salt types. Considering the physicochemical type of Spitsbergen waters used in the experiment, the following order under which salts leave the solution can be expected: 1—carbonates, whose saturation limit is the

lowest, i.e. about 0.1 g/dm^3 $CaCO_3$; 2—sulphates, with a saturation limit of about 1.8 g/dm^3 $CaSO_4$; 3—chlorides, with a very high saturation limit of about 350 g/dm^3 NaCl and KCl. In the course of the experiments

Fig. 1 The location of the areas investigated in Spitsbergen 1—Werenskiold Glacier, 2—unglaciated Fugleberget basin, 3—Bertil Glacier, 4—Polish Polar Station at Hornsund

the mineralization of the water under study did not exceed 5 g/dm^3, and therefore the possible crystallization of carbonates (calcite) and sulphates (gypsum) must be expected. However, in the water under study the content of these salts was relatively small. Chloride salts prevailed. These salts can gather on the crystal walls and can often be crystallization nuclei.

The present paper does not give a description of ice crystallization and the effects of this process. Information on this subject can found in cryochemical literature and also in a large number of glaciological papers, e.g. in the books of P.A. Shumskii (1955) and B. A. Savelev (1971). The cryochemical processes under natural conditions have mainly been investigated in sea water.

An increase in solution mineralization as a results of freezing causes a lowering of the solidification point of the solution. If the temperature of the solution stabilizes close to the solidification temperature the freezing process stops. The lowering of the solidification temperature of each solvent, thus including water which contains a given amount of the dissolved substance, only depends on the properties of the solvent and concentration of the solved substance. It does not, however, depend on the kind of this substance (Barrow 1978).

The solidification temperature of the solution (T_{Krz}) only depends on the molar concentration (m) of the solved substance, according to the relation

(1) $$T_{Krz} = K_{Krz} \, m$$

where K_{rz} is a cryoscopic constant whose value for water is 1.86.

The maximum concentration of salts registered in the course of the experiments exceeds 5 g/dm^3. In view of the fact than in these solutions chloride and sodium ions, above all NaCl salts[1], dominate the molar concentration of the solution with such concentration is of the order of 0.1 $mole/dm^3$. And, therefore, the solidification temperature of the solutions obtained in the final phase of the experiments is

$$T_{Krz} = -1.86 \cdot 0.1 \approx -0.2 \, ^\circ C$$

The air temperature range over which the experiment was carried out was from—9.9 to—14.2 °C and did not contribute to the stopping of the freezing process over the registration range.

Figs. 3 and 4 show a theoretical cryochemical curve which illustrates the relation between the volume of the unfrozen solution (V) and the salt concentration degree (mineralization Σ_M), according to the relation

$$V = f(\Sigma_M)$$

under the assumption that the whole solved substance remains in ionized state. The curve in Figs. 3 and 4 has the character of a bilogarithmic function and is given by the formula

(2) $$\log V = 3.50796 - \log \Sigma_M$$
$$\Sigma_{Mp} = 32.2$$

This curve was plotted for water from thawed glacial ice whose mineralization was 32.2 mg/dm^3 Σ_{Mp}.

Under the natural conditions the relation $V = f(\Sigma_M)$ is certainly far from the theoretical one. Its behaviour can be affected by the ionic composition of water, initial mineralization, freezing rate atc. One of the aims of the experiment was to determine the real cryochemical curve for the fresh

---

[1] 1 mole NaCl = 58.5 g/dm^3

water of Spitsbergen glaciers, for the water circulating in the permafrost, the precipitation water, including snow, and the water from thawed glacial ice. Another purpose of the experiment was to determine the ionic composition of the above waters in the course of the freezing
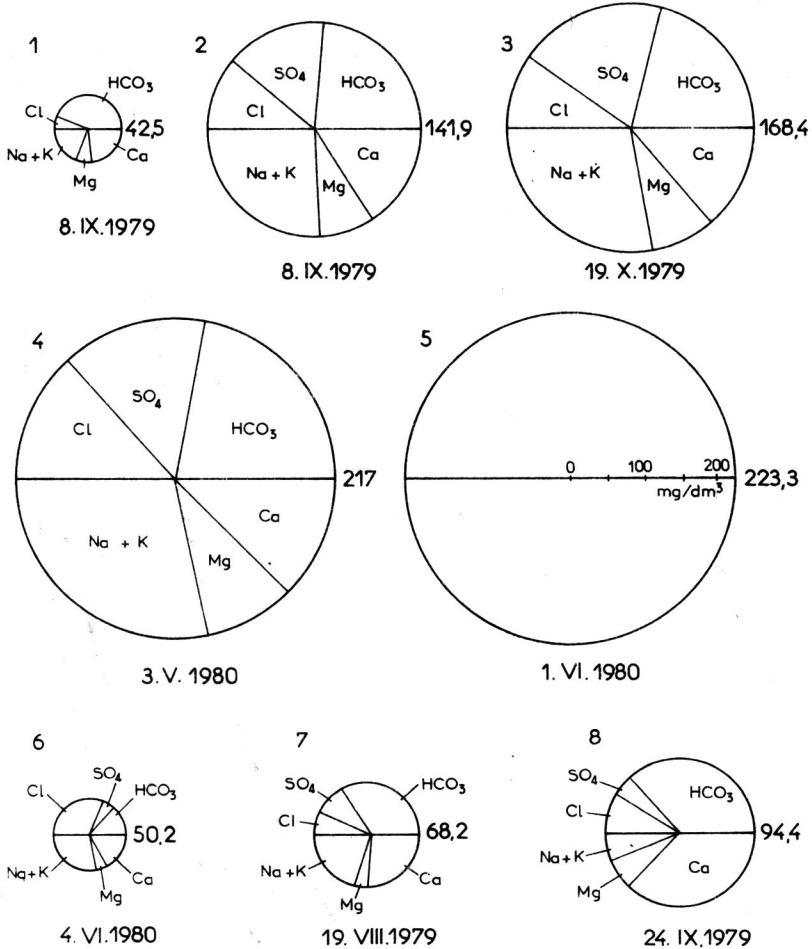

Fig. 2. Changes in the ionic composition and total mineralization of water in the Bertil Glacier, as a result of cryochemical processes 2-5 (autumn 1979 — winter 1979/1980), and in the Fugleberget basin, due to dissolution of carbonates 6-8 (spring 1980, summer and autumn 1979). 1—ablation water on the Bertil Glacier

process. In addition a succesful attempt was undertaken to obtain experimentally the water corresponding in its ionic composition and mineralization to the winter water of the Werenskiold Glacier.

In implementing the final objective the water taken from the Werenskiold Glacier in summer and autumn was used.

The experiment was carried out under the following procedure. Containers with freezing water were placed outside the building of the Polish Polar
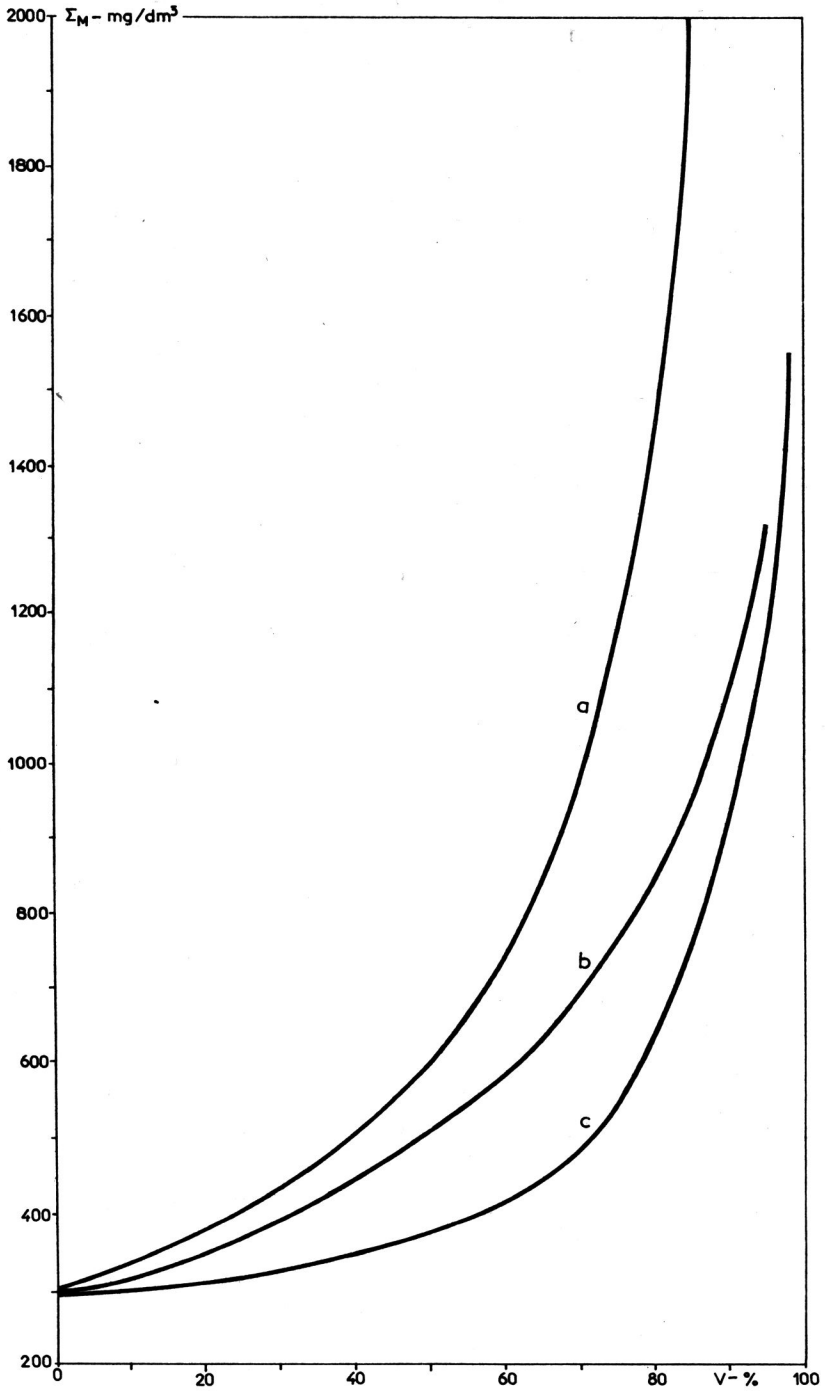
Station. They were $1 \, dm^3$ high-pressure polyethylene bottles in which the sensor of an electrical thermometer and electrodes were put in order to measure the specific conductivity and pH of the solution. The measurements were taken with and accuracy of $0.1\,°C$ for temperature, $1 \, \mu S$ for specific conductivity and 0.05 for pH, respectively. These elements were registered for $1 \, dm^3$ water by devices manufactured by the Hungarian company Radelkis set in the hydrochemical laboratory, at room temperature. The volume of the unfrozen water was determined each time by pouring it from the container into a callibrated vessel. Beside the container for which registration was taken, another container was set with an analogous water sample on which the same measurements were taken, during which the sample was moved into the laboratory. Additionally, samples for chemical analysis were taken from the other container. The results obtained for the second container served to control the registration for the first container and complemented the result with the ionic composition of the water.

The chemical analysis of the water included the determination of the basic ions: Ca^{2+}, Mg^{2+}, $Na^+ + K^+$, HCO_3^-, SO_4^{2-}, Cl^-. Apart from Na^+ and K^+ which were determined by the ionoselective method with Radelkis potentiometers, the other ions were determined using volumetric methods. Moreover, pH was determined by the potentiometric method (with an accuracy of 0.05) and by the colorimetric method (with an accuracy of 0.1); free CO_2 (with an accuracy of $1 \, mg/dm^3$) and also the specific resistivity of the solution ϱ_{18} (with an accuracy of 1 per cent) were also determined. Finally, from the specific resistance, the mineralization of the solution (Σ_M), in mg/dm^3, was calculated according to the formula

$$(3) \qquad \Sigma_M = \frac{720000}{\varrho_{18}}$$

achieving an accuracy of 10 per cent.

The method of the chemical analysis of water and the calculations are given in the instruction for the Polish field laboratory used in Spitsbergen (Markowicz, Pulina 1979).

The description of the experiment will neglect the difficulties encountered in the course of it. They involved both the inconvenience related to the settlement of ice crystals on the electrodes, the necesity of con-

---

Fig. 3. Changes in the total mineralization of water as a result of freezing and thawing. Analysis of water taken from the Werenskiold Glacier (the springs of the Kvisla River, 3 April, 1980). Initial mineralization $294.6 \, mg/dm^3$ a—theoretical freezing curve, b—experimental freezing curve, c—experimental thawing curve. Σ_M—total water mineralization in mg/dm^3, V — unfrozen water volume in per cent

structing ice-resistant elecrodes and the difficulties with registration of the final freezing phase[2]. Therefore, it was necessary to repeat the experiments many times so as obtain reliable results.

The experiments were carried out in the winter of 1980 at air temperature from—9.9 to—14.2 °C. Over this temperature range above 95 per cent of the solution volume froze for a dozen to more than twenty hours.

A dozen or so samples taken in the summer and autumn of 1979 and in the winter of 1980 were studied. They were mainly from the water inside the Werenskiold Glacier (the outflow of the Glacier River, from below the Angelfjellet and the Kvisla), from glacial ice and snow. These waters had different mineralization, from 30 mg/dm^3 in the case of the water from thawed glacial ice, through 120–150 mg/dm^3 in the water of the Werenskiold Glacier in autumn, to 800–1300 mg/dm^3 in the same glacial waters in winter. Several measurement cycles were carried out, including both the freezing and thawing of water. The thawing process was performed at room temperature (from 17 to 18 °C).

Fig. 3 shows the result of one of the experiments, obtained for a sample taken on 3 April, 1980 from the outflow of the Kvisla River from the Werenskiold Glacier. The mineralization of this water was 294.6 mg/dm^3. Fig. 3 shows three curves: the theoretical one (a) and the experimental curves of freezing (b) and thawing (c). These curves have similar behaviour according to the biblogarithmic function. However, they do not coincide. In its initial part, up to about 50 per cent of the frozen water volume, the freezing curve is close to the theoretical curve, but the remaining part is much different from it. This seems to indicate that when nearly 50 per cent of the volume is frozen, causing an approximatedly double increase in water mineralization, salts leave the solution and settle on the container walls and ice crystals. Analysis of the thawing curve, which is farthest from the theoretical one, leads to the following conclusion: the process of salt solution is slower as the solution thaws than that as the solution freezes.

Fig. 4 gives the results of the experments involving the freezing of six samples taken from the water circulating inside the Werenskiold Glacier. Here are some results from an anlysis of the cryochemical curves obtained:

1. As the water freezes, there occurs an increase in the mineralization (Σ_M), which strictly depends on the unfrozen water volume. (V). The process agrees with the function $V = f(\Sigma_M)$ which has biologarithmic (power) character and takes the form $\log V = a + b \cdot \log \Sigma_M$.

2. The experimental curves obtained for the freezing process are greatly different from the theoretical curve. Their inclination is smaller, indicating

The equations shown in the figure:

$$\text{a.} \quad \log V = 4{,}23420 - 1{,}48171 \ \log \Sigma_M$$
$$\Sigma_{Mp} = 32{,}2$$

$$\text{b.} \quad \log V = 5{,}52275 - 1{,}66525 \ \log \Sigma_M$$
$$\Sigma_{Mp} = 124{,}0$$

$$\text{c.} \quad \log V = 5{,}67953 - 1{,}67713 \ \log \Sigma_M$$
$$\Sigma_{Mp} = 147{,}6$$

$$\text{d.} \quad \log V = 5{,}69029 - 1{,}49255 \ \log \Sigma_M$$
$$\Sigma_{Mp} = 294{,}6$$

$$\text{e.} \quad \log V = 6{,}65718 - 1{,}60564 \ \log \Sigma_M$$
$$\Sigma_{Mp} = 793{,}8$$

$$\text{f.} \quad \log V = 9{,}42711 - 2{,}40214 \ \log \Sigma_M$$
$$\Sigma_{Mp} = 1240{,}3$$

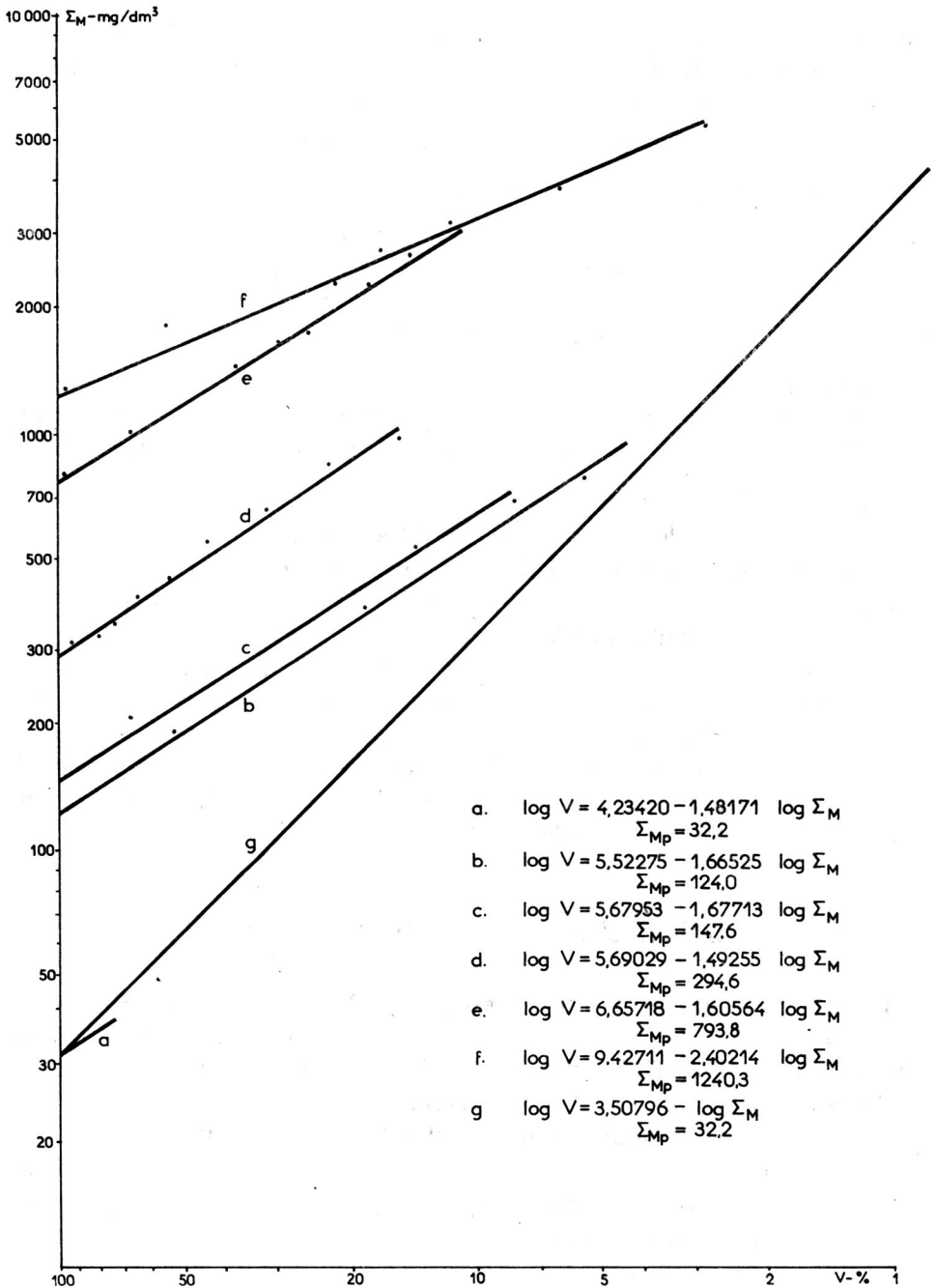$$\text{g} \quad \log V = 3{,}50796 - \log \Sigma_M$$
$$\Sigma_{Mp} = 32{,}2$$

Fig. 4. Experimental cryochemical curves for the water of the Werenskiold Glacier (1–6) obtained the hydrochemical laboratory of the Polish Polar Station at Hornsund in Spitsbergen in the winter of 1980. 7—theoretical curve. Σ_M—total water mineralization in mg/dm^3, V—unfrozen water volume in per cent

that salts party leave the solution as the latter freezes. In weakly and medium mineralized waters, up to 1 g/dm^3, the inclination of the cryochemical curves is similar. The function take here the form:

(4) $$\log V = 4.23420 - 1.48171 \log \Sigma_M$$

in the case of the water from thawed glacial ice,

(5) $$\log V = 5.52275 - 1.66525 \log \Sigma_M$$

for the weakly mineralized autumn water inside the glacier,

(6) $$\log V = 6.65718 - 1.60564 \log \Sigma_M$$

for the medium mineralized winter water inside the glacier.

In turn, for the mineral water, above 1 g/dm^3, the inclination of the curve is smaller compared to that of the other curves. The function takes here the following form,

(7) $$\log V = 9.42711 - 2.40214 \log \Sigma_M$$

The obvious conclusion can thus be drawn, that the process in which salts leave the solution as it freezes is here much more intense than in weakly and medium mineralized waters.

It seems relevant to make here a marginal comment that the 1 g/dm^3 limit is arbitrary but certainly convenient, since it is generally assumed in hydrochemical classification. With a closer analysis of the curve in Fig. 4 it can be concluded, however, that this curve increases its inclination only from about 1.8 g/dm^3 on. This is probably related to the CaSO$_4$ saturation limit reached by the water under study.

3. The cryochemical effects in the Bertil Glacier

The Bertil Glacier lies in the central part of West Spitsbergen (Dickson's Land) at a distance of a few km northeast of the mine and mining settlement Pyramide. This settlement is situated on the northern shore of the Mimer Bay, an arm of the Billefiorden.

The Bertil is small mountain glacier, about 6 km long, situated in a deep valley at 120–550 m a.s.l., between the ridges of the Great Pyramide (935 m a.s.l.) and of the Reuterskilfjellet (1029 m above sea level) with the peak of the Little Pyramide.

Investigations of this glacier were performed in the autumn and winter of 1979/1980 by a Polish-Russian glaciological expedition (Pulina 1981). These were hydrological and hydrochemical examinations and also glacier caves were explored. The direct aim of these investigations was the project of utilizing the water from this glacier in the mine and settlement Pyramide.

In winter water was found to outflow from inside the Bertil Glacier.

This water formed a field of naled ice below the bank of terminal moraines. The final part through which the water from the Bertil Glacier flowed was the Elsa Cave, discovered in the course of the investigations mentioned above. This cave can be reached by a 300-meter tunell through which the water is drained from the inside of the glacier to the water-pipe network supplying the settlement Pyramide.

Hydrological and hydrochemical investigations were carried out in October and November 1979, while in the last winter months of 1980 water samples
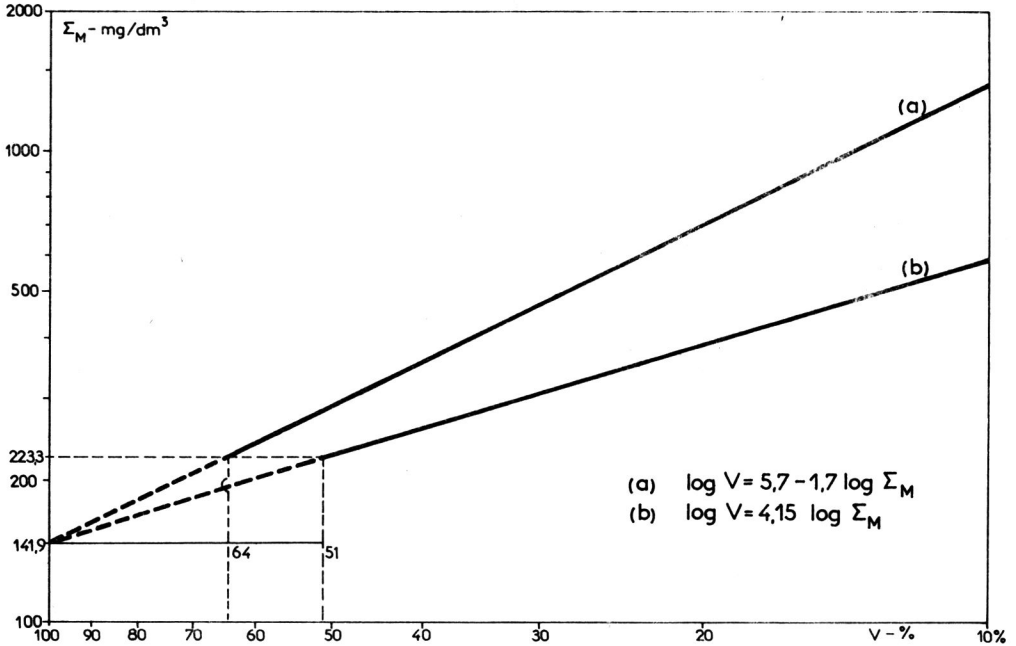
Fig. 5. Cryochemical curves for the water inside the Bertil Glacier. The method for calculation of the frozen water volume in the glacier in the winter 1979/1980 with an increase in the water mineralization from 141.9 to 223.3 mg/dm^3. a—theoretical curve, b—experimental curve

were taken for chemical analyses. Fig. 2 shows the results of 4 measurement series in the form of cricular diagrams which illustrate the mineralization and ionic composition of this water. It follows from these diagrams that from 8 September, 1979 to 1 June, 1980 the mineralization of this water increased from 141.9 mg/dm^3 to 223 m g/dm^3, while its ionic composition remained unchanged. This was always the same water, of the $(Na^+ + K^+) - HCO_3^- - SO_4^{2-}$ (Ca^{2+}) type, which came from a transformation of the spring and summer precipitation water. The discharge in the main collector, constituted by the galleries of the Elsa Cave, steadily decreased from about 8 dm^3/s at the beginning of the period under study to 1.5 dm^3/s at the end the winter. It should be noted that the decreased dischange at the end of the winter

was caused by the freezing of the narrow gallery of the cave. This was accompanied by a swelling of the water in the other, unexplored galleries belonging to the main collector. Phenomena of this type have often been observed in some glaciers in the vicinity of the Hornsund Fiord, including the ice cave which is the outlet of the water collector in the East Torell Glacier.

The increase in the water mineralization found in the Bertil Glacier can be explained cryochemically. Fig. 5 shows the theoretical and the experimental cryochemical curve for the water inside the Bertil Glacier. Analisis of Fig. 5 permits some conclusions to be drawn:

1. Over the 6 winter months the water mineralization increased from 141.9 to 223 mg/dm^3, as a result of the freezing of 49 per cent of the water volume circulating in the Bertil Glacier at the begining of October.

2. Knowing the actual water volume which flowed from the Bertil Glacier over 6 winter months to be about 70 thousand m^3, i.e. at least 51 per cent of the unfronzen water, it is possible to determine the volume of the remaining 49 per cent of frozen water. It is thus slightly less than 70 thousand m^3. It follows from these calculations that the original water wolume in the channels of the Bertil Glacier was at least 140 thousand m^3. This is certainly less than the actual amount, since at the end of the winter season still large amounts of water were flowing from the glacier.

4. Cryochemical effects in the Werenskiold Glacier

The basin of the Werenskiold Glacier lies in the southwestern part of the Wedel-Jarlsberg Land, in the centre of the western range of the coastal mountains at the outlet of the Hornsund Fiord. The mountain ridge around the valley of the Werenskiold Glacier run up as high as 600 to 900 m a.s.l. The highest peaks over these ridges are the Tonefjellet (945 m a.s.l.), the Slyngfjellet (788 m) above sea level and the Skålfjellet (670 m a.s.l.). The bottom of the valley on which the Werenskiold Glacier is based is at 30 to 70 above sea level in the lower part of the glacier, 100 m above sea level in the central part and as high as 150 to 250 m above sea level in the central glacier cirque (Czajkowski 1981). This differentiation suggests a considerable cleft of the central valley and large delevellings, of above 500 m in the lower part of the valley and of 700 m in the central glacial cirque.

The mountain Werenskiold Glacier and three glaciers decendiny from lateral cirques constitute and almost 80 per cent of the basin of more than 44 km^2. The remaining area includes the steep, unglaciated slopes of the valley and the unglaciated forefield of the glacier. The mian thickness

of the Werenskiold Glacier is about 100 m. This thickness increases to about 250 m in the glacial cirques. The glacier ends on land, while its flat front about 3 km wide descends to an internal outwash closed at all sides by lateral moraines and a terminal one. The lenght of the glacier is nearly 7 km along the central axis, while the diameter of the central firn field is as long as 3.5 to 4 km. This glacier divides into three distinct longitudinal bands, each of which is connected to its own glacial cirque and drained by its own central underground channel which begins a glacial river. The rivers flowing from these glaciers join in the internal outwash into one Glacial River[3]) which, through a gap in the terminal moraine, takes the glacial water to the Nottingham Bay.

The Werenskiod basin is closed by hydrometric profile with a limnigraph set at the point where the Glacial River breaks through the terminal moraine.

The basin bedrock is compared of metamorphic rocks of the Hecla Hoek succession, among which crystalline micaceous and chlorite schists quarzites and quarzite arkozes, amphibolites and greenstone dominate. Subordinate marbles are also worthy of note (Smulikowski 1968).

The Werenskiold basin was the object of Polish glacional investigations which were started in 1957, during III International Geophysical Year (1957–1960), and continued by expeditions organized by Wrocław University together with the Institute of Geophysics, Polish Academy of Sciences, in 1970–1974. Climatological and glaciological research was then carried out (Kosiba 1960, Baranowski 1977), and from 1971 a systematic registration has been made of the outflow of water from the Werenskiold Glacier (Pulina 1974), to be continue annually in summer seasons until 1981, expect for the period 1975–1978. In 1979–1980 these investigations were performed throughout the polar hydrobiological year, including winter (Pulina, Pereyma, Kida, Krawczyk 1985). It was found that three rivers which drain the particular parts of the Werenskiold Glacier are active throughout winter, while the water which flows from them freezes in the forefield of the glacier making large naled ice fields. This ice thaws in spring. The volume of this water which flows in winter from the Werenskiold Glacier was also determined (Table I).

As a result of year-long hydrological research in the Werenskiold Glacier, the effects of the cryochemical processes in winter were found in the form of the increased mineralization of the water inside the glacier and the crystallization of salts both from the winter naled ice and on the surface of fine fluvioglacial sediments.

---

[3] The total outflow of water from the Werenskiold Glacier by the Glacial River was not formed until the late 1960. Previously the water flowed down the Kvisla River, which drained the northern part of the glacier, and down the Glacier River, which drained the remaining part.

Analysis of the mineralization curve (Σ_M) of the water of the Glacial River from the summer of 1979 to the winter of 1980 (Fig. 6) shows a multiple increase in mineralization between these two seasons. The first two distinct jumps in the mineralization were observed in the second half of the summer, from 30 mg/dm^3 to 62 mg/dm^3, and in the early autumn, from 51 mg/dm^3 to 107 mg/dm^3. This increase in the mineralization was accompanied by a slight change in the ionic composition of this water, from HCO^- − Ca^{2+} − $(Na^+ + K^+)$ or Cl^- to HCO_3^- − Ca^{2+} − Mg^{2+}. The third mineralization jump occurred in the secound half of the autumn

Table I.

The water volume in the Werenskiold Glacier in the winter 1979/1980

period	M mg/dm^3	V,₂		V₁		V₂		V	
		Thousand m^3	m^3/s	%	mln. m^3	%$^{x)}$	mln. m^3	%	mln. m^3
Sept. 1979–may 1980	80–370	720	0.049	92.8	9.3	7.2	0.7	100	10.0
Sept. 1979–Oct 1979	80–142			64	6.4	36	3.6	100	10.0
Oct. 1979–May 1980	142–370			81.2	2.9	18.8	0.7	100	3.6

V₂ — the unfronzen water volume floving from the Glacier (field measurements),
V₂ — the unfronzen water volume in the glacier,
V — the total volume of frozen and unfrozen water,
%^{x} — the percentage volume of unfrozen water determined by a cryochemical experiments according to formula (5).

and was from 80 mg/dm^3 to 142 mg/dm^3. It was accompanied by a slight change in the ionic composition which consited in an increase in the percentage of the Mg^{2+} contents, while the share of the ions Ca^{2+} and HCO_3^- decreased. The hydrochemical type, however, remained unchanged: HCO_3^- − Ca^{2+} − Mg^{2+}. The greatest mineralization jump was found in the winter and was from 120.9 mg/dm^3 in the middle of November 1979 to 204.7 mg/dm^3 in the early February of 1980 and 372.1 mg/dm^3 at the end of March 1980. These high values remained until the end of the winter season. In May they were 241.9, 294.6 and 387.6 mg/dm^3. At that time the water type Ca^{2+} − HCO_3 − SO_4^{2-} dominated. A higher mineralization, of as much as 1300 mg/dm^3, was found in the outflow of the Glacial River (9 April, 1980). This water had, however, lost contact with the central glacial stream.

It is possible to explain the first two water mineralization jumps in the Glacial River in the summer and autumn seasons by recognizing the increasing share of the more strongly mineralized water from the unglaciated part of the basin and as the effect of the corrosive processes caused by water circulating in the glacier and its base. The successive mineralization jumps, in the second half of autumn and in winter, cannot be explained by the increasing share of the water of longer retention inside the glacier or the transit
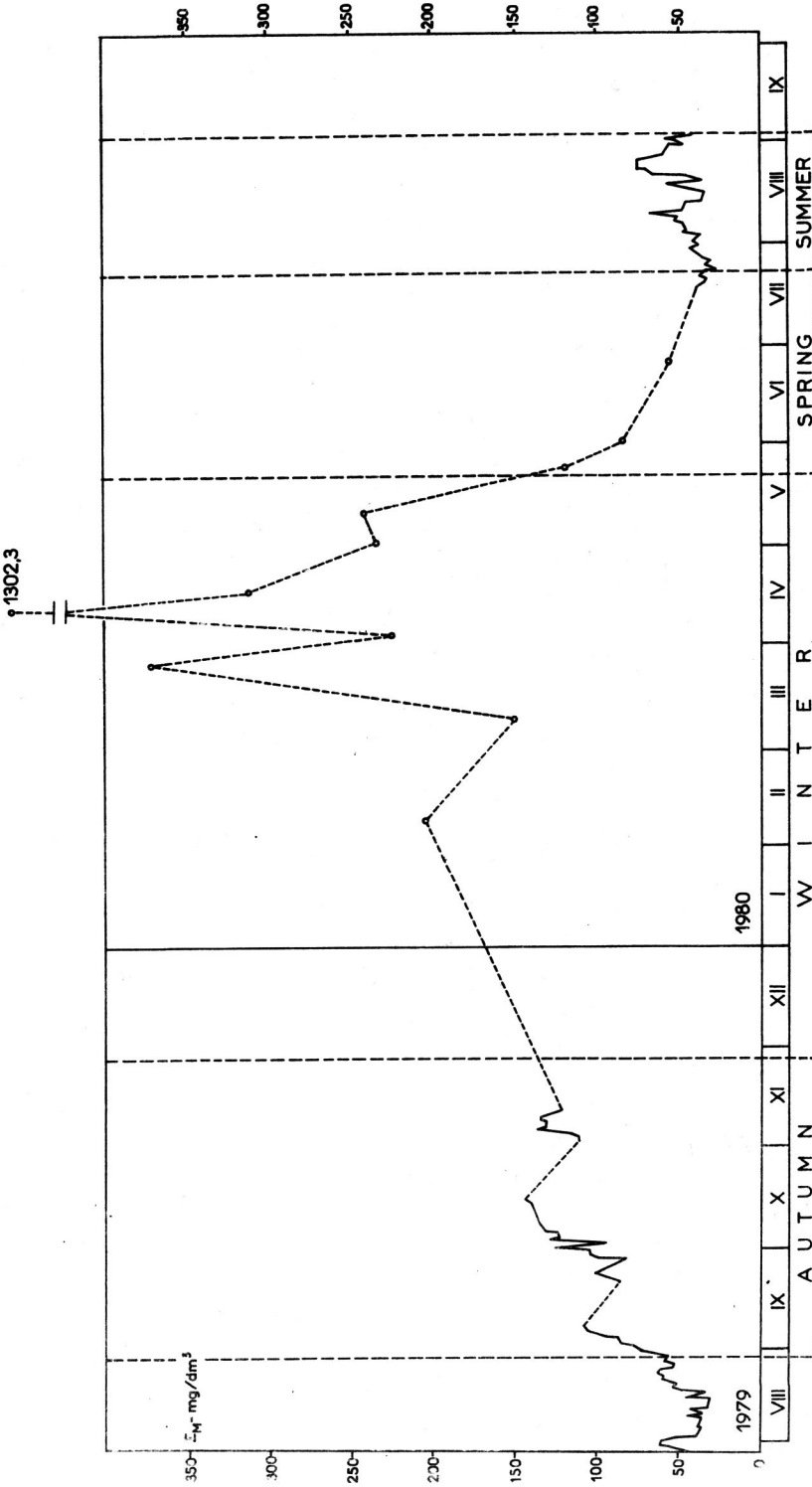
Fig. 6. Total mineralization of the water of the Glacial River taking water from the Werenskiold Glacier in the hydrological year 1979/1980.

water from the unglaciated slopes of the basin, since at that time the outflow consists mainly of water from inside the glacier with increased mineralization of the order of 110—370 mg/dm^3 and of the type Ca^{2+} — HCO_3^- — SO_4^{2-}. Therefore, the large, triple increase in the mineralization of this water, unaccompanied by a change in its ionic composition, can be explained only cryochemically. This thesis was proved by experimental research carried out at the Polish Polar Station at Hornsund, in the course of which water closer to that circulating in the glacier in winter was achieved from the water which circulated in it in autumn. The results of this experiment were given in the introductory part of the present paper.

The results make it possible to determine the percentage of the frozen water in the glacier and also, when the outflow from the glacier in autumn is known, to define the water volume circulating in the glacier in winter. Moreover, in the case of the Werenskiold Glacier, for which the outflowing water volume in the winter season 1979/1980 is known, it is possible to calculate the water volume inside the glacier at the beginning of the winter season, and thus to determine the volume of the channels and zones in which this water is. Although most of this water freezes in winter but it thaws in spring, affecting the chemical composition of the spring water flowing from the glacier.

Fig. 7 shows a method for the calculation of the water volume in the Werenskiold Glacier from experimental results (curve b) for the mineralization jump from 80 to 142 mg/dm^3 and from 110 to 370 mg/dm^3 (V_1 in Table I). Curves b in Fig. 7 represent the direct result obtained in laboratory by freezing the autumn water taken from the Werenskiold Glacier (compare with Fig. 4). The function of this bilogarithmic curve can be given by formula (5). It follows from the curve in Fig. 7 that the frozen water volume which was then in the Werenskiold Glacier, was over 92 per cent (V_1), with 80–137 mg/dm^3 between the end of the autumn and the end of the winter of 1980. When the remaining 8 per cent is assumed to be the amount of water flowing from the Werenskild Glacier—this value is known for the winter 1979/1980 and is above 720 thousand m^3 (V_2' in Table I) it is easy to calculate the actuel water volume in the glacier at the end of the autumn of 1979 (V). This value was 10 mln m^3. The values given here are lower, since it is necessary to account for the fact that not all water flowed from the Werenskiold Glacier at the end of the winter of 1980. Further analysis of the measurement data from the Werenskiold Glacier, which has not been elaborated fully yet, may make it possible to determine how much water remained in the glacier. This problem is essential for the determination of the actual amount of water inside the Werenskiold Glacier in the winter season and thus of volume of the water channels and zones in the glacier.

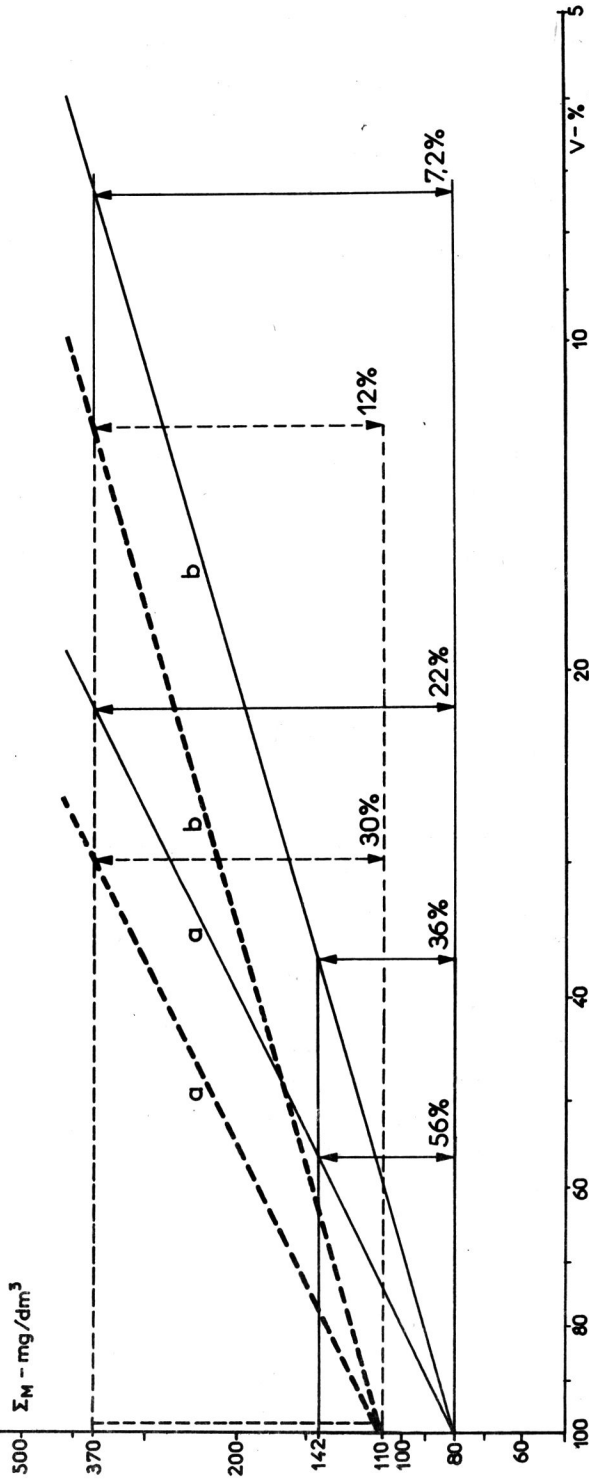In the spring of 1980 it was possible to observe the characteristic

Fig. 7. Cryochemical curve for the water inside the Werenskiold Glacier. The method for calculation of the frozen water volume in the glacier in the winter 1979/1980 with an increase in the mineralization from 80 to 142 mg/dm³ and from 110 to 370 mg/dm³. a—theoretical curve, b—experimental curve. Σ_M—total water mineralization in mg/dm³, V—un frozen water volume in per cent.

phenomenon of a decrease in the water mineralization in the Glacial River from about 390 mg/dm^3 at the end of winter to 28 mg/dm^3 at the end of spring. This decrease in mineralization was accompanied by rapid increase of discharge caused by the intensive thawing of winter snow. In terms of the ionic composition this water underwent at time some slight changes. The winter type in which the ions $Ca^{2+} - HCO_3^- - SO_4^{2-}$ (Mg^{2+}) dominate became the type $HCO_3^- - Ca^{2+} - Mg^{2+}$ $(Na^+ + K^+)$. In the second half of spring there was an increase in the water mineralization, which at the beginning of summer achieved the maximum value of about 70 mg/dm^3.

The behaviour of the curve for the mineralization of the Glacial River in spring resembles that of the curve for ice thawing and it is therefore also a cryochemical effect. In the initial thawing phase the most strongly mineralized water flows out; in its mass this water form the prevailing part of the water unfrozen in winter or the water from the first thawing phase, which dissolved the salts settled on the crystal walls in the course of the freezing process. The outflow in the final phase consists of the most weakly mineralized water, from thawed metamorphised snow, which contains small amounts of salts.

5. The cryochemical effects in the unglaciated Fugleberget basin

On the northern shore of the Hornsund Fiord, within the area of the raised sea terraces and the southern slopes of the mountain ridge of the Ariekammen (511 m a.s.l.)—the Fugleberget (569 m a.s.l.) a basin was set for special hydrological and hydrochemical investigations (Fig. 1). This basin is drained by the small stream Fuglebekken for five months in the year. Its area is 1.3 km^2. The basin is unglaciated but lies within the permafrost. Here there are some small patches of long-term snow in the nival niches in the upper part of the mountain slope. The basin is formed of dark metamorphic rocks (micaceous schists and paragneisses) from the Precambrian Hecla Hoek succession, with numerous marbles and inserts (Birkenmajer, Narębski 1960, Smulikowski 1965).

Hydrological investigations were performed in 1979–1980 during an expedition by the Polish Academy of Sciences. They included both the registration of water levels and their physicochemical composition in the hydrological polar year and the water reserve in snow and also the changes in its mineralization in winter. In 1979–1980 a metereological station located near the Polish Polar Station was working. It was near the western border of the Fugleberget basin. The preliminary results of the investigations in this basin has been published (Pereyma 1981; Pulina, Krawczyk, Pereyma 1985).

In the course of these year-long investigations particular attention was paid to changes in the mineralization of water flowing from the Fugleberget basin in the autumn and winter season of 1979 and in the early spring of 1980. From 9 September, 1979 to 22 October, 1979 i.e. from the middle of autumn to almost the end of the hydrological winter season, a steady increase in the water mineralization from 74 to 120–125 mg/dm³ was observed. In autumn the increase in mineralization was accompanied by a simultaneous
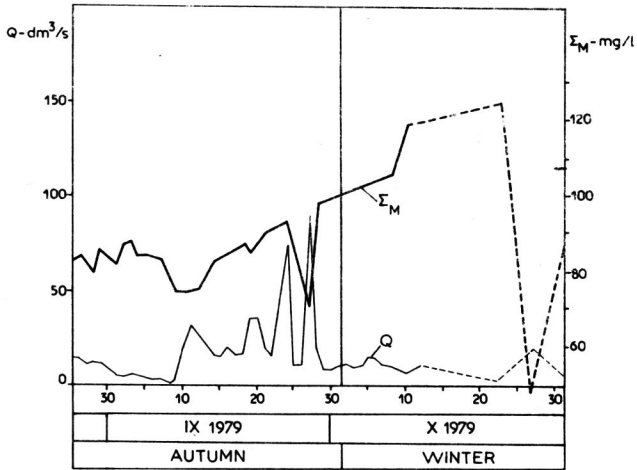

Fig. 8. Variation in the water mineralization (Σ_M) and discharge (Q) in the stream draining the Fugleberget basin in the autumn and winter of 1979

increase in flow caused by intensive rainfalls (Fig. 8). In winter, in turn, an increase in the water mineralization coincided with lower water levels. The increased water mineralization in autumn can partly be explained by stronger corrosion, since at that time the water of the type HCO_3^- — Ca^{2+} — Cl^- coming from dissolved carbonate rocks dominates. However, the increased water mineralization in the hydrological winter season cannot be so explained. Calcium and bicarbonates decrease in the ionic composition of this water, to be replaced by chlorides, sodium and potassium. Finally, the hydrochemical type of this water changes to $Cl^- - (Na^+ + K^+) - SO_4^{2-}$ Subsequently, there follows a distinct „condensation of salts" in this water which comes from a mixing of autumn carbonate and precipitation waters. This phenomenon can be explained cryochemically.

In the winter of 1980 the mineralization and the outflow of water from the basin were as shown in Fig. 9. On the day preceeding the outflow from the basin, i.e. on 1 June, 1980 the mineralization of the snow slush was 81.9 mg/dm³. The ionic composition of this water, shown in Fig. 2. shows that what occurs here is the type Cl^- $(Na^+ + K^+) - SO_4^{2-}$, which dominates in precipitation. All the precipitations in 1979–1980 were analyzed at the Polish Polar Station. The mineralization of this water is several times

as lov and is on average 17.5 mg/dm^3 (Pulina, Krawczyk, Pereyma 1985).
From 2 June, 1980 to 23 June, 1980 the mineralization of the water
flowing from the basin (water from thawed winter snow) decreased from
81.9 to 27.9 mg/dm^3, with a simultaneous, very high increase in discharge
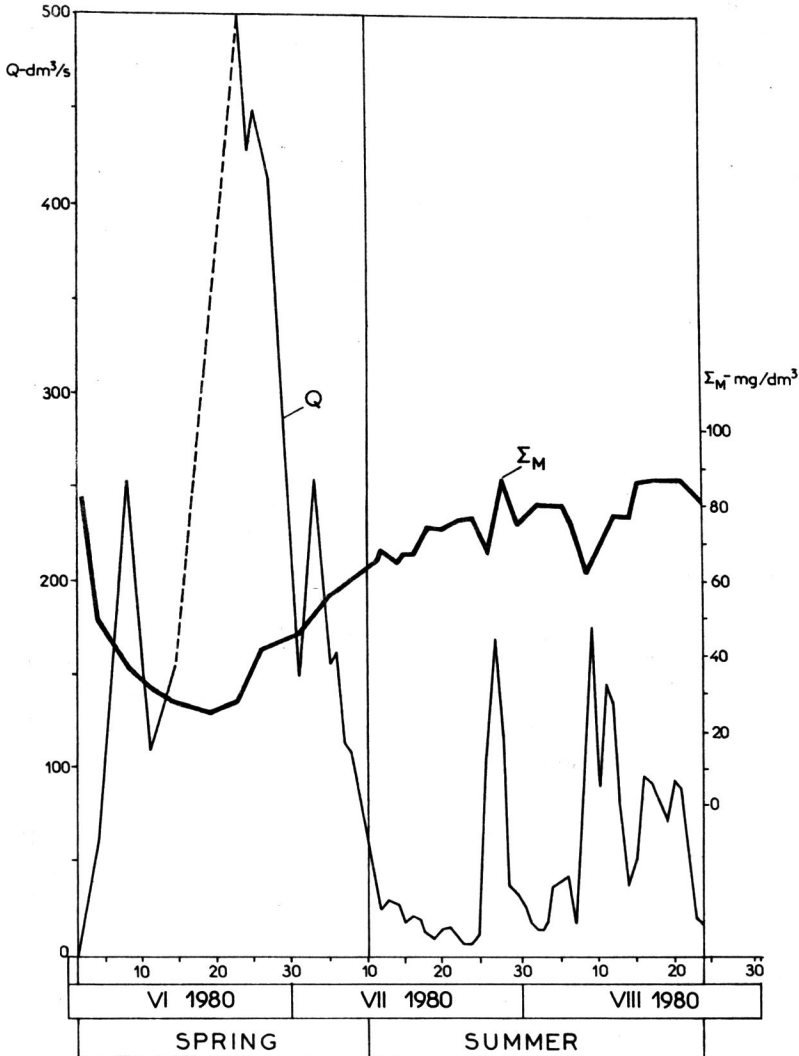from 0 to 500 dm^3/s. It can be noted that the ionic composition of this water

Fig. 9. Variation in water mineralization (Σ_M) and discharge (Q) in the stream draining the
Fugleberget basin in the spring and summer of 1980

remained unchanged. The relatively high water mineralization in the initial
phase of snow thawing can be explained cryochemically, since this phenomenon
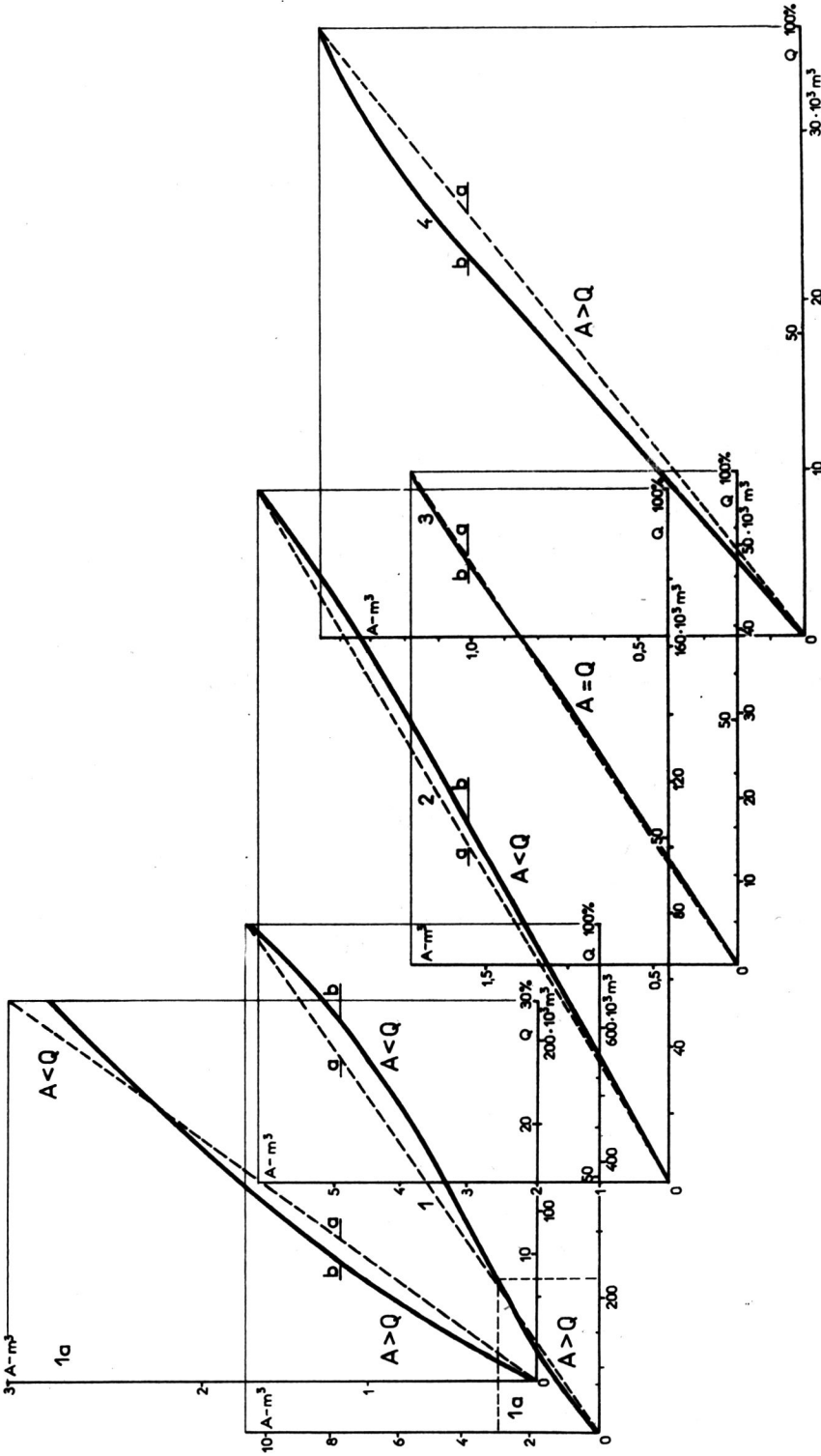resembles the process involved in ice thawing. From 23 June, 1980 on there

Fig. 10. Curves for the relation between the volume of dissolved salts (A—cumulated values of the ionic run-off in m³) and the water outflow volume (Q)—cumulated values of the outflow in thousand m³) in the four seasons of the hydrological polar year 1979/1980 from the Fugleberget basin. 1—spring, 2—summer, 3—autumn, 4—winter. a—curve based on the seasonal mean (dashed line), b—curve based on 24-hour values (solid line), 1ᵃ—part of the spring season

was a steady increase in the mineralization of water flowing from the Fugle-
berget basin. It was accompanied by a rapid decrease in water outflow.
The ionic composition of this water changed despite the fact that it came
from thawed winter snow. The ions of calcium and bicarbonates began
to dominate in this water. It changed its hydrochemical type to HCO_3^- —
Ca^{2+} — Mg^{2+}. This was a result of intensive corrosion caused by the active
thaw water, since there occurred an intensive dissolution of the carbonate
rocks present in the Fugleberget basin.

When based on a detailed analysis of changes in the total mineralization
and ionic composition of the water leaving the Fugleberget basin, the above
facts indicate the possibility of the occurrence of cryochemical effects
in two seasons of the polar hydrological year.

Fig. 10 shows for the four seasons of the hydrological polar year 1979/1980
curves illustrating the relation between the volume of dissolved salts
(the ionic run-off A, in m^3) and the outflowing water volume (Q, in thousand
m^3) from the Fugleberget basin. The diagrams in this figure have been
constructed on the basis of the cumulated values of A and Q. The solid
line „b" represents 24-hour values, while the dashed line "a" gives the seasonal
mean based on the initial and final values. In the plots for the winter
and the early spring the curve for the 24-hour values runs above the seasonal
mean. In order to emphasize this fact in spring, a more detailed curve,
shown in Fig. 10/1^a, was constructed. It can therefore be concluded that
the increase in the rock mass removed from the basin (A — m^3) with
respect to the same water mass flowing from the basin (Q — thousand m^3)
is greater than the seasonal mean. This phenomenon is particulary distinct
in winter. A good explanation of this phenomenon is the "condensation
of salts" in the solution as a result of freezing. It should be stressed that
the increased water mineralization caused by the dissolution of carbonate
rocks, well distinct in the second half of spring and in summer, is very
clear in the plots shown here. The curve for the relation A/Q lies
here below the seasonal mean.

6. Conclusions

The results of theoretical considerations of the significance of cryochemical
effects and the results of laboratory experiments presented here were confirmed
in the natural glacial and periglacial environment in Spitsbergen. These
processes were found even in the areas built of weakly soluble rocks
in which very weakly mineralized waters circulate. The effect of cryochemical
processes can be seen in the changes in water mineralization not only
in the glaciated areas (the Bertil and Werenskiold Glaciers) but also in the

unglaciated areas with permafrost (the Fugleberget basin). An essential fact is here the presence of cryochemical effects not only in autumn and winter, when water freezes inside the glaciers, in the area of active permafrost and on the surface of the ground and ice (the freezing effect), but also in spring when the previously frozen water and winter snow thaw (the thawing effect).

The cryochemical effects in the form of changes in water mineralization were found in Spitsbergen not only in the polar hydrological year 1979/1980. The earlier investigations carried out on the Werenskiold Glacier (Pulina 1974) in the summer and autumn seasons of 1972 and 1973 also found a distinct increase in the mineralization of water inside the glacier from the middle of autumn on. Similar results were obtained for the water of the Nordfall Glacier in 1978 and 1979 (Leszkiewicz, Wach, Waga 1982). The behaviour of the water mineralization found in the hydrological basins set on Queen Elizabeth Island in the Canadian Arctic (Mc Cann, Howarth, Cogley 1972; Cogley 1972) also seems to confirm the supposed effect of cryochemical processes.

A direct cryochemical effect is the precipitation of salts both in the ice of the naled type and on the ice-free surfaces built of fine moraine or glacial sediments. Such phenomena are universal in Spitsbergen. The author observed them on the naled ice arising from the freezing water flowing from the glaciers in winter (e.g. from the Werenskiold, East Torell and Gås Glaciers), in the cave being a part of the outlet of the main channel which drained the East Torell Glacier and within the terminal moraines of most glaciers around the Hornsund Fiord. The precipitation of salts took the form of efflorescences several millimeters large. These were mostly sulphate salts (including gypsum).

The phenomenon of salt precipitation was observed by investigators in some areas of Spitsbergen, e.g. by the French outhors in the area of the Kongsfjord (Corbel, Gallo 1970; Corbel, Murat, Gallo 1970), by the members of the Polish expeditions to the Oscar II Land[4]; In 1978 A. Jahn[5] from Wrocław Uniwersity observed salt precipitation on the naled ice on the shore of the Tempel Fiord.

The origin of the salt precipitations in Spitsbergen has so far been explained by the crystallization of gypsum from sea water which is transported by wind onto the coast. Another proposition has been that of a direct eolian transport of gypsum crystals which precipitate on the surface of the freezing see ice. Still another hypothesis has been proposed by A. Jahn, who relates

---

[4] The investigations of the salt efflorescences were performed by J. Drozdowski from the Institute of Geography of the Polish Academy of Sciences in Toruń

[5] This paper was presented at VI Speleological school of Wrocław and Silesian Universities at Lądek Zdrój in February 1980.

the origin of the efflorescences to the freezing of strongly mineralized water in the regions where gypsum is present.

Without excluding the possibility of the transport of these salts from the sea, places with salt efflorescences of solely cryochemical origin, e.g. glacial caves, have been found in the area of Hornsund.

The salt precipitation in the naled ice caused by cryochemical processes is certainly a universal process in the regions with permafrost and built of soluble rocks (rock-salt, gypsum, limestones etc.). This is confirmed by the results of the investigations of naled of East Siberia carried out by the Soviet researchers. This phenomenon is considered highly significant geochemically there, since it causes salt precipitation and decreases chemical denudation by 10 per cent (Alekseev, Savko 1975; Tolstichin 1970).

In addition to sulphate or sulphate-carbonate salts present in naled ice, calcite efflorescences have been found in the regions built of carbonate rock in Spitsbergen. The location of calcite and analysis of the conditions under which it arises in the periglacial environment also indicate their cryochemical origin. The calcite efflorescences have most often the shape of "mushrooms" several millimeters large or irregular efflorescences and built of sinter calcite. They occur commonly on the limestone rubble which forms talus cones at the foot of limestone rock walls (the slopes of the Sofiekammen, mainly at the Gnålberget, and the northern and western slopes of the Tsjebysjovfjellet) and also on the limestone rock terraces of the southern shore of the Hornsund Fiord in the area of the Gås Bay (beneath the ridges of the Wurmbrandegga and the face of the Tsjebysjovfjellet). They have also been found on the walls of limestone caves e.g. in the Gnålgrotte and in a cave in the slope of the Kopernikusfjellet in the central part of South Spitsbergen (Pulina 1977). These calcite microforms resemble "grape" dripstones common in caves in the Tatra Mountains or the Alps, which are attributed a cryochemical origin (Pulinowa, Pulina 1972).

An increase in the mineralization of the water circulating inside the Spitsbergen glaciers caused a decrease in their solidification temperature. Althougt this value is small, being a few tenths of degree below $0°C$, but it can essentially affect the retention of water in the glacier throughout the entire winter season. This hypothesis can be confirmed by the results of a drilling made at the end of the winter season of 1980 on the Amundsen Plateau in the central part of South Spitsbergen[6]). At a depth of about 150 m beneath the surface of the ice plateau, a water-bearing layer more than 3 meters high, with water of increased mineralization, was found.

---

[6] This drilling reached a depth of about 580 m, breaking through the ice cover of the Amundsen Plateau to the rock bottom. Glaciological investigations were carried out in May 1980 by the Glaciological Expedition of the Soviet Academy of Sciences in Moscow and the Polar Expedition of the Polish Academy of Sciences.

The cores taken from these layers show that water was present here in a network of small channels with diameters of several to a few dozen millimetrs.

The recognition of the cryochemical effect as the cause of the increased mineralization of water circulating in the glaciers and in the active zone of permafrost makes it possible to use new hydrometric methods. They were demonstrated in the case of the Bertil and Werenskiold glaciers. These methods permit, for example, the calculation of the amount of water circulating inside the glaciers in the winter season and the volume of channels inside the glaciers. The author is convinced that further investigations of gechemical processes will confirm their important role in the polar geographical environment.

7. Summary

The investigations of the author in the field of hydrology and hydrochemistry performed in the glaciated and unglaciated regions in Spitsbergen (Fig. 1) showed the large significance of cryochemical processes. They have an effect in the form of:

1. the increased mineralization of water flowing from glaciers and areas of permafrost in autumn and winter (Fig. 6, 8) and the relatively high water mineralization in the first phase of the spring outflow (Figs. 6, 9);

2. the precipitation of salts in the form of efflorescences, most often sulphate and sulphate--carbonate in winter naled ice and in glacial caves, and also calcite efflorescences on the walls of limestone caves and on limestone rubble.

The effects of cryochemical processes found in the glacial and periglacial environment in Spitsbergen were confirmed experimentally at the hydrochemical laboratory of the Polish Station at Hornsund. The function of the behaviour of the processes of freezing and thawing of Spitsbergen waters (4–7, Figs. 3,4) under conditions close to narmal were derived. The results of these experiments not only confirmed the field investigations but also served to determine the volume of water circulating in the glaciers in winter (Figs. 5, 7; Table I).

8. Резюме

Гидрологические и гидрохимические исследования, проведенные автором на покрытых и непокрытых льдом территориях Шпицбергена выявили большую роль криохимических процессов.

Они проявляются в виде:

1. Увеличенной минерализации в осеннем и зимнем сезоне вод, вытекающих с ледников и территорий многолетней мерзлоты (рис. 6, 8) и относительно высокой минерализации вод в первой фазе весеннего стока (рис. 6, 9).

2. Выделения соли в виде налетов чаще всего сульфатных и сульфатнокарбонатных в зимнем льде наледей и в ледовых пещерах, а также кальцитовых налетов на стенах известняковых пещер и на известковистом щебне.

Обнаруженные в гляциальной и перигляциальной среде Шпицбергена эффекты криохимических процессов подтверждены при помощи экспериментов, проведенных в гидрохимической лаборатории Польской полярной станции в Горнзунде. Получены функции хода процессов замерзания и размерзания вод на Шпицбергене (4—7 рис. 3, 4) в условиях

близких к натуральным. Результаты этих экспериментов не только подтвердили полевые исследования, но были использованы при определении объема воды, циркулирующей в ледниках зимой (рис. 5, 7, таб. 1).

9. Streszczenie

Badanie autora artykułu z zakresu hydrologii i hydrochemii przeprowadzone na Spitsbergenie w obszarach zlodowaconych i niezlodowaconych stwierdziły duże znaczenie procesów krio-chemicznych Objawiają się one w postaci:
1. Podwyższonej mineralizacji wód w sezonach jesiennych i zimowych wypływających z lodowców i z obszarów wieloletniej zmarzliny (rys. 6, 8) oraz stosunkowo wysokiej mineralizacji wód w pierwszej fazie odpływu wiosennego (ryc. 6, 9);
2. Wytrącania soli w postaci wykwitów najczęściej siarczanowych i siarczanowo-węglanowych w zimowych lodach nalodziowych i w jaskiniach lodowych oraz wykwitów kalcytowych na ścianach jaskiń wapiennych i gruzie wapiennym.
Stwierdzone w środowisku glacjalnym i peryglacjalnym Spitsbergenu efekty procesów kriochemicznych zostały potwierdzone eksperymentalnie w laboratorium hydrochemicznym Polskiej Stacji Polarnej w Hornsundzie. Uzyskane zostały funkcje przebiegu procesów zamarzania i rozmarzania wód spitsbergeńskich (4–7, ryc. 3, 4) w warunkach bliskich naturalnym. Wyniki tych eksperymentów nie tylko potwierdziły badania terenowe ale posłużyły do określenia objętości wód krążących w lodowcach w okresie zimowym (rys 5, 7 tab. I)

10. References

1. Alekseev V. R., Savko N. F. 1975 — Teoria nalednych processov — Nauka, Moskva.
2. Baranowski S. 1977 — The subpolar glaciers of Spitsbergen seen against the climate
3. Barrow G. M. 1978 — Chemia fizyczna (Physical chemistry) — PWN Warsaw.
4. Birkenmajr K., Narębski W. 1960 — Precambrian amphibolite complex and granitization phenomena in Wedel-Jarlsberg Land, Vestspitsbergen — Studia Geol. Polon., IV, Warszawa.
5. Mc Cann S. B., Howarth P. B. 1972 — Fluvial processes in a periglacial environment (Queen Elizabeth Islands, Canada) — Mc Master Univ. Transactions No 55.
6. Cogley J. G. 1972 — Processes of solution in the Arctic limestone terrain — Mc Master Univ. Special Publ. No 4.
7. Corbel J., Murat M., Gallo G. 1970 — Etude physico-chemique et hypotheses de formation d'un gypse cristalise decouvert sur les neiges du Spitsberg — C.R. Acad. Sc. Serie D. 270, Paris
8. Corbel J. et Gallo G. 1970 — Cryokarsts et chimie des neiges eu zone polaire — Rev. Geogr. d. Pyrenees Sud-Quest, 41, Toulouse.
9. Czajkowski R. 1981 — Radarowe pomiary miąższości Lodowca Werenskiolda (Radar measurements of the thickness of the Werenskiold Glacier) — VIII Sympozjum Polarne, Katowice.
10. Kosiba A. 1960 — Some of results of glaciological investigations in SW Spitsbergen — Zesz. Nauk. Uniw. Wrocław, B, 4, Wrocław.
11. Markowicz M., Pulina M. 1979 — Ilościowa półmikroanaliza chemiczna wód w obszarach krasu węglowego (Quantitative chemical semicroanalisis of water in carbonate karst areas) — Prace Nauk. Uniw. Śląsk. Nr 289, Katowice.
12. Pulina M. 1974 — Preliminary studies on denudation in Spitsbergen — Bull. Acad. Polon. Sc. XXII, 2, Warszawa.

13. Pulina M. Uwagi o zjawiskach krasowych w południowej części Spitsbergenu (Remarques sur les phenomenes kartiques dans la partie meridional du Spitsbergen) — Kras i Speleologia, 1(X), Katowice.
14. Pulina M. — Karst-related phenomena at the Bertil Glacier, West Spitsbergen — Kras i Speleologia 4(XIII). Katowice.
15. Pulina M., Krawczyk W., Pereyma J. 1985 Bilans hydrologiczny oraz denudacja chemiczna w niezlodowaconej zlewni Fugleberget, SW Spitsbergen (Hydrological balance and chemical denudation in the unglaciated Fugleberget basin, SW Spitsbergen) — Pol. Polar Res. Warsaw.
16. Paulina M., Pereyma J., Kida J., Krawczyk W. 1985 — Charakterystyka roku hydrologicznego 1979/1980 w zlewni lodowca Werenskiolda SW. Spitsbergen (Characteristics of the hydrological polar year 1979/1980 in the basin of the Werenskiold Glacier) — Pol. Polar Res. Warsaw.
17. Paulinowa M.Z., Paulina M. 1972 Phenomenes cryogenes dans les grottes et gouffres des Tatras — Biul. Peryglacjalny, 21 Łódź
18. Savelev B. A. 1971 — Fizika, chimja i strojenie prirodnich ldov i mierlych gornych porod — Izd. Mosk. Iniv. Moskva.
19. Smulikowski W. 1968 — Some petrological and structural observations in the Hecla Hoek succession between Werenskioldbreen and Torellbreen, Vestspitsbergen — Studia Geol. Polon. XXI, Warszawa.
20. Smulikowski W. 1965 — Petrology and some structural data of lower metamorphic formations of the Hecla Hoek succesion in Hornsundt, Vestspitsbergen — Studia Geol. Polon. XVIII, Warszawa.
21. Šumskij P. A. 1955 — Osnovy strukturalnogo ledovedenija — Izd. Akad. Nauk, Moskva.

Paper received 1982 March 17