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Water in the Hornsund glaciers in the light of isotopic investigations

Abstract: The differentiation of the isotopic composition of glacial water in some Hornsund glaciers was found to depend on its position with respect to the firn line, situation in the circulation system and on seasonal variations of air temperature. Intensive ice thawing in the ablation zone is marked by decreased values of the tritium content in the discharge of the glacier, whereas water from thawing snow nad firn increases these values. The isotopic differentiation which occures in waters in the main flow systems indicates the magnitude of the shares of water from thawed ice firn and snow in the total drainage of the glacier.

Key words: Arctic, water in the Hornsund glaciers, Spitsbergen

1. Introduction

The determination of the water regime of the Hornsund glaciers is an important part of the investigation of their dynamics. This problem has been studied by scientific expeditions of the Polish Academy of Sciences, Wrocław University and Silesian University. One of the present authors, who took part in the expedition of the Polish Academy of Sciences in the summer season of 1979, had the opportunity to carry out hydrological research over the area of several Hornsund glaciers (A. Różkowski, 1980). The investigations covered the Hans, Werenskiold, Arie, Gås and Nordfall Glaciers (Fig. 1). Their aim was to observe the water regime of the glaciers.

The hydrological investigations also included the sampling of water, snow, firn and ice for the purpose of isotopic measurements. In the course of the sampling particular attention was paid to the drainage systems

of glacial water. The glaciers were sampled in July and August 1979. Some control sampling measurements were also carried out in September of that year. In all, 59 samples were taken for the determination of the tritium content and 63 for the investigation of the stable isotope, composition mainly of oxygen. The isotopic measurements were taken at the laboratory of the Institute of Physics and Nuclear Techniques at the Academy of Mining and Metallurgy in Cracow.

Fig. 1. Glaciers in southwest Spitsbergen
1 — morraines, 2 — areas uncovered by ice, 3 — glaciers studied.

This paper reports on an analysis of the results of pilot determination of this isotopic composition of water, snow, firn and ice in terms of the genesis of glacial water and its circulation ways. An explanation of the stratification of the isotopic composition of ice in the profile of a crevasse in the Hans Glacier is also proposed. Since a relation was found to exist between the differentiation of the isotopic composition of glacial water

and both its position in the circulation system and seasonal temperature variations, it was necessary to give in the first part of the paper a general hydrological characterization of the glaciers and to present the climate conditions of Hornsund. For the sake of Polish readers, a very general characteristic of the isotope method was also included.

The authors wish to express their gratitude to Prof. Dr. hab. M. Pulina, the head of the polar expedition of the Polish Academy of Sciences in 1979/1980, for his assistance in the organisation of field research and valuable discussions. They are also grateful to Dr. A. Kamiński and Dr. J. Pereyma for their kind remarks and to J. Karkoszka, M.Sc. and J. Waga, M.Sc. for their help in field research. Separate acknowledgement is also due to the members of the Zagłębie Speleological Expedition to Spitsbergen in 1979 for their sampling of the crevasse in the Hans Glacier.

2. The glaciers and climate of Hornsund

The region where the glaciological investigations were carried out in the area of Fiord Hornsund lies between 76°23′ and 77°09′ North and between 15°10′ and 16°7′ East (Fig. 1).

The glaciers in this area cover both culminations and depressions of the rock base; they fill, however, mainly the valley among mountains and plateau. The accumulation regions of the glaciers lie low, on the ordinates 350–600 m. Large variations can be seen in the relief of their surface, which is related to the great differentiation of their base.

Large glaciers, from dozen-odd to several score km^2, usually have common firn fields on the plateau, while small mountain glaciers have firn fields close to the mountain crests. Large glaciers often flow to the fiord, concluding with an ice wall undercut deeply by the sea. Most of small glaciers flow onto flat sea terraces, marking their fronts with moraine banks, or feed large glaciers.

S. Baranowski (1977) assings Hornsund glaciers to the subpolar marine type. Such glaciers have a complicated thermal regime. According to his observations, these glaciers are characterized by "warm" accumulation zones and "cold" ablation zones, apart from the summer surface layer. They are wet throughout their mass or part of it in the accumulation zone and over the surface of the ablation zone in summer. In summer, over its whole surface, snow and ice thaw, mainly as a result of high values of the radiation balance and turbulent exchange. In the accumulation zone, because of the thawing and large porosity of firn, ablation water infiltrate into the glacier. Ice thaws in a particulary intensive way in the ablation zone. The water flow from the glacier has a superficial, inglacial and subglacial character. The magnitude of the water flow varies between the ranges of particular

glaciers, depending on the season and, in the ablation period, even on the time of day.

The complex thermal regime of subpolar glaciers affects significantly the formation of the circulation ways of glacial water, particulary the character of its flow and drainage. In the ablation period three basic systems of glacial water circulation occur: 1) superficial, 2) marginal, 3) subterranean (A. Różkowski, 1980). It is mainly through in—and subglacial channels that water reaches the forefield of the glacier.

The water of the surface circulation system is represented by the water of glacial streams (Fig. 2), dammed lakes (Fig. 3) and glacial rivers (Fig. 4). The streams flow in meandering channels. The inclination of the glacier surface defines the direction of the flow and the hydraulic drops of the streams. The surface circulation system is fed during the ablation period. At the beginning of this period, vertical permeation and retention of thaw and rain water can be observed in the profile of snow and firn. The saturation of the snow and firn zone is followed by a horizontal flow of water in the streams to the morphological depressions in the glacier surface, where, when glacial wells uncover, an intensive drainage of retained water occurs. During intensive thawing in the accumulation zone there is further thawing of snow and firn, whereas ice thaws in the ablation zone. When the ablation process is over, the surface streams freeze and fill with snow. The feeding area of the streams consists of morphological basins formed on the glacier surface. The surface circulation system is drained through glacial wells and, in the border parts of the glacier, through marginal streams, dammed lakes and rivers.

The glacial wells (Fig. 5), visible in the ablation zone, take the surface water into glacier. The dammed lakes, which are contained by moraine and ice banks, collect water both from the surface and subterranean circulation systems. The glacial rivers take water from the surface and subterranean circulation systems to the fiord.

The marginal circulation system (Fig. 6) is related to the marginal streams which run along lateral moraines, usually in dead ice. In the forms of ice karst water flows mainly in—and subglacially. This circulation system is fed along its ways, by surface ice streams and mountain streams from tali, and locally, on a point basis by glacial wells. The drainage of this system is based on dammed lakes and surface currents flowing out of moraine and ice banks. In mountain glaciers the marginal and surface circulation system form the basic way of glacial water drainage. The marginal system of water circulation freezes because of its shallow position.

The subterranean circulation system is both in—and subglacial. In the ablation period it is fed by the drainage of the surface basins of the glacier and marginal streams through glacial wells by which water cascades to the main channels of the subterranean drainage. The drainage of the subterranean

Fig. 2. Hans Glacier — ice steam.

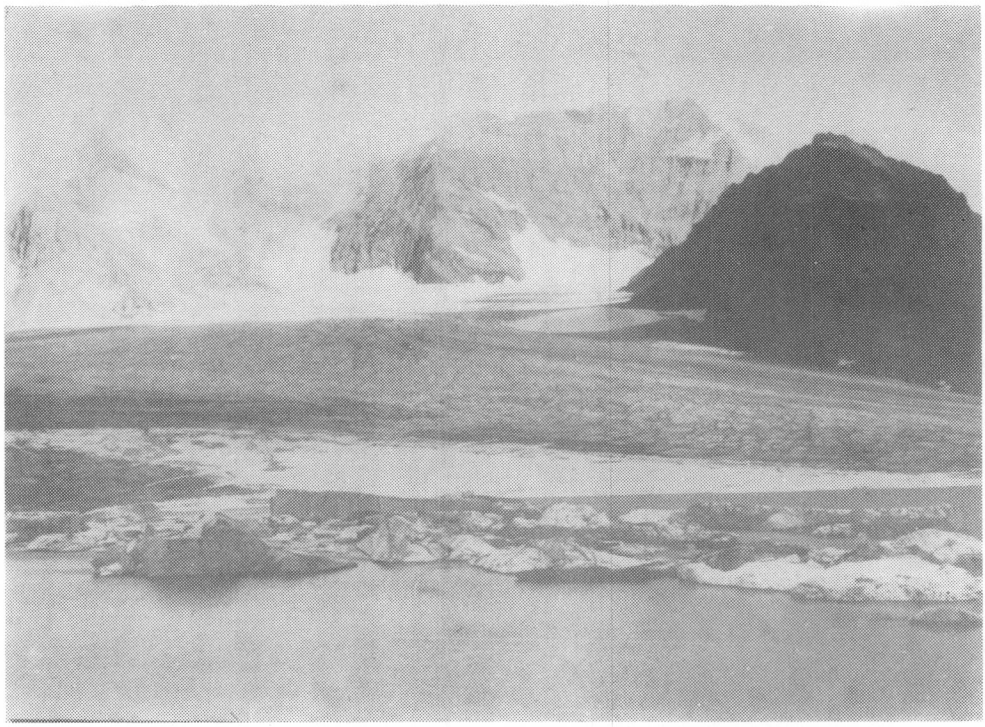

Fig. 3. Gas Glacier — ice-dammed lake at the glacier front.

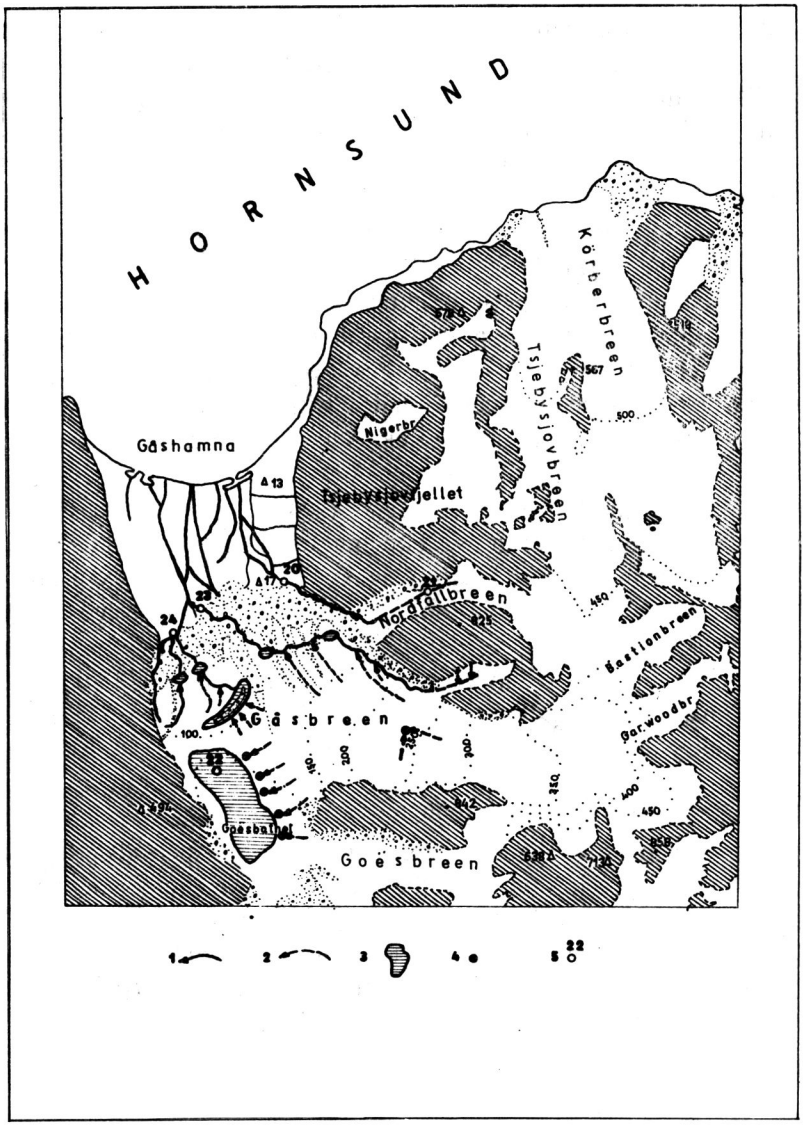

Fig. 4. Situation plan of Gas Glacier
1 — glacier streams and rivers, 2-ice streams studied, 3 — ice-dammed lake, 4 — ice walls studied, 5 — sampling points and their numbers acc. to Table 4.

circulation system is based on dammed lakes and glacial rivers which flow from ice and moraine banks. In the case of glaciers which end in the sea, water discharges at the glacier front through channels and glacial gates.

The development and existence of glaciars, and also their water regime,

strictly depend on the climate. The climate of Spitsbergen is characterized by a transitory form between a marine and a continental climate (L. S. Troitskij et al. 1975). This shows in the low mean air temperatures and moderate precipitation. There are data as to the climate variations in Spitsbergen in the recent millenium (S. Baranowski, 1977, L. S. Troitskij et al. 1975). In the period from the 1st to the 13th century, warmer weather caused the glaciers to retreat. The climate was then milder than now. A cooler climate, called the Little Ice Age, occurred from the 14th to the decline of the 19th century. This period involved a transgression of the glaciers. The lowest temperatures were noted in the 18th and 19th centuries. In this century, the climate in Spitsbergen has been stable (J. Pereyma, 1981). This region has a specific microclimate, with characteristic relatively low winter and high summer temperatures, and also long positive-temperature periods. Positive mean monthly temperature occur from June to September, permitting the ablation processes; negative ones in the remaining months favour the accumulation of now. The maximum intensity of the ablation process occurs from June through August. The mean temperatures of the periods of accumulation and ablation vary respectively between — 10° and — 11°C and between +3° and +5°C.

The 24-hour climate behaviour in the summer of 1979, depending on the conditions of atmospheric circulation, varied between 1.5 and 6.2°C. The hypsometry-dependent temperature gradient was 0.52°C/100 m.

Measurements performed at the Station of the Polish Academy of Sciences at Hornsund in the period 1979/1980 showed that the total amount of precipitation in the accumulation and ablation periods was 310 mm. The sum-total of precipitation in the firn zone of the glaciers was twice as high as the one noted at the Station of the Polish Academy of Sciences near the coast of the fiord. Table 1 shows, according to the results of measurements carried out by K. Lubomirski and S. Swerpel, the monthly sum-totals of precipitation at Hornsund in the period in question.

3. The characteristics of the glaciers invastigated and the sampling taken

Snow, firn and ice were sampled for the purpose of investigations of the tritium content and the stable isotope composition in the Hans, Werenskiold, Arie and Gås Glaciers (Fig. 1). The collective rainfall sample of the tritium content and the stable isotope composition in the Hans, Academy of Sciences.

The Hans Glacier (Fig. 7), with an area of about 45 km^2 and a 500 m difference in height between the accumulation zone and the glacier front,

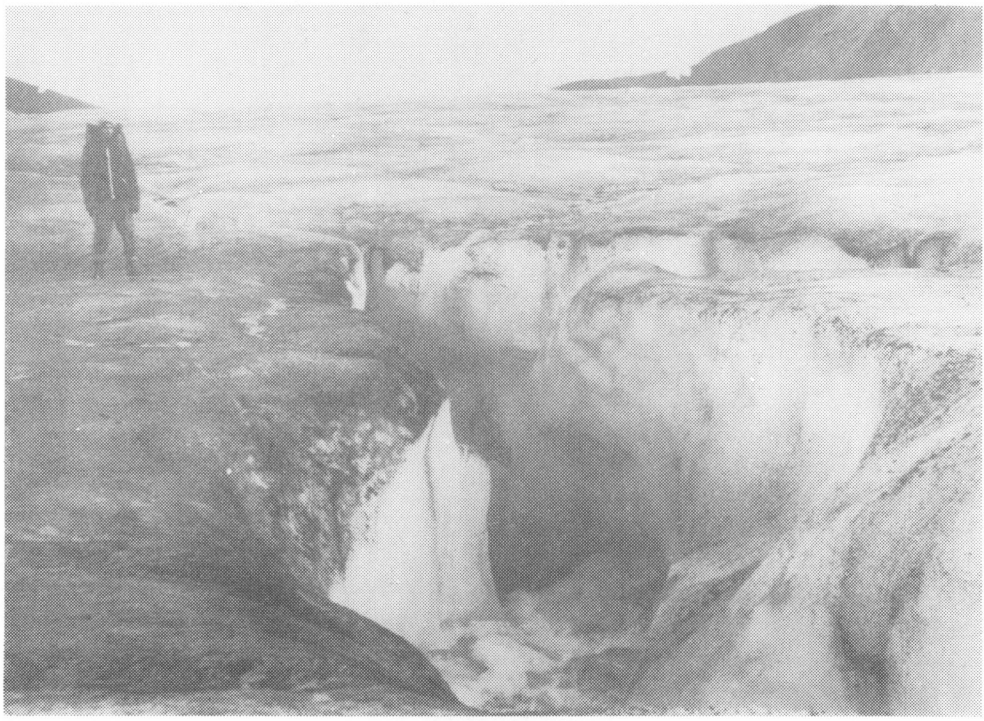

Fig. 5. Hans Glacier — ice well.

Fig. 6. Gas Glacier — marginal circulation system.

Table I.

Climate measurements at the Hornsund Station of the Polish Academy of Sciences

	I	II	III	IV	V	VI		VII	VIII	IX	X	XI	XII
p	1013.6	1005.5	1018.8	1011.9	1020.7	1013.7	p	1014.9	1013.8	1000.8	1013.5	1002.7	1001.2
T	−11.9	−11.1	−11.6	−8.1	−3.0	2.4	T	4.9	3.7	1.2	− 2.9	−4.9	−9.5
U	72	79	74	77	76	78	U	80	83	85	76	75	72
P	23.9	51.8	11.5	21.5	9.4	28.8	P	18.5	21.8	44.8	44.6	16.2	17.4

Legends: atmospheric pressure (p, hPa), air temperature (T, °C), relative air humidity (U, per cent) according to monthly means and the monthly sum-totals of precipitation (P, mm) at Hornsund in the period 1979/1980 (after K. Lubomirski, S. Swerpel, 1980).

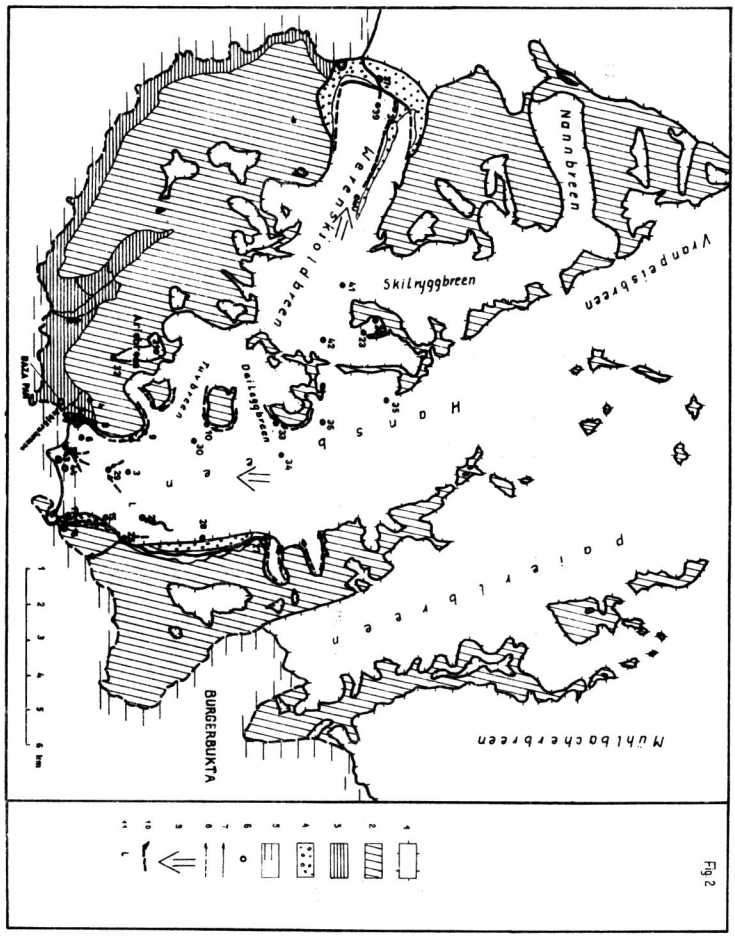

Fig. 7. Situation plan of Hans. Werenskiold and Arie Glaciers
1 — glaciers, 2 — mountains, 3 — terraces, 4 — morraines, 5 — sea, 6 — sampling point and its number acc. to Tables 2–4, 7 — glacier streams and rivers, 8 — major ice and marginal streams, 9 — direction of subsurface flow.

ends in the Hornsund Fiord. This glacier is in the regression phase. It is fed in the accumulation zone and by the lateral glaciers. This glacier has for a number of years been studied by expeditions of the Polish Academy of Sciences (A. Jahn, 1979), and, recently by geographers from Silesian University. The geophysical investigations carried out by the 1979 expedition of the Polish Academy of Sciences showed that at a distance of about 1,5 km from the front the thickness of the glacier was 40–60 m and reached, at a distance of 5 km, 200 m (S. Małoszewski, R. Czajkowski, private communication). In the accumulation zone the thickness should be greater. The radar measurements of R. Czajkowski (private communication)

Table II.

Sampling on Hans Glacier

Position of sampling point	Determination results			Sample no.	Sampled on	Sample kind	Characteristic of sampling point	Ordinate of sampling point m over sea level
	Tritium (JT)	18° (‰)	D (‰)					
ablation zone	25.8	−11.75	−80.0	6	26.07 1979	snow	glacier surface	+40
firn zone	25.7	−9.70		34	22.08	snow	glacier surface	+300
firn zone	27.8	−9.75		35	22.08	snow	glacier surface	+340
beyond glacier	20.1	−9.4	−60.0	4	24.07	water	terrace spring	+40
				8	28.07	water	spring flowing	
ground morraine	13.8	−10.2					from morraine	+40
outwashes	6.9			16	13.08	water	stream flowing dead ice	+30
				46	2.09	water	stream flowing from	
ablation zone	7.0	−9.45					morraine fed by dead ice	+20
ablation zone	20.7			27	17.08	water	surface stream	+250
				44	1.09	water	leakage from	
ablation zone	5.3						underneath morraine	+20
ablation zone	14.4	−10.85		3	24.07	water	ice stream	+160
ablation zone	5.7	−9.55		5	26.07	water	ice stream	+20
ablation zone	4.9			17	13.08	water	ice stream	+100
ablation zone	5.6	−10.5		25	15.08	water	ice stream	+175
ablation zone	5.7	−10.55		26	15.08	water	ice stream	+160
firn zone	41.7			36	22.08	water	ice stream	+320
ablation zone	7.6			45	1.09	water	ice stream	+10
ablation zone	9.6			43	1.09	water	ice stream	+30
ablation zone	19.8	−10.0		1	24.07	water	ice well	+170
ablation zone	17.4	−9.9		9	29.07	water	ice well	+210
ablation zone	16.7	−9.85		10	29.07	water	ice well	+220
ablation zone	10.6	−9.85		7	30.07	water	ice well	+150
ablation zone	4.4			15	13.08	water	ice well in dead ice	+160
ablation zone	8.0	−9.8		28	17.08	water	ice well in dead ice	+210
ablation zone	15.8	−9.75		29	19.08	water	ice well in dead ice	+140
ablation zone	0.7			30	20.08	water	ice well in dead ice	+230
				33	22.08	water	ice well inmarginal	
ablation zone	9.2	−9.8					circulation system	+280
ablation zone	12.1	−9.8		47	2.09	water	ice well	+170
ablation zone	0.0−4.5	−10.25−9.2		1	2.08	ice	crevasse 10 m deep	+120

have shown that in the cross-section of the glacier there are voids which permit inglacial water circulation.

The firn line runs at about 350 m over the sea level and the firn zone ranges from about 350 to 500 m over the sea level. The diverse relief of the glacier base causes a variation in its thickness and surface shape along the path of the ice flow. Large transverse cracking can be observed in the ablation zone in the area of the rock base elevations (Fig. 8). The surface of the glacier, which is inclined to the south, is characterized by a drop of 1.5–5.2 per cent, which, locally in the marginal zone, reaches 20 per cent. The glacier is drained by surface, marginal, in—and subglacial flow systems, where the in—and subglacial outflow dominates. The drainage is based at the Hornsund Fiord. Fig. 7 shows schematically the water circulation ways.

In order to determine the tritium content and the stable isotope, samples were taken of rain, snow composition ice water from glacial and moraine streams and glacial wells in the ablation and firn zones. In order to determine how the isotopic content of ice forms in the ablation zone, samples were taken, over a 10-metre profile, from an ice crack. The situation of sampling points is shown in Fig. 7, their characteristics and the results of the determinations made are given in Table II.

The Werenskiold Glacier (Fig. 7), which was investigated by S. Baranowski in 1977, is still undergoing study by a team of glaciologists from Wrocław University. It is a glacier with an area of about 22 km^2 in the regression phase. It is characterized by a difference of about 600 m in height of the surface between the glacier front and the upper limit of the accumulation zone. The glacier is fed in the accumulation zone and by the lateral glaciers, mainly by the Skilrygg Glacier.

The Werenskiold Glacier is characterized by a small angle of surface inclination, about 5.8 per cent, which increases in the upper accumulation zone to 20–30 per cent. It is drained by surface, subterranean, in—and subglacial flow systems. The drainage is based on the Kvisla Glacial River, which takes water from the glacier to the sea. In 1979 the firn zone occurred at about 400 m over the sea level. The ice thickness in this zone was about 235 m; the mean ice thickness in the glacier varied about 95 m, approximately (R. Czajkowski, 1981).

The sampling points on the glacier are shown in Fig. 7. In order to determine the tritium content and the proportion of stable isotopes, water samples were taken from the surface and subterranean drainage systems, as shown in Table III.

The Gås Glacier (Fig. 4) has for some recent years been investigated by a tream geographers from Silesian University. It is in the state of recession and in summer undergoes intensive ablation over its whole area. On its eastern side contacts with the Nordfall Glacier (Fig. 4).

Table III.

Sampling on Werenskiold Glacier

Ordinate of sampling point m over sea level	Determination results			Sample no.	Sampled on	Sample kind	Characteristic of sampling point	Position of sampling point
	Tritium (JT)	$\delta^{18}O$ ‰	δD ‰					
+20	26.8	−10.1		37	24.08	water	glacier river dehydrating glacier	flow through ice-moraine barriers
+25	1.9	−10.1		38	24.08	water	ice stream	ablation zone
+180	2.1	−10.05		40	25.08	water	ice stream	ablation zone
+300	20.4	−10.15		41	28.08	water	ice well	ablation zone
+440	48.4	−10.05		42	25.08	water	ice stream	firn zone
+490		−10.1		23	25.08	water	ice stream	firn zone
+540		−9.5		24	25.08	water	outflow from firn	firn zone
+28	22.8	−10.3	−70.5	39	24.08	water	erosion, inglacial outflow, origin of glacier river	ablation zone

The surface of the Gås Glacier is about 10 km^2, with differentiation of its height of the order of 500 m. It is characterized by a low inclination angle of about 5.7 per cent. This glacier is drained at the southwestern end by a dammed lake with an area of about 1.2 km^2 (J. Jania et al., 1981) and in the northwest by glacial streams (Fig. 8). These streams flow from ice and moraine bank, to proceed then on the outwash plain towards Gåshamna, a bay of the Hornsund Fiord.

In order to determine the tritium content water samples only were taken from the main drainage system (Fig. 4). Characteristics of the sampling points and the determination results are given in Table IV.

The Arie Glacier (Fig. 7) is a small mountain glacier with an area of about 0.6 km^2, 233–425 m over the sea level (A. Szponar, 1975). It is characterized by varied inclination of its surface within the limits 6–20 per cent. The glacier is drained mainly by glacial streams and the marginal flow system. The drainage is based on the glacial stream which feeds the Revelva River. It flows inglacially from moraine and ice banks. In order to determine the isotope, composition two water samples were taken from the basic drainage system (Table IV).

4. General characteristic of the isotope method

The isotope method, when applied in glaciology is based on all the rules known in isotope hydrogeology. However, it is enriched additionally by rules related to water circulation in the entire hydrosphere, i.e. with participation of all the three phases: gaseous, fluid and solid. A transition from phase to phase involves fractionation and the resultant large differentiation of the isotopic composition in Nature.

The object of the isotope method is to analyse and interpret variation in the composition of radioisotopes and stable isotopes in glaciers. The most frequent use is certainly made of those isotopes which make up a water molecule, i.e. the radioactive isotope of hydrogen, tritium (^3H), the stable isotope deuterium (^2H or D) and a stable isotope of oxygen (^{18}O). Developments in isotope glaciology, as in isotope hydrology, have been related to an improvement of detection methods, particularly at the turn of the 1960s and 1970s.

The knowledge of tritium concentration in a sample has so far been defined in tritium units (JT). One JT corresponds to a concentration of one tritium atom per 10^{18} atoms of plain hydrogen (^1H) and is equivalent to a specific activity of 3.2 pCi/dm^3. The decay period of tritium is 12.26 years.

Since 1952 tritium has been injected into the stratosphere in large amounts

Table IV.

Sampling on Gås Glaciér

Ordinate of sampling point m over sea level	Determination results			Sample no.	Sampled on	Sample kind	Characcteristic of sampling point	Position of sampling point
	Tritium (JT)	18° (%)	D (%)					
				20	7.08	water	glacier stream dehydrating Nordfall Glacier	outwash plain
+40	20.3							
				23	11.08	water	glacier stream dehydrating Gas Glacier, outflow from ice-morraine barriers	
+50	9.3							outwash plain
				24	11.08	water	glacier stream dehydrating Gas Glacier	
+50	8.8							outwash plain
+200	33.4			21	9.08	water	glacier stream dehydrating Gas Glacier, outflow from ice-morraine barriers	outwash plain
+120	28.5			22	9.08	water	ice-dammed lake, glacier drainage base Sampling on Arie Glacier	ablation zone
				32	21.08	water	outflow from inglacial channel, main glacier drainage	ablation zone
+272	16.7	−9.3						firn zone
+410	28.3	−8.95	−63	31	21.08	water	ice stream	

as a result of thermonuclear explosions, to reach a maximum in 1962. Since the latter year its intensity which is registered in precipitation has gradually fallen. Thus the time range of the tritium method for the purposes of dating goes back to the beginning of the nuclear age, since the natural production of tritium in the atmosphere by cosmic radiation is about 10 JT. In view of its decay period, this concentration, when considering radioactive disintegration, is close to the detection limit of Tritium which is accumulated in the stratosphere is injected into the troposphere mainly in late spring and in summer, to reach then a maximum, and a seasonal minimum can be observed in winter. Interpretation should account for this factor of season, although in some problems annual averaged values are used.

Since 1960 many stations in the network set by the World Meteorological Organization (WMO) and the International Atomic Energy Agency (IAEA) have recorded on a monthly basis the concentration of tritium (also stable isotope composition) in precipitation. In Spitsbergen, Isfjord Radio is such a station. The absolute annual tritium concentration maximum which the station registered in 1963 was about 1900 JT. In 1974, 1975 and 1976 the mean annual values were respectively 177,75 and 33 JT (IAEA, 1981).

The heavy stable water isotopes deuter and oxygen 18 play a much more important role than tritium in different glaciological investigations and provide the basic tool of the isotope method.

The content of the heavy isotopes in a water sample is expressed in a different way than that of tritium. The results of analysis of stable isotopes are given as a relative deviation in per mille from the international standard SMOW (Standard Mean Ocean Water). The deviation δ is defined as

$$\delta\,(^{0}/_{00}) = \frac{\text{Rsample} - \text{Rsmow}}{\text{Rsmow}} \times 1000,$$

where R is an absolute isotope proportion $^{18}O/^{16}O$ or $^{2}H/^{1}H$ for the sample and the SMOW.

As was mentioned earlier, the variation in the isotopic composition results from natural fractionation processes which occur for a transition of water between its phases. Heavy isotopes tend to remain in the more condensed phase and therefore when ice thaws the heavy isotopes increase in ice and decrease in the forming water. A transition to vapour mainly involves molecules which contain light isotopes. A contrary cause occurs for liquefaction and freezing when molecules with heavy isotopes are the first to enter the more condensed phase. An essential physicochemical process which affects the differentiation in the isotopic composition is the molecular exchange between phases. This process tends to an aqualization of the isotopic composition.

Since most water on the Earth is stored in oceans, water in the other reservoirs is most frequently depleted in heavy isotopes and the δ value takes a minus sign (the SMOW being ocean water for which arbitrarily zero is assumed). When vapourized from the ocean and carried with air masses, at some stage and at some temperature, water vapour reaches a state of saturation. The rain liquefaction causes vapour to decrease its content of heavy molecules and at the subsequent stages from precipitation to precipitation, it becomes increasingly light in terms of isotopes. The fractionation processes are very sensitive to temperature variations and therefore temperature is a direct or indirect parameter which affects the fractionation deree. This degree increases as temperature decreases.

In the case of precipitation the following conditioning global effects can be distinguished:

- A gradual decrease in the concentration of heavy isotopes passing from lower to greater latitudes, which is related to a decrease in temperature (the "temperature" effect, also called the "latitude" effect).
- A decrease in the concentration of heavy isotopes passing from the shores inland (the "continental" effect).
- A decrease in the concentration of heavy isotopes as the over-the sea level inncreases (the "altitude" effect).
- Seasonal changes which parallel temperature variation in a given area (the "seasonal" effect).

The concentrations in precipitation, both in rain and snow, of the two heavy isotopes, deuterium and are linked to each other by the relation $\delta^2H = 8\delta^{18}O + 10$, which is valid on a global scale and shown in diagrams as the so-called world meteoric water line. There are deviations from this line. From the therefore possible to use one of the isotopes, deuterium or oxygen- 18, since their concentrations can be recalculated to each other.

When precipitation occurs at great latitudes or high or high in the mountains, it is most often a snowfall which begins a cycle that is the most interesting for glaciology. The settled snow changes gradually into firn and then into ice. In the course of these processes homogenization occurs, both in terms of its physical and isotopic composition. The partial thawing of ice, the permeation of thaw water, involving recrystallization, and molecular exchange in a system of two or three phases—all these processes lead to an smoothing of the variations in isotopic composition which was initially coded in the fresh snow. The homogenization process is particularly favoured by the conditions which occur in the temperate glaciers where, depending on the zone of the glacier, even total homogenization can obtain. In the temperature conditions which favour the polar glaciers, the original

Fig. 8. Hans Glacier — ablation zone.

isotopic composition of snow may be "frozen" quite faithfully and code the information of interest for glaciology.

In general, the determination of the composition of stable isotopes and tritium in snow, firn, ice and glacial water can lead to the solution of, among other things, the following problems: accumulation rate, dating of different facies of the glacier, the internal regime of the motion of the glacier, the velocity of surface and total flow, the mass balance of the glacier and the water regime of the glacier. Some of these problems in which an essential role is played by glacial water and investigation of the regime of temperature glaciers require long-term observations. Those problems which are significant for the present paper will be discussed in greater detail below. A broader approach to the problems in question can be found in the papers of J. R. Gat (1980) and H. Moser and W. Stickhler (1980).

5. Interpretation of the results of isotopic investigations in terms of the genesis of glacial water

Glacial water which comes from thawing snow, firn and ice is characterized by differentiation in the tridium content and in the stable isotope composition. This differentiation is seasonal and, in the ablation period, can be observed even over 24-hours (H. Beherns et al., 1971). This phenomenon is related to both the occurrence of different concentrations of tritium and different compositions of stable isotopes in rain, snow, firn and ice, and to the share of water from these media which varies from season to scason (H. Moser, W. Stickhler, 1980).

The old ice from before 1952 contain hardly any tritium. The sampling results for an ice crevasse in the centre of the ablation zone of the Hans Glacier confirm this fully. It should be noted that the slight tritium concentration (4.5 JT) which occurs in the ceiling part of the ice profile can be related the process of sitope exchange with atmospheric maisture.

The winter ice samples are characterized by low tritium content whereas spring ice and rain have more of it. The seasonal differentiation of $\delta^{18}O$ and δD also rends towards increased isotope concentration. This phenomenon is related to an increase in evaporation efficiency and sublimation in spring and summer. In the ablation period, winter snow thaws later than spring snow does. Considering these facts, within the glaciers under study, differentiation of isotope gradients could be observed in water from thawing snow at different sampling sltitudes (Fig. 9).

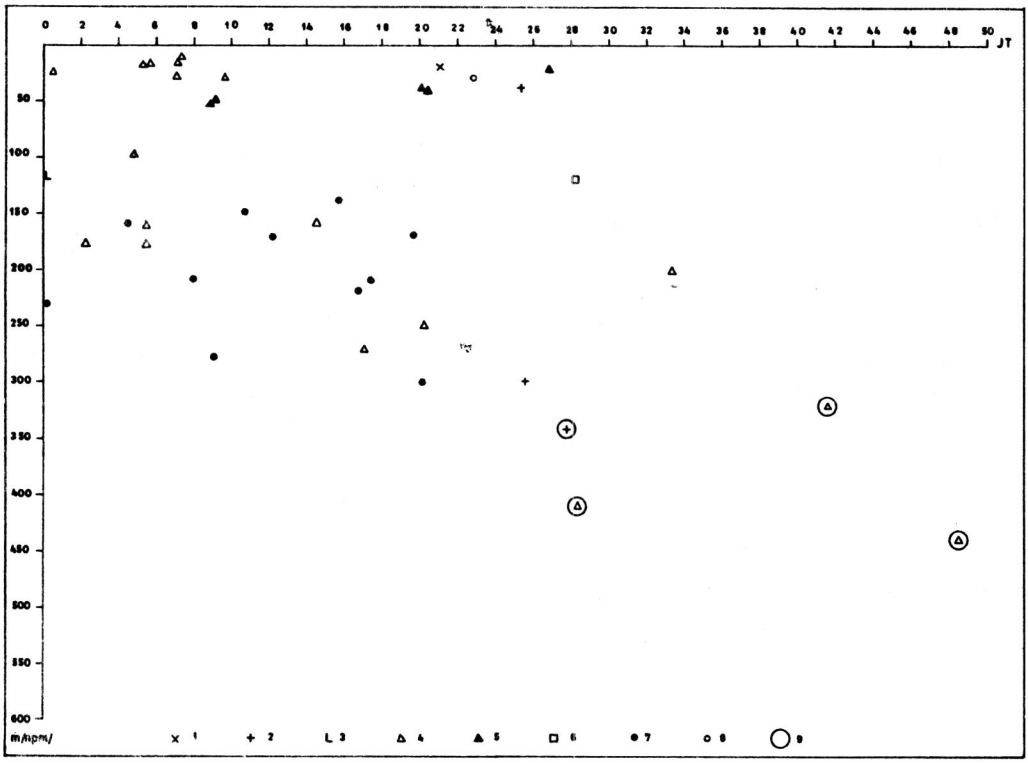

Fig. 9. Diagram of tritium concentration in the samples of rain, now, ice and glacier water studied

1 — rain, 2 — snow, 3 — ice crack, 4 — ice stream, 5 — glacier river or stream, 6 — ice-dammed lake, 7 — ice well, 8 — glacier erosion, 9 — samples from firn zone.

Fig. 5. Differentiation in the isotopr composition of ice in an ice crack

1 — histigram representing measurement results, 2 — averaged measurement results.

The isotope "seasonal" gradient disappears in the firn zone, which is related to the previously described homogenization processes during snow firnization. The firn zone contains higher tritium concentration, which is related probably to its greater content in precipitation in the previous years.

Accounting for the active ablation of the glacier under investigation in the recent years, the variable isotope differentiation which is observed in thawing snow water should above all be correlated with the thawing out of spring or winter snow, or both these snows in diferent proportions. It cannot be excluded that in some cases firn characterized by higher tritium concentration thaws.

In the period when the glaciers in the Hornsund area were sampled, in July and August, intensive ice thawing in the ablation zone was marked by lower tritium concentration in the discharge of the glacier, when higher values were characteristic for water from thawing snow (Table II—IV).

The isotope differentiation in the water in the main flow systems indicates quite unambiguously the magnitude of the share of water from thawed ice and snow in the total drainage of the glacier.

Fig. 9 shows the results of the determination of the tritium content in samples of rain, snow, ice and water taken from the area of the Hans, Werenskiold, Arie and Gås Glaciers. The diagram accounts for the altitude of sampling points, their position with respect to the firn line and, in the case of water, also the character of the drainage.

Most of sampled water has a lower tritium concentration than the one found in snow, with the latter varying between 25.7–27.8 JT (Table II). The conclusion can be drawn that the water under study comes from the thawing of both snow and ice.

The water from ice streams in the firn zone is characterized by the highest tritium content, varying between 28.3–48.4 JT. The large tritium differentiation in this water should be related above all to the thawing, in different proportions, of winter and spring snow. With the high tritium content one should not exclude the water supply from firn.

A higher tritium concentration than that in snow or similar one can be also observed in water samples taken from glacial rivers, inglacial outflows and the dammed lake when they form the basis of the drainage of the firn zone.

There is a general trend towards an increase in the tritium content in water taken from the ablation zone and with increasing altitude of their sampling spots. This does not apply to water from thawed dead ice.

The low tritium concentration, below 10 JT, which is found at the front of the glacier in ice streams, should be related to the fact that these streams are mainly fed by water from thawed ice.

The tritium content increases in sampled ice wells and streams as their altitude grows. At a sampling altitude of about 300 m over the sea level these values approximate the tritium concentration in snow. This indicates the dominating share of snow in the feeding of the surface flow system.

Taking into account the results of measurements of water flow and of the determination of the isotopic composition of snow, ice and water, some general conclusion can be drawn regarding the drainage of the glaciers under study in the summer of 1979.

In the case of the Hans Glacier ice streams and the marginal flow system which drain the ablation zone at the front of the glacier carry water characterized by low tritium concentration. This concentration varies between 5.3–13.8 JT, on average 7.7 JT, indicating that the water originates mainly from ice thawing. Considering the tritium content in water from ice thawing, on average 4.5 JT, and in snow 26 JT, the share of water from ice thawing in the total surface drainage of the front of the glacier in the period under study varied between 55 and 95 per cent approximately,

on average 85 per cent. This is confirmed by the fact that the glacier retreats.

The main water masses, which come from the drainage of the firn zone and partly of the ablation zone, are discharged directly to the fiord through a system of subterranean flow, in part also by the marginal system. This water is characterized by increased tritium concentration.

The tritium concentration in the Glacial River Kvisla which takes water from the Werenskiold Glacier is 26.8 JT. Considering that in the ice streams of the ablation zone the tritium content is of the order of 2 JT, compared with 22.8 JT in the glacial spring, 20.4 JT in an ice well in the central part of the glacier and 48.4 JT in the firn zone, the conclusion can be drawn that the glacier is drained mainly in — and subglacially. In the subterranean flow, water from thawing snow and firn dominates.

The determination of the tritum content in water performed on the Gås Glacier gave interesting information about the ways by which this glacier is drained. The Nordfall Glacier which descends towards the Gås Glacier is drained by a drainage system which carries water from snow and firn thawing, which is indicated by the high tritium content (34.3 JT). The ice streams which drain the Gås glacier and flow through ice and moraine banks towards the Gåshamna Bay (Fig. 4) carry mainly water from ice thawing. This is indicated by the tritium concentration of the order of 8.8–9.3 JT. The ice dammed lake Goes drains above all water from thawing snow, which is indicated by the tritium content of 28.5 JT.

It is extremely difficult to interpret the results of the determination of the isotope oxygen -18 ($\delta^{18}O$), in view of the complex mechanizm of the enrichment of heavy isotopes in glacial water. The concentration of stable isotopes in precipitation depends on the altitude and varies from season to season. The metamorphism of snow and its phase transformations also cause changes towards an increase of heavy isotopes in the snow cover and ice. In the light of these facts, the results of single determinations of the heavy isotope composition (Tables II–IV) cannot have given reliable data.

The samples of snow, firn, ice and water investigated showed the existence of the gradient $\delta^{18}O$ which varies between -8.9 to -11.75 per mille. Particularly slight differences occur in the values of $\delta^{18}O$ between snow and ice. Taking into account the slight differentiation in the surface altitude between the glaciers, it is difficult to relate unambiguously the values of $\delta^{18}O$ to the altitude factor. However, there was a distinct seasonal differentiation of the isotope composition in precipitation, e.g. for summer precipitation $\delta^{18}O$ was on average — 5.05 per mille, for winter snow — 11.75 per mille, and about — 9.7 per mille for spring and winter snow in the firn zone (Table II).

Fig. 10. Gas Glacier — drainage of the glacier by glacier streams.

As in the case of tritium, the values of $\delta^{18}O$ in the glacial water examined depend on the medium from which it has thawed.

Analysis the results of isotopic measurements of water from the Hans and Werenskiold Glaciers (Tables II and IV) shows the dependence of values of $\delta^{18}O$ on the position with respect to the firn line. This is the case above all with the Arie Glacier where the water of the ice stream in the firn zone is characterized by increased values of heavy isotopes ($\delta^{18}O = -8.9$ per mille). This indicates distinctly the large share of spring snow in the supply to the streams.

Within the range of the intensive ablation zone, water, which comes from ice thawing and is characterized by low tritium concentration, has value of $\delta^{18}O$ between -9.2 to -10.5 per mille. This differentiation should be related to the thawing out of ice at different depth with respect to the surface and is confirmed by the isotopic composition of ice in the profile of the crevasse of the glacier which is described below.

The variable content of heavy isotopes in water with increased tritium content probably depends on the snow from which they have been thawed out. Probably, it is also necessary to include changes caused by the metamorphism of snow and its phase transformations under the conditions of 24-hour temperature variation in the ablation zone.

It follows from the above discussion on hydrology of glaciers that in the present case it is more useful to know the tritium concentration in water than to know its composition of stable isotopes.

6. Interpretation of the results of isotopic investigations in terms of the stratification of the isotopic composition of ice in the ablation zone

The aim of the sampling of the ice crevasse in the ablation zone of the Hans Glacier was to determine the differentiation of the isotopic composition of ice which feeds thaw water. This vertical crevasse was at 120 m over the sea level at a distance of 1.5 km from the front of the glacier (Fig. 10). Furrow sampling was performed, when the ice overlayer had been removed, in layers of solid ice whose thickness was marked by different colour which suggested climate changes in the accumulation period. Therefore the thickness of the layers sampled varied between 5 cm and more than 1 m.

Fig. 11 shows the results of measurements of the isotopic composition of oxygen. The step histogram represents the direct results of the measurements, whereas the dashed curve was constructed by weighted averaging of the isotopic composition for successive segments corresponding to 0.5 cm depth

of the profile. The aim in the processing of the direct results of the measurements was to adjust random wariation caused by sampling and measurement errors and to eliminate distortions caused by the irregularity of the layers sampled.

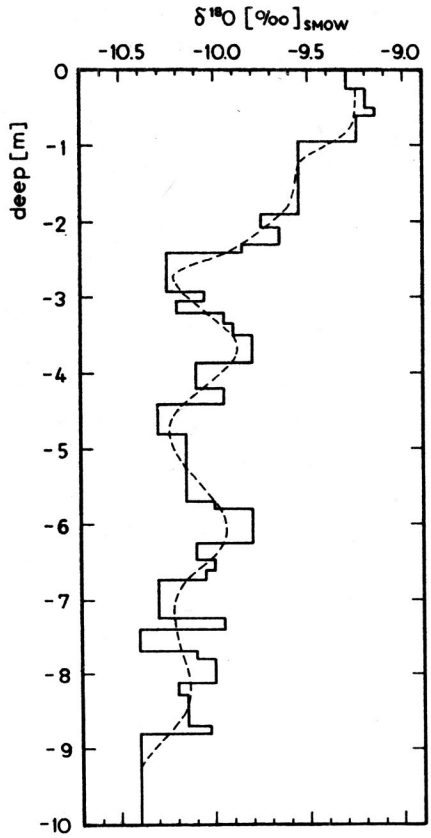

Fig. 11. Hans Glacier — ice well

It follows from Fig. 11 that the isotopic composition of ice, which is rather homogeneous down to depth of about 1 m ($\delta^{18}O$ = about −9.25 per mille), changes significantly towards a decrease of the heavy isotope content down to about 2 m depth. In the remaining 8 m part of the profile distinct oscilations occur. Three of such oscilations follow at regular intervals of about 2 m and are characterized by a mean isotope composition of about −10.1 per mille, tending to decrease their value. The maximum differentiation of the isotopic composition of oxygen occurs for the first and last sections of the profile and is about 1.2 per mille.

Fig. 12. Gas Glacier — outflow of a glacier stream through ice-morraine barriers.

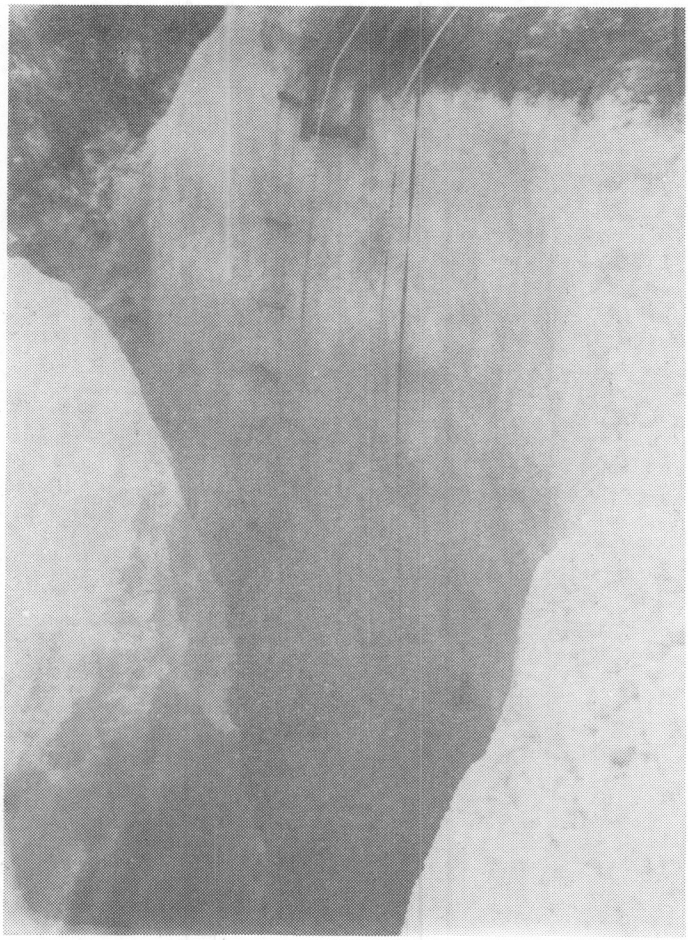

Fig. 13. Hans Glacier — sampled ice crack in ablation zone.

Considering the dynamic character of the glacier, it is possible to interpret the above direct data. In view of this, the vertical profile of the crevasse represents layers which were formed in different, higher parts of the glacier and at different times. According to the classical model of glacier motion, the lower parts of the profile are formed from snow accumulated higher and earlier.

It seems that the maximum differentiation of about 1.2 per mille observed in the isotopic composition can reflect the above model. According to the data of W. Dansgaard et al. (1973) which also concern Spitsbergen, the mean one per mille change oxygen isotope composition in precipitation is related to the 1 °C variation of the mean precipitation temperature. Considering the temperature-altitude gradient of 0.52 °C/100 m mentioned above, it can be expected that the 1.2 per mille isotope differentiation of oxygen observed would correspond to the altitude difference of the supply region more than 200 m between the ceiling and floor layers of the profile. This difference may be greater when it is assumed that this differentiation has been counterbalanced by the processes of firn and ice homogenization throughout their history. Since, however, the ceiling and floor layers are from different time periods, the additional assumption is necessary that the climate conditions were similar in this area at those times. From the general characteristics of the Hans Glacier, it follows that it is possible to interpret in the present way the maximum change in the isotopic composition of ice in the crevasse.

It seems imposible to solve the problem of the stratigraphic interpretation of this profile only on the basis of isotopic data. The zero tritium content in ice, within measurement error, only gives information that it dates from before the Nuclear Age. The information derived from the mean isotopic composition of the highest 1 m section of the profile is interesting but slight. The value of −9.25 per mille is in fact the same as the mean value of the isotopic composition of precipitatin for the period 1960–1976 recorded at Isfjord Radio Station, which is −9.31 per mille (IAEA, 1981). This signifies that the climate conditions when the precipitation settled in this layer resemebled the present-day canditions to a large extent. Since no seasonal changes in the isotopic composition have remained in the profile of the creasse isotopic data cannot be used to define a time period corresponding to the whole profile and the less so to locate it on the time axis.

From the data of K. Birkenmajer (1980) on the annual increase of contemporary ice in the ice domes in the Hornsund area (from 1924 to 1974), which is 0,4 m/yr, and considering the plastic ice compression in the ablation zone, the profile in question comprises a time interval of much more.

In the light of these data, the three oscilations noted in ice at intervals of about 2 m (Fig. 11) are in no relation to seasonal changes

in the isotopic composition of precipitation and reflect rather the climate variations of the period or supply area when or where snow, and later ice, was formed at the beginning of their progression in the glacier. The regularity of these variations can be rather random.

There are indirect data regarding the Werenskiold Glacier, which lies next to the Hans Glacier, suggesting on the basis of the measurement of the age of fossil mosses by the ^{14}C method (H. Chmal, 1981), that the ice at the front of the glacier dates from about 500–600 years ago. The isotopic results do not confirm this communication or contradict it. The isotope information encoded in the ice of the profile are not related to the greatest cold of the Little Ice Age in the 18th and 19th centuries, either.

In summary of the problems related to the results of the investigations of the profile of the ice crevasse on the Hans Glacier, it is necessary to stress that quite clear differentiation of isotopic ice has remained in the ablation zone of the temperate glacier type, despite the intensive homogenization processes, which is not a typical phenomenon.

7. Резюме

Проведен анализ рекогностировочных обозначений изотопового состава воды, снега и льда нескольких ледников Горнзунда (ЮЗ Шпицберген) с целью определения ледниковых вод и выяснения пути их циркуляции. Дана попытка выяснения стратификации изотопового состава льда в профиле стенки трещины в леднике в зоне абляции. Установлена зависимость различий изотопового состава ледниковых вод от их положения по отношению к линии фирна, расположения в системе циркуляции и от сезонных колебаний температуры воздуха.

Интенсивное таяние льда в зоне абляции выступает в виде пониженных величин трития в текущем льде, воды же тающего снега ведут к большим величинам. Различия изотопового состава в водах главной системы стока указывают на большую роль вод от таяния льда, фирна и снега в общем дренировании ледника.

8. Streszczenie

W artykule dokonano analizy rekonesansowych oznaczeń składu izotopowego wód, śniegu i lodu z kilku lodowców Hornsundu (SW. Spitsbergen) w aspekcie określenia pochodzenia wód lodowcowych i wyjaśnienia ich dróg krążenia. Zaproponowano również wyjaśnienie stratyfikacji składu izotopowego lodu w profilu szczeliny lodowej położonej w strefie ablacji. Stwierdzono zależność różnicowania się składu izotopowego wód lodowcowych od ich położenia w stosunku do linii firnu, umiejscowienia w systemie krążenia oraz od sezonowych wahań temperatury powietrza. Intensywne topnienie się lodu w strefie ablacji zaznacza się obniżonymi wartościami trytu w odpływie lodowca zaś wody topniejącego śniegu podwyższają te wartości. Zróżnicowanie izotopowe występujące w wodach głównych systemów przepływu wskazuję na wielkość udziału wód z wytopionego lodu, firnu i śniegu w ogólnym drenażu lodowca.

9. References

1. Baranowski S. (1977) — The subpolar glaciers of Spitsbergen seen againts the climate of theirs region. Ac. Univ. Wratisl. No. 410. Wrocław.
2. Behrens H. et al. (1971) — Study of the discharge of alpine glaciers by means of environmental isotopes and dye tracers. Zeit. fur Gletch. u. Glazialgeologie, Bd. VII, H. 1–2 Insbruck.
3. Birkenmajer K. (1980) — Glacier—ice accumulation rates for the past 50 years (1924–1974) at Hornsund, south Spitsbergen. Studia Geol. Polonica, Vol. LXVI, part XI. Warszawa.
4. Chmal H. (1981) — Ruch lodowca Werenskiolda w świetle datowania mchów fosylnych Materiały VIII Symp. Polarn. (The motion of the Werenskiold Glacier in the light of dating of fossil mosses. Proc. VIII Polar Symp. — in Polish) Inst. Geogr. US Sosnowiec.
5. Czajkowski R. (1981) — Radarowe pomiary miąższości lodowca Werenskiold. Mater. VIII Symp. Polarn. (Radar measurements of the thickness of the Werenskiold Glacier. Proc. VIII Polar Symp. — in Polish) Inst. Geogr. US Sosnowiec.
6. Dansgaard W., Johnsen S. J., Clausen H. B. and Gundestrup N. (1973) — Stable Isotope Glaciology. Meddelelser om Gronland Vol. 197, No 2.
7. Gat J. R. (1980 — The Isotopes of Hydrogen and Oxygen in Precipitation. Chapter 1 in Handbook of Environmental Isotope Geochemistry (P. Fritz and J. Ch. Fontes Eds) Elsevier Sci. Pub. Com., Vol. 1, Amsterdam.
8. IAEA (1981) — Statistical Treatment of Environmental Isotope Date in Precipitation. Tech. Rep., No. 206. IAEA, Vienna.
9. Jahn A. (1979) — Geneza i historia polskiej myśli polarnej. (Origin and history of Polish polar thought — in Polish) Czas. Goegr. L. Wrocław.
10. Jania J., Lentowicz Z., Szczypek T., Wach J. (1981) — Szkic geomorfologiczny rejonu Gasdalen (południowy Spitsbergen). Mat. VIII Symp. Polarn. (A draft geomorphological characterization of the Gasdalen area (South Spitsbergen). Proc. VIII Polar Symp. — in Polish). US Sosnowiec.
11. Moser H., Stickhelr W. (1980) — Environmental Isotopes in Ice and Snow. Chapter 4 in Handbook of Environmental Isotope Geochemistry (P. Fritz and J. Ch. Fontes Eds Elsevier Sci. Pub. Comp., Vol. 1 Amsterdam.
12. Pereyma J. (1981) — Klimat obszaru Hornsundu Spitsbergen Zachodni (Climate of the Hornsund area West Spitsbergen) Archives Dept. of Meterology and Climate. Wrocław University. unpubl. doct. diss. in Polish.
13. Różkoski A. (1980) — Drogi krążenia wód w lodowcach Fiordu Hornsund na Spitsbergenie. Przegl. Geol., nr 5 Warszawa.
14. Szponar A. (1975) — The marginal zone of the Arie glacier. Results of investigations of the Polish Scientific Spitsbergen Expeditions 1970–1974, vol. I, Acta Univ. Wrastisl. Wrocław.
15. Troitskij L. S. et al. (1975) — Oledennenye Spitsbergena (Svalbarda). Resultaty issledavanij po mezhdunarodnym geofizicheskim proektam. Izd. Nauka Moskwa.

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