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RESULTS OF TRACER EXPERIMENTS WITH FLUORESCENT DYES ON VERNAGTFERNER (OETZTAL ALPS, AUSTRIA) FROM 1974 TO 1982

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With 9 figures

SUMMARY

From 1974 to 1982 repeated tracer tests using fluorescent dyes were carried out in the highly glaciated drainage basin of Vernagtbach. These tests enabled the quantitative determination of the runoff in the forefield of the Vernagtferner, the calculation of travel times of the stream water and estimations of the relative contributions to the entire runoff originating from individual streams. In addition, tracer tests were carried out in the firn area of the glacier resulting in data concerning the storage and travel time of meltwater inside the glacier.

ERGEBNISSE VON MARKIERUNGSVERSUCHEN MIT FLUORESZENZFARBSTOFFEN AM VERNAGTFERNER (ÖTZTALER ALPEN, ÖSTERREICH) IN DEN JAHREN 1974 BIS 1982

ZUSAMMENFASSUNG

Im stark vergletscherten Einzugsgebiet des Vernagtbachs (Ötztaler Alpen, Österreich) wurden in den Jahren 1974 bis 1982 mehrfach Markierungsversuche mit Hilfe von Fluoreszenzfarbstoffen durchgeführt. Mit diesem Hilfsmittel konnten der Abfluß im Vorfeld des Vernagtferners mengenmäßig bestimmt, Fließzeiten des Bachwassers errechnet und die Abflußanteile einzelner Bäche am Gesamtabfluß abgeschätzt werden. Außerdem wurden im Firngebiet des Gletschers Markierungsversuche durchgeführt, die Aussagen über die Fließzeit des Schmelzwassers im Gletscher erbrachten.

1. INTRODUCTION

The Alpine glaciers are natural hydrological reservoirs of unique character. In the glacierized Alpine regions precipitation is accumulated mainly during the winter months from October until April. Only in the months of May through September can precipitation partially melt and thus run off. The portion of the precipitation that does not melt contributes to the regeneration of glacier substance, is thus withdrawn from the water circulation for decades and will only melt when the glacier movement again carries it to the glacier surface. The natural control of this storage system is achieved in the following way: While in hot and dry spells the discharge of Alpine streams and rivers in unglacierized basins decreases, the melt on the glaciers reaches its maximum and so contributes ideally to an increase of the stream flow. It is therefore of interest to examine the runoff regime in and from glaciers. The aim of such an investigation is to quantitatively determine the runoff in glaciers and to obtain information on travel paths and travel times of meltwater in the glacier itself. Useful tools for this purpose are tracers, e. g. fluorescent dyes (Behrens, 1971 a and b). This paper comprehensively

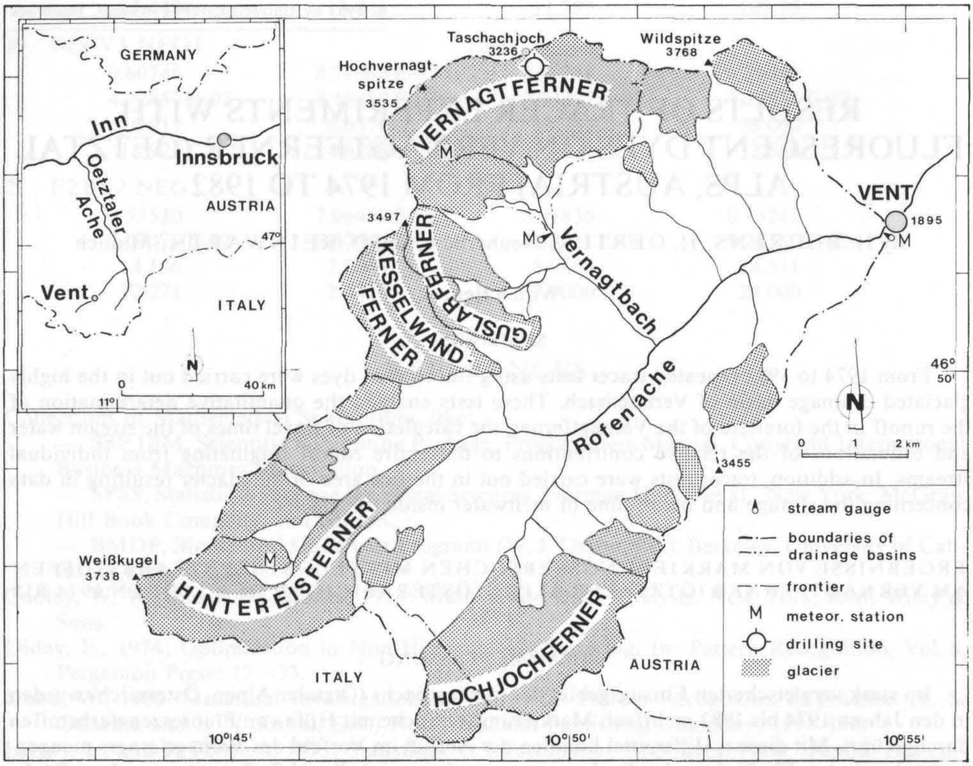

Fig. 1: Map of the drainage basin of Rofenache in the Oetztal Alps (Austria)

describes the tracer tests on the Vernagtferner and in its forefield in the Oetztal Alps (fig. 1) from 1974 to 1982. These results were partially used to form a model of the glacial runoff as described by Oerter et al. (1981) and Baker et al. (1982).

Tracer tests with fluorescent dyes in the Alpine area are also reported, for example, from Hintereisferner in the Oetztal Alps (Ambach et al., 1974; Behrens et al., 1971 and 1976), from Kesselwandferner in the Oetztal Alps (Ambach and Eisner, 1979) (fig. 1), from Pasterze (Glockner Mountains, Austria) (Ramspacher, 1981) and from Großer Aletschgletscher in the Berne Alps, Switzerland (Lang et al., 1979).

2. THE AREA OF INVESTIGATION AND THE RUNOFF IN THE GLACIER

The area of investigation is mainly the drainage basin of the Vernagtbach (Oetztal Alps) with special consideration directed to the drainage basin of the gauge station Vernagtbach ($A_b = 11.44$ km^2, 81 % glacierized) including the Vernagtferner

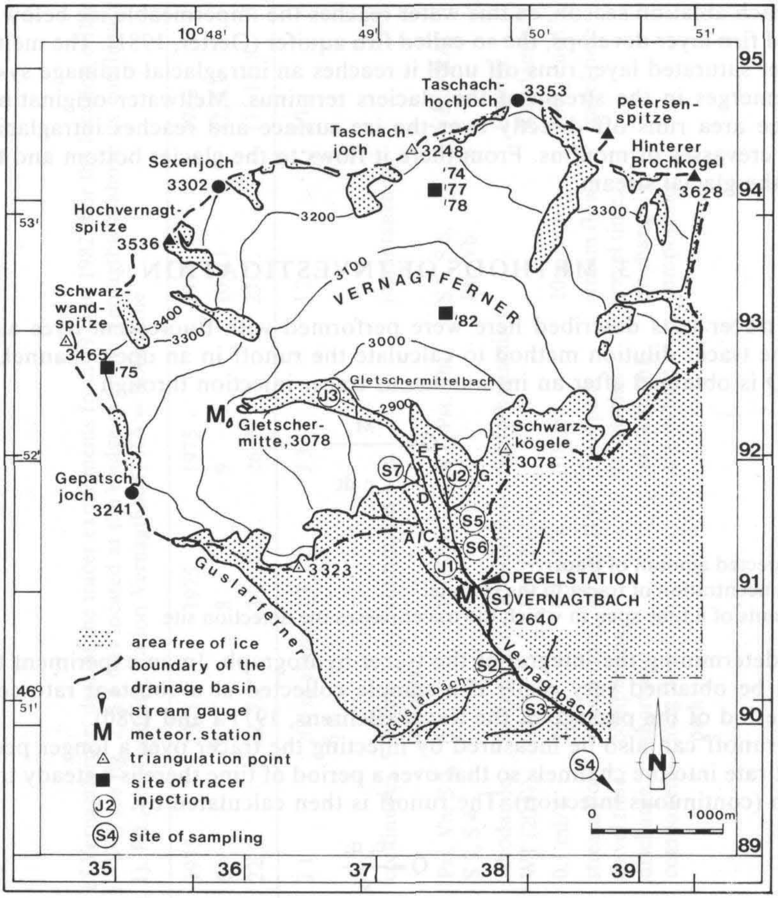

Fig. 2: Map of the area of investigation showing the injection points on the glacier (black quads, with dates) and within the glacial forefield (indicated by J) as well as the sampling points (indicated by S). The sampling point S 4 is located near the meeting of Vernagtbach with Rofenache (see fig. 1). The letters A/C, D till G are marking streams in the glacial forefield. Also are shown the boundary of the drainage basin of the stream gauge "Pegelstation Vernagtbach", covering an area of 11.44 km², 81 % of which is glacierized

($A_g = 9.30$ km²). Figure 2 shows an outline map of the area being investigated indicating the location of the gauge station Vernagtbach (Bergmann and Reinwarth, 1976) which served as central sampling station and logistic base with an automatic sampler since 1978, as well as the position of tracer injection points and further sampling points. The streams in the area of investigation are distinguished by high hydraulic gradient and strong turbulence — two good prerequisites for uniform mixing of tracer and stream water.

Like all glaciers in the Eastern Alps the Vernagtferner is temperate. Thus during the ablation season water exists both in liquid and in solid phase in the glacier at the same time, so that the meltwater permeates the porous snow and firn without refreezing. In each ablation season, as this water reaches the impermeable ice below, a water saturated firn layer develops, the so called firn aquifer (Oerter, 1981). The meltwater in this water saturated layer runs off until it reaches an intraglacial drainage system and finally emerges in the stream at the glaciers terminus. Meltwater originating in the snow free area runs off directly over the ice surface and reaches intraglacial pipes through crevasses or moulins. From there it flows to the glacier bottom and then collects in the glacial stream.

3. METHODS OF INVESTIGATION

The tracer tests described here were performed with fluorescent dyes as tracers. Using the tracer dilution method to calculate the runoff in an open channel, the discharge Q is obtained after an instantaneous tracer injection through

$$Q = \frac{M}{\int_{t_1}^{t_2} c \, dt}$$

M = injected amount of tracer
c = concentration of tracer in the channel
t_1, t_2 = limits of a time span in which the tracer passes the detection site

by first determining the integral of the tracer hydrograph. In an experiment this integral can be obtained very easily if a sample collected at a constant rate covers the whole period of the passage of the tracer (Behrens, 1971 a and 1980).

The runoff can also be measured by injecting the tracer over a longer period at a constant rate into the channels so that over a period of time there is a steady tracer distribution (continuous injection). The runoff is then calculated by

$$Q = \frac{c_i \, q_i}{c}$$

c_i = concentration of the tracer solution
c = concentration of the tracer in the channel
q_i = injection rate of the tracer solution

with the condition that q_i is very small in comparison to Q.

The applicability of this method of runoff measurement depends on a complete distribution of the tracer over the entire section of the stream; applicability criteria therefore are the same values of the concentration-time integral at all points along the cross section of the stream at the sampling site in the case of instantaneous injection or an even tracer distribution along this cross section (during the phase of steady tracer concentration) in the case of continuous tracer injection. In addition, the tracers must be conservative, i. e. they may not be lost to a measurable degree through adsorption, decay by light or other means. With unsteady state flows, as they occur in the runoff from glaciers with large diurnal variations, the requirements for the measuring of stream flow using tracers are not always met. However, this can be compensated for by additional measurements with a second tracer (Behrens, 1971 a). Travel times are determined with tracers over specific travel paths by instantaneously injecting the

Table 1: Discharge measurements in the forefield of Vernagtferner: data of the tracer experiments from 1974 to 1982. For the location of th tracer injection (J 1—J 3) and of the sampling (S 1—S 7) see fig. 2. S 4 was located at the bridge over the Vernagtbach above its confluenc with Rofenache (fig. 1). Pst. Vb = gauging station Vernagtbach; RA = Rofenache

year	1974	1974	1975	1975	1975	1975	1976	1982
number	1	2, 3 4 5	6	7	8	9	10, 11	12, 13
date	26./27. 7.	6. 6. 7. 6. 23. 9.	22. 7.	22. 7.	24./25. 7.	26. 7.	23. 7.	11., 12. 8.
location of tracer injection	J 1	J 1	J 1	200 m above S 4	J 1	J 3	J 2	J 1
type of injection	continuous	instantaneous	continuous	instantaneous	continuous		instantaneous	
location of sampling	S 1	S 1	Pst. Vb, S 2, S 3, S 4	S 4	Pst. Vb	S 7, Pst. Vb	S 5, S 6, Pst. Vb	Vent/RA
tracer	Rhodamin WT (20 %)	Sulforhodamin G	Rhodamin WT (20 %)	Sulforhodamin G	Rhodamin WT (20 %)	Sulforhodamin G		Uranin, Rhodamin B
dose of tracer	0.1 ml/s	—	0.1 ml/s	25 g	0.1 ml/s	100 g	10 g each	100 g each
goal of experiment	stream flow measurement		stream flow, travel time, discharge components	stream flow, comparison, short and long flow path	stream flow	flow path (Gletschermittelbach), travel time	stream flow, travel time, discharge components	travel time

tracer substance at the start of this path and by registering its concentration in the water at the end points of each section of measurement in relation to the time of measurement. The mean travel time coincides with the centroid of the tracer hydrograph.

It is advisable to examine the tracer-concentration of the extracted samples in the laboratory. Spectral fluorimetric measurements are desireable especially when using several tracers at the same time (Behrens, 1971 b, 1973). The detection limit for the used fluorescent dyes is of the order of 10^{-4} to 10^{-5} g/m³.

4. TRACER TESTS ON RUNOFF BEHAVIOUR IN THE GLACIAL FOREFIELD

4.1 EXECUTION OF TEST

Table 1 shows a summary of tracer experiments on runoff carried out in the glacial forefield from 1974 to 1982 including date and location of the tracer injection and the location of sampling (fig. 2), the method of injection (instantaneous or continuous injection) as well as the kind and amount of the tracer used. The purposes of each test are also indicated. Often several conclusions can be drawn from one tracer test.

4.2 RESULTS

4.2.1 RUNOFF MEASUREMENTS

Samples taken for control purposes approximately 50 m below the injection point J 1 (fig. 2) proved that an even cross sectional distribution of the tracer had been given for the stream already after this short distance. A double runoff measurement (tab. 1, no. 6 and 7), in which one tracer had to travel approximately 3 km and another only 200 m showed that a possible adsorption of the tracer can be excluded. The runoff

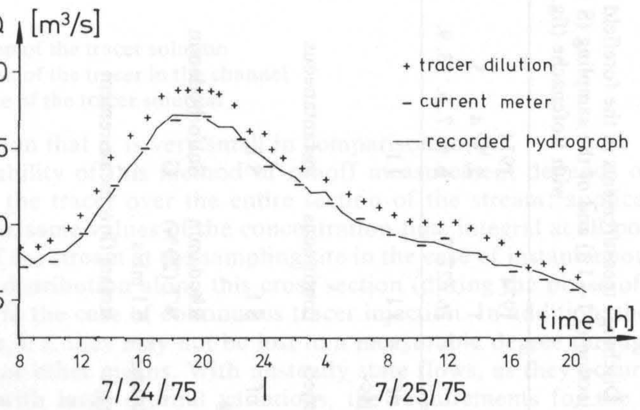

Fig. 3: Discharge at the gauge station Vernagtbach on July 24 and 25, 1975: Results of measurements by the dye-dilution method and by current meter. In addition the figure shows the hydrograph calculated with the aid of the water-stage record and current meter calibration

values calculated differed only by 0.06 m^3/s and were thus within the experimental error of ±3 % (see fig. 5).

Table 2: Stream flow measurement at the gauge station Vernagtbach: Results of single measurements by the tracer dilution method compared with measurements by the current meter, as well as with the water stage record (in 1976 hourly mean values). The numbers of the measurements refer to those in table 1. The streamflow values given for experiment no. 8 are mean values over 36 hours (fig. 3)

date	hours	no.	stream flow ($m^3 s^{-1}$) determined by tracer dilution	current meter	water stage record
6. 6. 1974	15.30	2	0.813		
	16.00			0.811	
	16.20	3	0.816		
7. 6. 1974	9.35			0.480	
	10.00	4	0.470		
26. 7. 1974	18.15	1	1.00	0.990	
23. 9. 1974	14.45	5	0.360		
22. 7. 1975	11.00	6	1.46		1.36
	12.00		1.49		1.42
	13.00		1.50	1.51	1.42
	14.00		1.60		1.45
	14.30		1.65		
	15.00				1.74
24. 7. 1975	8.00—	8	2.24	2.07	2.10
25. 7. 1975	20.00				
23. 7. 1976	10.45	10	1.88		
	10.00—11.00				1.80
	16.30	11	1.97		
	16.00—17.00				1.60

The comparison of the runoff values in table 2 shows a satisfactory conformity considering the terrain, and thus proves the above described tracer dilution method to be appropriate for alpine streams. Figure 3 shows an example of a 36-hour runoff measurement on 24th and 25th of July 1975 (table 1, no. 8). The values determined by the tracer dilution method were slightly higher (by an average of 8 % over 36 hours) than those gained by the current meter.

4.2.2 TRAVEL TIMES

Figure 4 shows two examples of the concentration-time distribution of the tracer in the runoff at the gauge station after an instantaneous tracer injection into Gletschermittelbach. Individual samples as well as 10 minute averages were used. As the runoff changed only slightly during the period of observation the change of concentration is assumed to be equal to the change of the tracer load. The mean travel time of tracer from injection point J 3 down to the gauge station was approximately 79 min., from sampling point S 7 down to the gauge station approximately 27 min. Table 3 shows the average travel times of the remaining travel distance of the Vernagtbach until it meets the Rofenache. A mean travel velocity (quotient of stream length and travel time) of approximately 0.8 m/s is determined for the runoff in the glacial forefield. Apparently, under these runoff conditions, the meltwater has a mean travel time of approximately 0.5 hours from leaving the glacier till reaching the gauge station (average distance 1.3 km); higher runoff has slightly shorter travel time. The tests in Gletschermittelbach showed that the subglacial runoff occurred more slowly. Extrapolating for the snow free ice area in summer, the travel time of the ice meltwater should not exceed 2 hours in the subglacial channels.

Table 3: Travel times to or from the gauge station Vernagtbach in the streams of the glacial forefield or in the Vernagtbach, respectively. (The altitude and distance data are derived from maps *1:10000* or *1:25000*.) For the location of the different points see figure 1 and 2. Q_{VB} = stream flow at the gauge station Vernagtbach during the time of experiment

location	altitude (m a.s.l.)	distance (m)	mean slope (%)	travel time (min)	mean travel velocity (m/s)	stream flow Q_{VB} (m^2/s)
J 3 (Gletschermittelbach)	2950	2100	15	79	0.45	1.25
S 7 (near glacier tongue)	2730	900	10	27	0.55	1.25
gauge station	2640	—	—	—	—	—
S 2 (Guslarbach)	2550	650	14	13	0.83	1.5
S 3	2500	1050	13	18	0.97	1.5
S 4 (near Rofenache)	2130	3000	17	63	0.80	1.5
Vent/Rofenache	1904	8000	9	96	1.38	2.91
				81	1.63	4.91

Table 4: Stream flow measurement in the forefield of Vernagtferner on July 7, 1975

sampling point	time (h · min)	stream flow (m^3/s)
S 5	10.30	0.24
	16.10	0.26
S 6	10.30	1.12
	16.15	1.13
Pst. VB	10.45	1.88
	16.30	1.97

4.2.3 RUNOFF COMPONENTS

In order to evaluate the contribution of various sub-basins, experiments were carried out in the years 1975 and 1976, at times with a decreasing discharge hydrograph, i. e. at times with a neglegible production of meltwater on the glacier. At the lowest measuring point S 4, the following composition is obtained for July 22nd, 1975 at 13.00: 52 % originate from the drainage basin of the gauge station Vernagtbach (including the Vernagtferner), 6 % travel to the Vernagtbach between the gauge station and the junction with Guslarbach; the Guslarbach (including the main portion of the Guslarferner) contributes 20 % to the entire runoff and further 20 % originate from the remaining drainage basin of the lower Vernagtbach (fig. 5). Table 4 demonstrates that on July 23rd, 1976 the western tributaries A/C and D (fig. 2) contributed 40 % to the

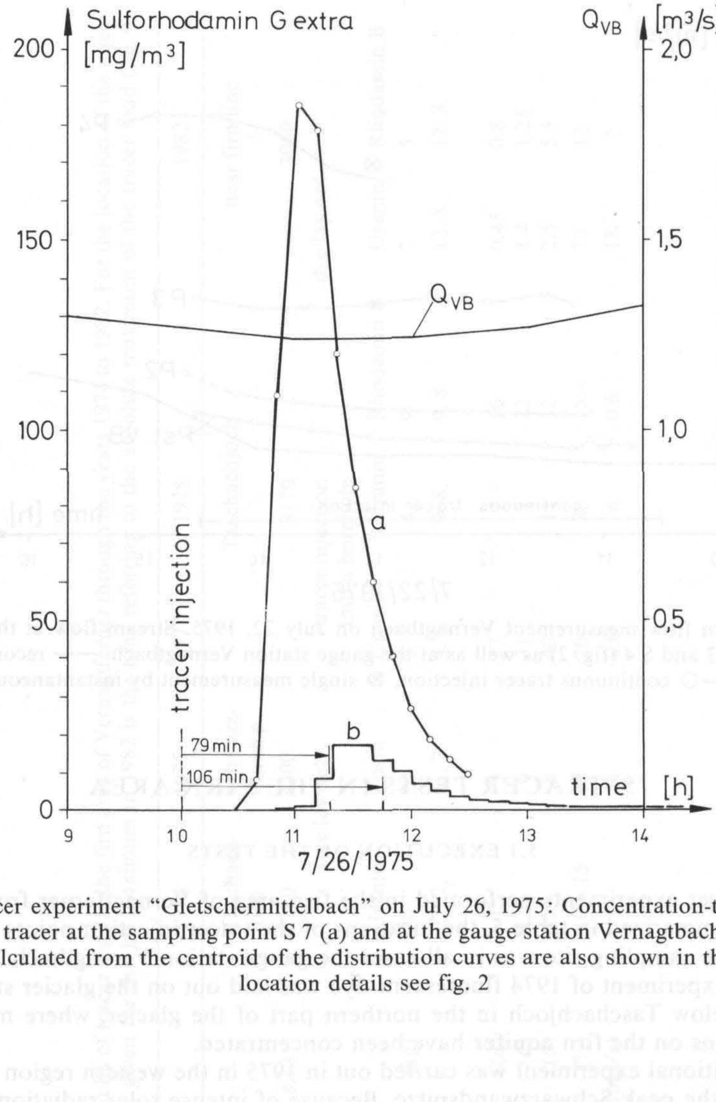

Fig. 4: Tracer experiment "Gletschermittelbach" on July 26, 1975: Concentration-time distributions of the tracer at the sampling point S 7 (a) and at the gauge station Vernagtbach (b). The travel times calculated from the centroid of the distribution curves are also shown in the figure. For location details see fig. 2

total glacial runoff, whereas the eastern tributaries as well as the streams E and F, situated in the middle of the glacial forefield, contributes 13 % of the stream flow at the gauge station Vernagtbach.

The comparison of the tracer concentrations in fig. 4 shows that the runoff in stream D amounts to approximetely 10 % of the runoff at the gauge station.

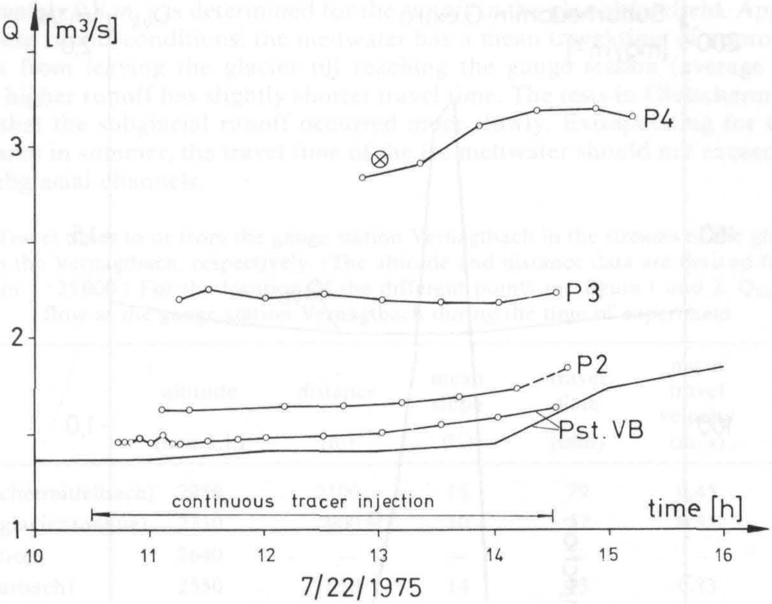

Fig. 5: Stream flow measurement Vernagtbach on July 22, 1975. Stream flow at the sampling points S 2, S 3 and S 4 (fig. 2) as well as at the gauge station Vernagtbach. —— recorded hydrograph, O——O continuous tracer injection, ⊗ single measurement by instantaneous injection

5. TRACER TESTS IN THE FIRN AREA

5.1 EXECUTION OF THE TESTS

The tracer experiments performed in the firn area of Vernagtferner from 1976 to 1982 are summarized in table 5, the locations of the tracer injection points are shown in fig. 2. The sampling site was in all cases the gauge station Vernagtbach.

In the experiment of 1974 fluorescent dye was laid out on the glacier surface in a flat area below Taschachjoch in the northern part of the glacier, where most of the investigations on the firn aquifer have been concentrated.

An additional experiment was carried out in 1975 in the western region of the glacier below the peak Schwarzwandspitze. Because of intense solar radiation and associated large amounts of meltwater during the lay out period relatively rapid infiltration of the dye into the snow could be observed.

During the tracer test in 1977, again located in the flat area below the Taschachjoch, the tracer was injected into the firn aquifer through 4 boreholes. The boreholes had depths of between 18.7 and 24.3 m. After completion of the boreholes, shortly before tracer injection, the water level was between 18.5 and 21.9 m below the glacier surface.

In 1978, at about the same location as in 1977, Uranin disodium salt of fluoresceine was injected into two boreholes (depth 17.5 m, water level 17 m below the glacier surface), and at the same time, 50 m eastwards Rhodamin B was evenly poured over

Table 5: Comparison of the results of tracer tests at the firn area of Vernagtferner through the years 1974 to 1982. For the location of the injection points see fig. 2. The time given for the 1st maximum in 1982 is the time referring to the absolute maximum of the tracer load (fig. 9)

year		1974	1975	1977	1978		1982	
location of injection point		Taschach-joch	Schwarz-wandsp.	Taschachjoch			near firn line	
altitude of injection point (m a.s.l.)		3180	3300	3170			3050	
kind of injection		dye lay out		tracer injection into a borehole			dye lay out	
tracer		Uranin	Eosin	Uranin	Uranin	Rhodamin B	Uranin	Rhodamin B
amount of tracer	(kg)	20	20	5	4	9	2	5
date of injection		27. 7.	11. 7.	4. 6.	9. 8.	9. 8.	12. 8.	12. 8.
time until:								
1st appearance	(d)	7	3	17	2	16	0.45	0.8
1st maximum	(d)	12	6	21	7	22	1.4	1.25
centroid	(d)	15	8	40	11	32	2.5	5.5
recovered tracer amount	(%)	10—15	40	20	80	5	70	12
maximum tracer load	(mg/s)	3	24	0.6	6	0.6	18	5

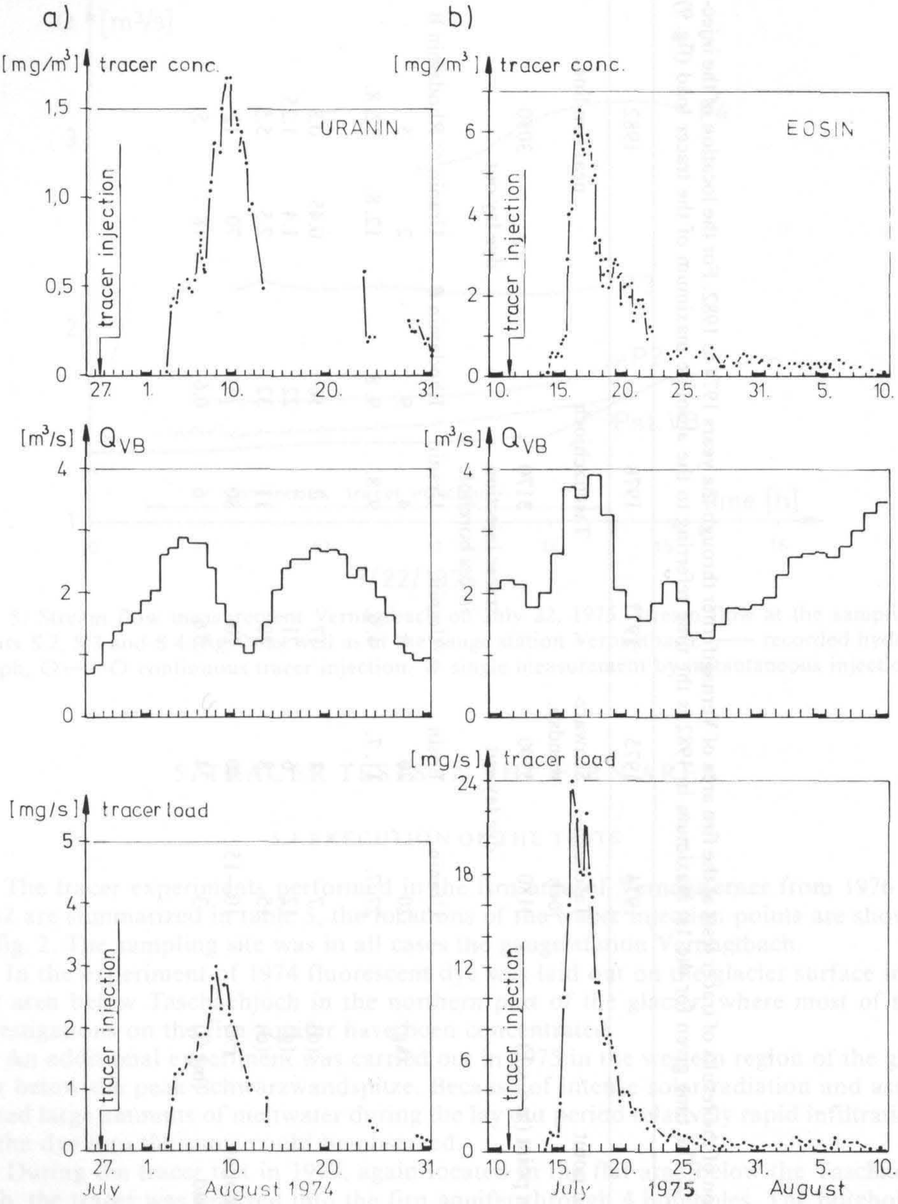

Fig. 6: Tracer experiments Vernagtferner 1974 and 1975: Hydrographs of tracer concentration, stream flow and tracer load at the gauge station Vernagtbach referring to the tracer injections (dye laid out on the firn surface) in 1974 beneath Taschachjoch (a) and 1975 beneath Schwarzwandspitze (b) (fig. 2)

$10 \times 10\ m^2$ of the surface. Light snow fall set in while laying out the dye. In the course of night the dye mark was completely covered by fresh fallen snow.

In 1982 a place in the lower part of the firn area, about 100 m above the transient snow line of August, was chosen for a simultaneous lay out of two different dyes, Uranin and Rhodamin B. Uranin was much better dissolved in water than Rhodamin B and penetrated very quickly into the firn, whereas a larger amount of Rhodamin B remained on the surface and was well visible for several days. (The behaviour of Rhodamin B was quite similar in 1978, during the marking at Taschachjoch.)

5.2 RESULTS

5.2.1 THE TRACER HYDROGRAPH

In 1974 the Uranin showed up at the gauge station for the first time 7 days after the dye lay out at the Taschachjoch (fig. 6). After further 5 days the maximum of the tracer load passed the gauge station (the tracer load equals the product of tracer concentration times stream flow). The tracer output during the period of observation can only be estimated roughly as the sampling was interrupted after August 15th. It was 2—3 kg, respectively 10—15 % of the amount of tracer laid out on the glacier surface.

In 1975 the tracer was already evident at the gauge station on the third day after injection below Schwarzwandspitze (fig. 6). After 3 more days a first maximum of the tracer load was observed and 5 days after the first evidence, the tracer load started to decline rapidly again. From August 22nd onwards the Eosin concentration sunk below

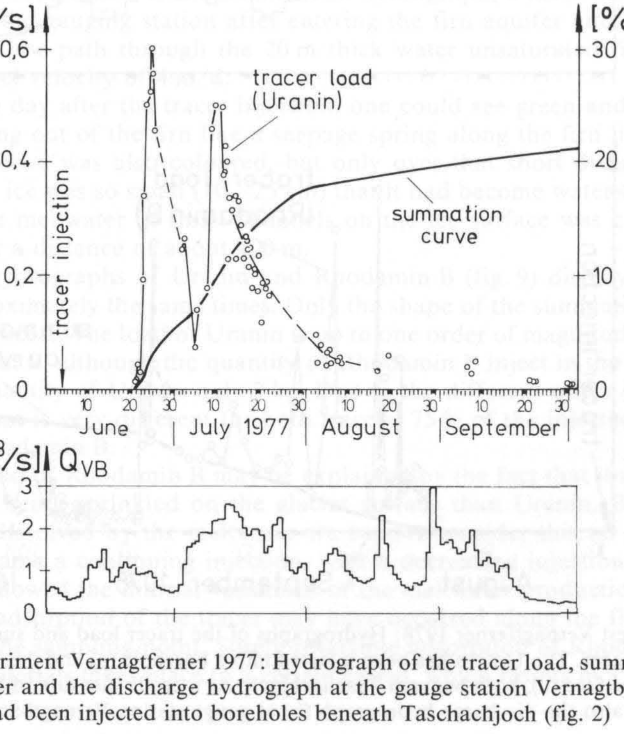

Fig. 7: Tracer experiment Vernagtferner 1977: Hydrograph of the tracer load, summation curve of the recovered tracer and the discharge hydrograph at the gauge station Vernagtbach. The tracer had been injected into boreholes beneath Taschachjoch (fig. 2)

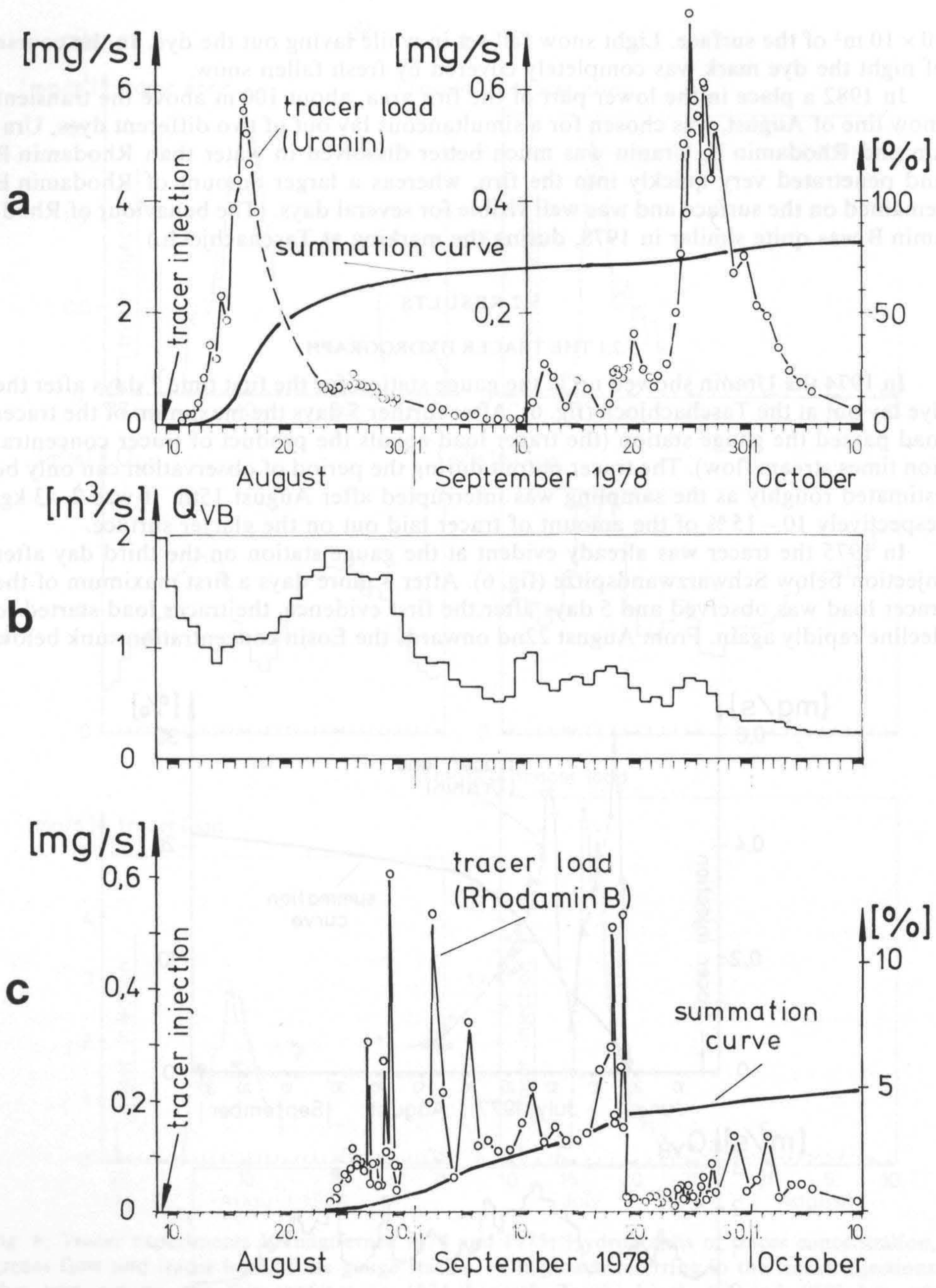

Fig. 8: Tracer test Vernagtferner 1978: Hydrographs of the tracer load and summation curves of the recovered tracer. The Uranin has been injected into a borehole (a) and the Rhodamin laid out on the glacier surface (c), both beneath Taschachjoch. As a crude measure of the ablation on the glacier, also the discharge hydrograph (b) at gauge station Vernagtbach is shown

the detection limit. The amount of tracer detected before August 22nd was 7.5—8 kg or 37—40 % of the total injection.

The hydrograph of the tracer load in 1977 (fig. 7) is characterized by two maxima. The first maximum appears 4 days after the first tracer evidence, altogether 21 days after tracer injection into the boreholes. The second increase of tracer load starts with a delay of 4 days after a distinctive increase of stream flow and leads to a second maximum after further 5 days.

In 1978 the hydrograph of the Uranin load (tracer injection into a borehole) shows a significant maximum 7 days after tracer injection (fig. 8) which cannot be correlated with a maximum of meltwater production or runoff. On the contrary, the main peak with its rising branch occurs synchronously with a large decrease of the firn water table hydrograph and the reduction of the firn aquifer (Oerter et al., 1981). This proves that the glacier discharges water although there is no significant production of meltwater on the glacier surface at the same time. The hydrograph of the tracer load shows another peak from 24th to 28th September 1978. Here, however, the tracer load only made up 1/10 of the main peak. A very high tracer output of 81 % was achieved in this tracer experiment.

The hydrograph of the Rhodamin B load shows no significant peak after a dye lay out on the glacier surface. After the dye had been laid out, it was covered by fresh snow and the ablation in the area of this tracer injection was interrupted for at least 7 days due to bad weather. Taking August 16th, 1978 (1 day after the runoff minimum) as the recommencement of the firn ablation and thereby as the beginning of the permeation of the meltwater, 8 days go by until the tracer first arrives at the gauge station Vernagtbach. By comparison to the Uranin load hydrograph, it takes the water at least 3 days to reach the gauging station after entering the firn aquifer and further 5 days remain for the flow path through the 20 m thick water unsaturated firn. This corrsponds to a travel velocity of 4 m/d.

In 1982, one day after the tracer injection, one could see green and red coloured meltwater flowing out of the firn like a seepage spring along the firn line. The water saturated firn above was also coloured, but only over that short distance where its depth above the ice was so small (10—25 cm) that it had become water saturated. The flow path of the meltwater in small channels on the ice surface was clearly marked southwards over a distance of about 400 m.

The tracer hydrographs of Uranin and Rhodamin B (fig. 9) display maxima and minima at approximately the same times. Only the shape of the summation curves differ for the two tracers. The load of Uranin is up to one order of magnitude greater than that of Rhodamin B, although the quantity of Rhodamin B inject in the firn had been 5 kg, and the quantity of Uranin only 2 kg. Due to the different tracer loads also the total tracer output is very different for both tracers, 75 % of the injected Uranin, and only 10 % of Rhodamin B.

The small load of Rhodamin B may be explained by the fact that it was much less dissolved when being sprinkled on the glacier surface than Uranin. Because it was only gradually dissolved by the meltwater we cannot consider this an instantaneous injection. It became a continuing injection, with a decreasing injection rate, and the tracer output followed the diurnal variations of the meltwater production and runoff. Also, losses by adsorption of the tracer may have occurred along the flow path from the marking to the sampling point. Surely reversible adsorption of Rhodamin B at the morainic bed materials takes place to a certain extent, which results in a retardation of the tracer flow.

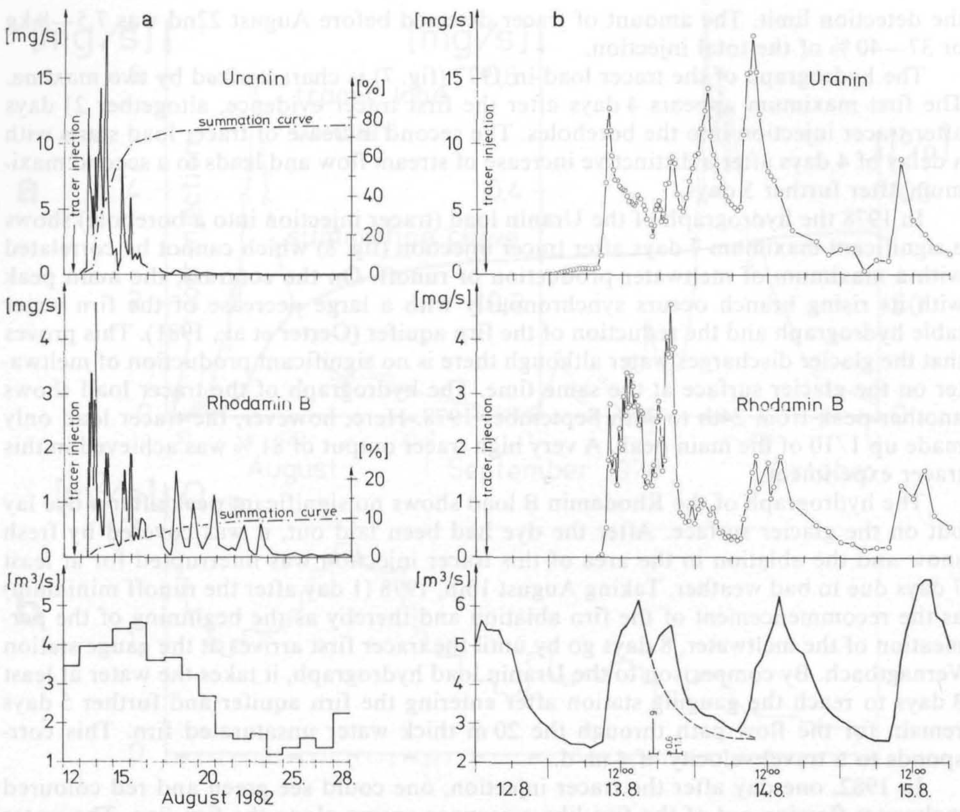

Fig. 9: Tracer experiment Vernagtferner 1982: Hydrographs of the tracer load and summation curves of the recovered tracer in comparison with the discharge hydrograph at the gauge station Vernagtbach during August 12 till 28 (a) and in more detail during the first four days after the tracer injection (b). The hours with rainfall on the 13th are indicated by horizontal lines below the discharge hydrograph in part b of the figure. The amount of rainfall, indicated by vertical lines, was 9 mm during the first event and in total 1.7 mm during the following events. The dotted line show the estimated hydrograph without rainfall runoff

In spite of the differences in the amount of the tracer load of Uranin and Rhodamin B both tracer hydrographs show a synchronous course, with coinciding minima. The shape of the Uranin peak is more pointed than that of the Rhodamin B peak, so that the maxima coincide not so well as the minima. Calculating the location of the centroid of the tracer hydrographs (within the first 25 days after the tracer injection) one obtains 2.5 d for Uranin and 5.5 d for Rhodamin B.

Discussing the temporal course of the tracer hydrograph (fig. 9b) one recognizes that the minima appear mostly between 7 and 8 a.m. The increase of the tracer load starts together with the increase of the discharge. Due to the different shapes of the tracer peaks the maxima of Uranin appear earlier than the discharge maxima, whereas the maxima of the broader Rhodamin B peaks coincide in a better way with the stream flow maxima. It seems as if the meltwater runoff on the ice surface comes to a standstill during the night hours, and so also the transport of tracer. The meltwater and the tracer percolating through the firn build up along the firnline, and a surge like tracer runoff occurs, when the melting starts again in the morning hours.

In addition both tracer hydrographs show three more distinct peaks during the night hours from August 13th through 14th. Also the discharge hydrograph shows such a peak, which is due to rainfall runoff. Probably the rain water running off on the ice surface takes away the tracer still remaining there (1st and 2nd peak), and on the other hand the rain reactivated the percolation of tracer through the firn and the further run-off (3rd peak), till it comes again to a standstill after midnight. During this event once more the values of the tracer load differ from each other whereas the maxima and minima of the two hydrographs occur at approximately the same times.

5.2.2 DISCUSSION ON THE RESULTS OF THE TRACER EXPERIMENTS

The comparison of the 5 tracer tests in the years 1974 to 1982 (tab. 5) does not give a very clear picture, and thus can only be interpreted with knowledge of the ablation conditions of each year. All marking points (fig. 2) are approximately 3.5 km away from the gauge station Vernagtbach. This means that from Schwarzwandspitze as well as from Taschachjoch the meltwater had to travel 2.2 km within the glacier and 1.3 km in the glacial forefield.

The results of the dye lay out of 1975 and of the tracer injection into a borehole of 1978 show a high degree of similarity. At the place of the tracer lay out below Schwarz-wandspitze the firn layer is only a few meters thick. Here the flow path through the unsaturated firn was short and the flow rate was almost the same as after a direct tracer injection into the firn aquifer. Due to the thin firn layer this tracer test beneath Schwarzwandspitze is not comparable with the other tracer experiments, when the tracer was laid out on the glacier surface in the upper firn area.

The two dye lay outs at Taschachjoch have in common a small tracer load and a low recovery rate, both caused by the long vertical flow path in the water unsaturated firn. The dye was laid out at the beginning of a raise of the stream flow at the gauge station Vernagtbach in 1974, i. e. a period of ablation in the accumulation area. Hardly 7 days passed until the first arrival of the tracer at the gauge station Vernagtbach and further 5 days until the passage of the maximum. These time periods correspond with those of the tracer experiment of 1978, when the interruption of the ablation at that time by snow fall is taken into consideration. The first tracer evidence occurred 8 days after the restart of ablation, the tracer maximum following after further 6 days.

The results of the tracer injection into a borehole in 1977 can be compared to the other tests only with great difficulty. This is certainly due to the particularly bad ablation conditions of summer 1977. It is possible that the dye injected in early summer — before the onset of ablation — deposited itself in the injection boreholes and, as the firn aquifer had not yet developed, was diluted and deposited in the firn so much so that it no longer travelled through the glacier as a uniform tracer cloud.

These tracer tests show that meltwater can run off from the firn area to the gauge station within a few days. A travel velocity of approximately 4 m/d can be estimated for the flow path through the water unsaturated firn in the area below Taschachjoch (firn thickness approximetely 20 m). This travel velocity corresponds to the value of 4.5—5 m/d which was derived from the changes of the firn water table (Oerter et al., 1981).

Proceeding on the assumption of an average travel time of 12 days for the distance from the glacier surface (below Taschachjoch) down to the gauge station, the water takes 7 days from reaching the firn water body to its arrival at the gauge station.

Assuming that the meltwater runs through the intraglacial runoff system to the gauge station Vernagtbach in a few hours, 7 days can be estimated as the mean travel time for the runoff in the firn aquifer. By means of the travel velocity one can calculate the distance the meltwater is capable of passing through the firn aquifer within this time period. At a travel velocity of 6 m/d (Oerter and Moser, 1982) the meltwater could have covered a distance of 42 m in 7 days. This distance appears very short, but agrees with the results of other tests (Oerter, 1981) according to which the firn aquifer must be drained in intervals between 50 and 90 m. Very short travel times in the firn aquifer also resulted from the evaluation of tracer tests at Aletschgletscher (Lang et al., 1979) and at Hintereisferner (Ambach et al., 1974).

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