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Band 26, Heft 2, S. 169-177
ZEITSCHRIFT FÜR GLETSCHERKUNDE
UND GLAZIALGEOLOGIE
Universitätsverlag Wagner, Innsbruck, Austria

1993

Band 26, Heft 2 (1990), S. 169—177

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ABSTRACT

In 1988, surface velocities and strain rates were measured on the Taku Glacier, one of the major glaciers of South East Alaska. Surveys of a cross-glacier profile reveal a partial parabolic flow profile with a maximum measured surface velocity of 50 cm/day occuring near the center of the glacier. Independent surveys of three triangular fields spaced evenly across the movement profile formed the basis of calculating principal strain tensor elements with a maximum extensional strain rate of $395 \cdot 10^{-6}$ per day and a maximum compressional strain rate of $-333 \cdot 10^{-6}$ per day. Stress conditions are reduced from the strain rate results and a mass flow rate of $362 \cdot 10^{6}$ kg/day across the movement profile is derived. The results indicate how dynamic and active the Taku Glacier is.

ERMITTLUNG VON OBERFLÄCHENGESCHWINDIGKEITEN, VERFORMUNGSVERHALTEN UND MASSENTRANSPORT IM BEREICH DES TAKU-GLETSCHERS, JUNEAU EISFELD, ALASKA

ZUSAMMENFASSUNG

Auf dem Taku-Gletscher, einem der großen Gletscher Südost-Alaskas, wurden im Jahre 1988 Oberflächengeschwindigkeiten und Verformungsraten gemessen. Die Vermessung eines Profiles quer über den Gletscher zeigt einen nahezu parabolischen Geschwindigkeitsverlauf mit einer maximalen Fließgeschwindigkeit von 50 cm/Tag in der Mitte des Gletschers. Drei voneinander unabhängige Dreiecke, gleichmäßig über das Geschwindigkeitsprofil verteilt, dienten als Basis für die Ableitung der Hauptwerte der Verformungstensoren. Die Maximalwerte liegen bei $395 \cdot 10^{-6}$ pro Tag für die Dehnung und bei $-333 \cdot 10^{-6}$ pro Tag für die Kompression. Aus den Ergebnissen der Verformungsuntersuchungen werden die Spannungsverhältnisse abgeleitet und schließlich ein täglicher Massentransport im Profil von $362 \cdot 10^{6}$ kg/Tag berechnet. Die Ergebnisse zeigen, wie dynamisch und aktiv der Taku-Gletlscher ist.

1. THE SETTING

The Taku Glacier is part of the Juneau Icefield, which extends north 120 km from Juneau, Alaska at approximately 58° north latitude (fig. 1). The area of the icefield is approximately 4000 km². The Taku, via tributary glaciers, originates in its neve located at 1800 to 2000 m above sea level on the United States and Canadian border. The mountains in which the icefield lies are most properly called the Northern Boundary Range.

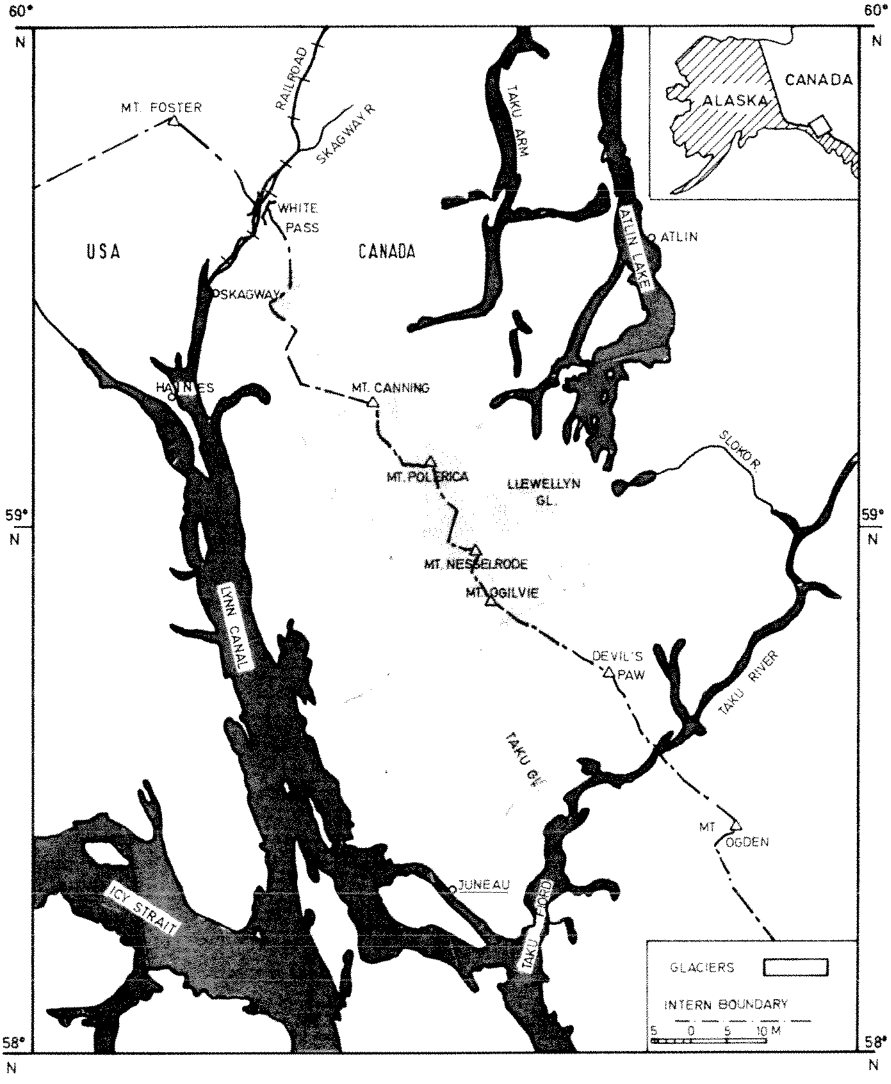

Fig. 1: The Juneau Icefield, Alaska-Canada in the Northern Boundary Range

From the upper neve to tidewater the Taku is in excess of 45 km. Numerous tributary glaciers make this the primary drainage of the Juneau Icefield. Relatively warm waters in the adjacent Gulf of Alaska engender very frequent winter storms. Liquid equivalents of precipitation on the seaward side of the range are in excess of 250 cm at many stations.

The Junea Icefield and the Taku Glacier in particular have been studied extensively by the Junea Icefield Research Program.

2. SURFACE VELOCITY

During the 1988 Junea Icefield Research Program, the movement "Profile IV" in the vicinity of Camp 10 on the Junea Icefield, Alaska-Canada was re-established. It is located approximately 26 km above the glacier's terminus and 5 km above the mean neve line. The elevation above sea level is approximately 1100 m. The length of the profile is some 5 km (fig. 2).

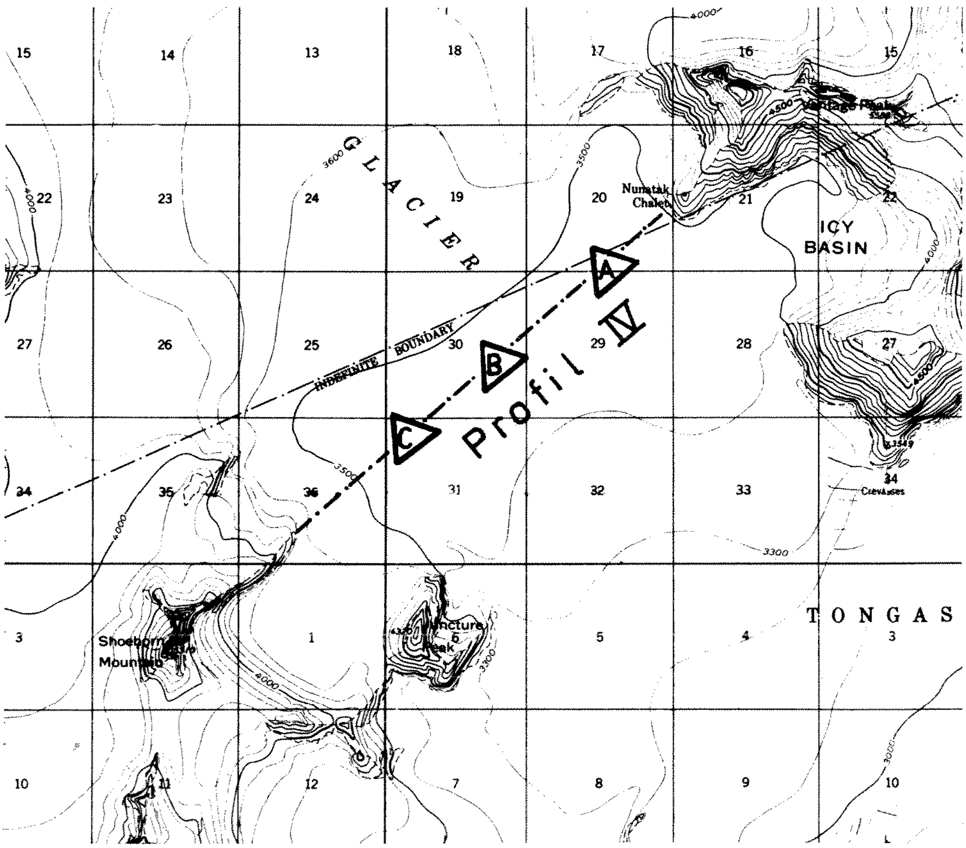

Fig. 2: The main Taku Glacier, the movement Profile IV, and the strain triangles

This profile line has historically been a source of intense study. Results of annual surveys of across-glacier stakes report a velocity profile that varies from parabolic to plug flow (Miller 1958). A glacier bore-hole experiment was conducted (Miller 1958) in order to determine physical properties and flow characteristics of the glacier. Bedrock profiles that record the glacier's depth have been obtained from various seismic techniques and from gravity measurements (Poulter et al. 1949). Also seasonal accumulation and ablation rates have been recorded since forty years.

In 1988 a study of surface flow rates and for the first time also surface strain rates was conducted on this very Profile IV. Twelve rods and three strain triangles were evenly spaced across the glacier perpendicular to the glacier's flow (fig. 2). The rods of the movement profile and the strain triangles were initially surveyed and then re-surveyed several days later to determine how the positions of the rods and the shapes of the triangles had changed. For the surveys precise optical theodolites and electronic distance measuring instruments were used. Due to heavy ablation special precautions had to be taken in order to guarantee point identity of the survey stations and targets on snow between the observation epochs (Byers et al. 1988).

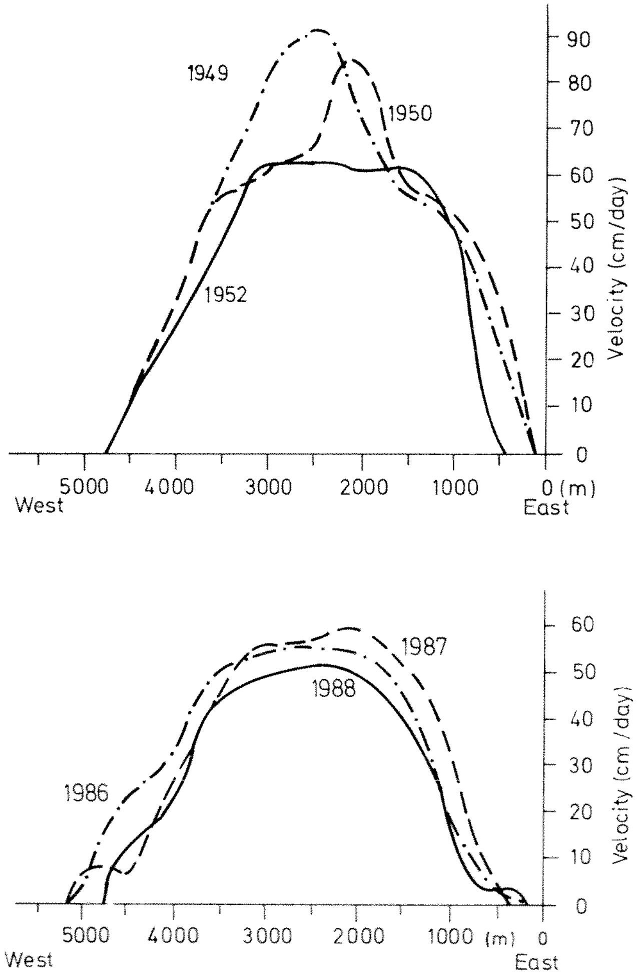

Fig. 3: Surface velocity patterns at Profile IV
a) 1949, 1950, 1952 b) 1986—1988

For comparison, fig. 3 a depicts the velocity profiles from the 1949, 1950, and 1952 surveys (Miller 1958) while fig. 3 b presents the 1986, 1987, and the 1988 surveys of Profile IV (Kersting 1986; Blachnitzky 1987; Daellenbach 1989). Surveys of the late 1940's and early 1950's reveal a maximum surface velocity rate ranging between 50 and 90 cm/day. The maximum surface velocities between 1986 and 1988 ranged between 50 and 60 cm/day. In each study, the maximum surface velocity was measured approximately at mid-glacier. The glacier flow patterns of the late 1940's and early 1950's exhibit a Block-Schollen or plug flow while the patterns between 1986 and 1988 show a partial parabolic streaming flow.

3. SURFACE STRAIN RATES

As mentioned, three triangles were evenly spaced across the movement profile (triangles A, B, C; fig. 2). The triangles were equilateral with side lengths of some 500 m. The three side lengths and the three angles of each triangle were precisely observed. Re-observation after a period of time led by comparison to the distortions of the individual elements. The distortions of the six elements of a triangle serve as the basis for the analysis of principal strain rates occuring in the area of that triangle. The least squares estimation of the strain tensor elements and their transformation to the so-called strain ellipse representing the principal strain rates and their orientation is given e. g. by Welsch (1981). In contrast, Nye (1959) applies diamond-shaped quadrilateral figures for strain measurements.

The spacing of the triangles allows to show how the orientation and magnitude of the strain rates vary across the glacier. Fig. 4 depicts the results (see also table 1). The representation of strain accumulation for each strain triangular study field is given as a two-dimensional, homogeneous strain ellipse; $\dot{\varepsilon}_1$ is extentional (maximum principle strain) $\dot{\varepsilon}_2$ compressional (minimum principle strain). Also mapped are the representative surface crevasses that existed in each area.

Strain triangle Taku A yielded the largest strain rates of the three study areas. The orientation of the maximum principle strain rate $\dot{\varepsilon}_1$ was perpendicular to the observed pattern of crevasses. This field was heavily crevassed by the time the initial survey was made.

Strain triangle Taku B was situated approximately at mid-glacier in an area of high surface velocities. The maximum principle strain rate measurement was approximately 1/16th of that experienced in Taku A. This dramatic decrease in the magnitude of strain rate correlates well with the nearly complete absence of surface crevasses in the Taku B study area. The orientation of $\dot{\varepsilon}_1$ was perpendicular to the few observed surface crevasses only in a general way.

Strain triangle Taku C experienced a maximum principle strain rate of about 1/2 that of Taku A. As in Taku A, the orientation of $\dot{\varepsilon}_1$ was perpendicular to the observed pattern of surface crevasses.

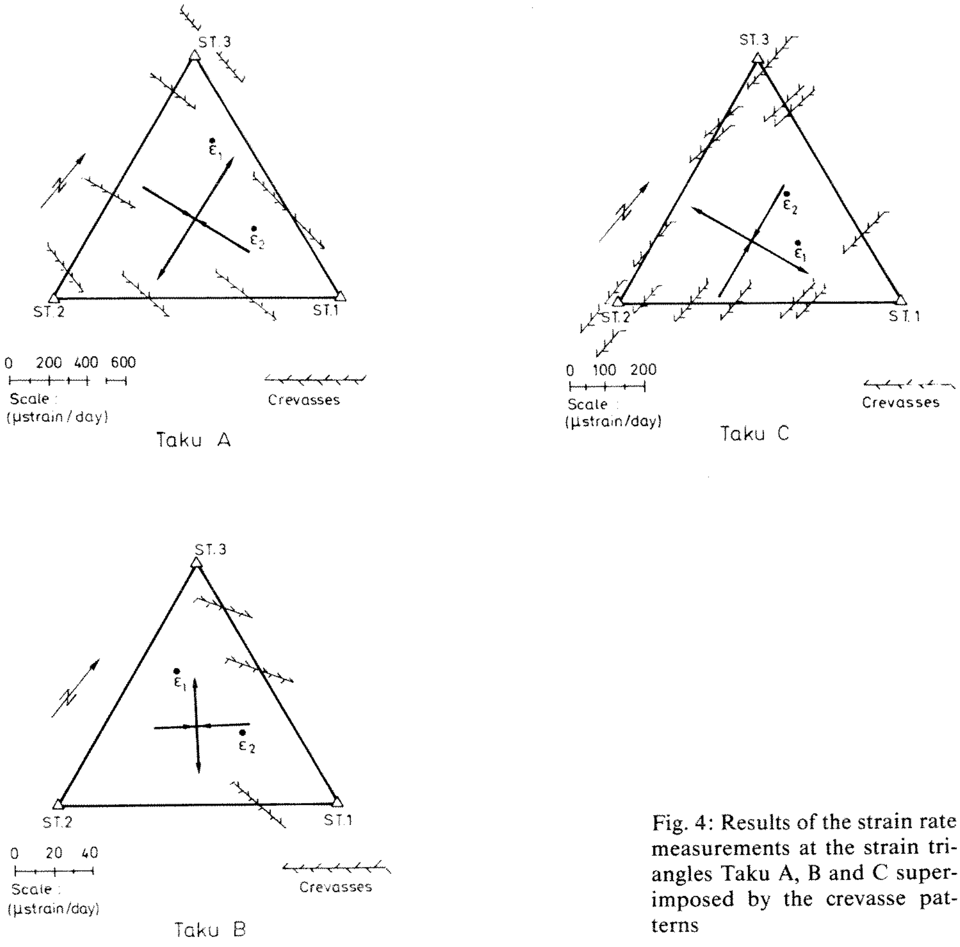

Fig. 4: Results of the strain rate measurements at the strain triangles Taku A, B and C superimposed by the crevasse patterns

4. STRESS CONDITIONS

Based on a series of laboratory tests, Glenn (1955) developed a flow law for ice. This flow law describes an exponential relationship between stress and strain rates:

$$\dot{\varepsilon} = \mathrm{k} \cdot \tau^{n}.$$

$\dot{\varepsilon}$ is the effective shear strain rate

$$2\,\dot{\varepsilon}^2 = \dot{\varepsilon}_1^2 + \dot{\varepsilon}_2^2 + \dot{\varepsilon}_3^2,$$

where $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are evaluated from the strain triangles and $\dot{\varepsilon}_3$ is determined through the continuity condition (no volume change)

$$\dot{\varepsilon}_1+\dot{\varepsilon}_2+\dot{\varepsilon}_3=0;$$

k is an empirical constant largely dependent on temperature, n is an empirical constant which is dependent on physical characteristics of the ice, τ represents the effective shear stress. In the same vicinity as the present study, the constants k and n were determined by Miller (1958) to be 0.019 and 3, respectively.rinciple stress deviators σ_i' are found from (Nye 1959)

$$\sigma_i'=(\tau/\dot{\varepsilon})\dot{\varepsilon}_i.$$

Since the vertical stress $\sigma_3=0$ on the ice surface, the actual horizontal principal stresses σ_i, given by the relationship

$$\sigma_i'=\sigma_i-\frac{1}{3}(\sigma_1+\sigma_2+\sigma_3)$$

are

$$\sigma_1=2\sigma_1'+\sigma_2',$$
$$\sigma_2=\sigma_1'+2\sigma_2'.$$

Finally, the hydrostatic stress σ is defined by $\sigma=⅓(\sigma_1+\sigma_2+\sigma_3)$.

The results for the areas under investigation are recorded as table 1.

Table 1: Stress conditions of the Taku Glacier calculated from measured strain-rates (strain-rates in 10^{-6} per day; stresses in bars)

Study Area	$\dot{\varepsilon}_1$	$\dot{\varepsilon}_2$	$\dot{\varepsilon}_3$	$\dot{\varepsilon}$	τ	σ_1	σ_2	σ
Taku A	395	−334	−61	368	27	53	20	24
Taku B	25	− 26	2	26	11	20	9	10
Taku C	178	−176	− 2	177	21	42	21	21

5. MASS FLOW RATE

The total mass flow rate Q across a transverse section of the glacier is a usefull calculation when considering the glacier's mass balance. By assuming a steady flow rate, independent of time the conservation of mass equation becomes

$$Q=\rho\cdot A\cdot U_{ave}$$

where ρ is the average density of glacial ice (917 kg/m^3), A is the cross-sectional area of the transverse section across the glacier, and U_{ave} is the average velocity normal to the transverse section.

The bedrock profile in the vicinity of movement Profile IV has been determined with seismic measurement techniques (Poulter et al. 1949); fig. 5 illustrates the transverse section across the glacier. The total cross-sectional area was found to be $A=1.35\cdot10^6$ m^2.

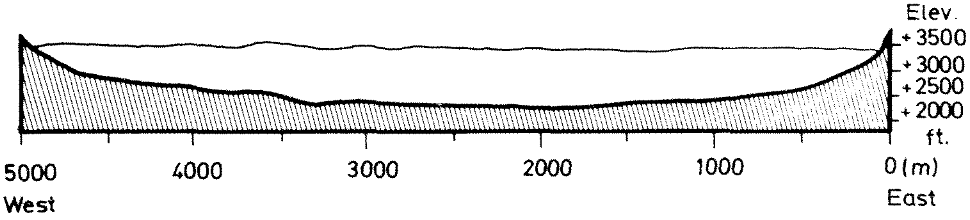

Fig. 5: Transverse section across the main Taku Glacier in the close vicinity of Profile IV

The value for U_{ave} is determined from empirical formulas which relate on the basis of a simplified flow model (Nye 1952; Miller 1958) the velocity profiles U_0 at the glacier's surface and U_z at a given depth z:

$$U_z = U_0 - \frac{2k}{n+1} \cdot z \cdot \tau_z^n$$

where τ_z is the shear stress on a layer at a depth z according to

$$\tau_z = z \cdot \rho \cdot g \cdot \sin \alpha$$

with the constant density ρ; g is the acceleration due to gravity and α is the angle of the slope. Assuming a slope of $\alpha = 1^0$, $\tau_z = 1.57 \cdot 10^{-3} \cdot z$ bar.

U_0 (see fig. 3b, profile 1988) has been expressed as a function of the width w of the glacier by a best-fitting polynomial curve of fourth order. U_z is then a function of the width w and the depth z of the glacier.

U_{ave} can finally be derived with the following relationship

$$U_{ave} = \frac{1}{A} \int_0^z \int_0^w U(w, z)\, dw\, dz$$

with the result of $U_{ave} = 29$ cm/day.

Calculating the velocity U_D due to deformation for the measured ice thickness D and subtracting it from the observed surface velocity U_o yields the velocity of basal sliding $U_b = U_D$. When averaging it across the profile with the result $U_{b_{ave}} = 0.57\ U_o$, the statement (Miller 1958) that "two-thirds of the down-glacier movement ... is due to bottom slip" is verified.

With the average density ρ, the cross-sectional area of the transverse section A, and the average velocity normal to this transverse section U_{ave}, the total mass flow rate Q across movement Profile IV is eventually calculated to be approximately $360 \cdot 10^6$ kg/day.

ACKNOWLEDGEMENT

This paper is dedicated to the memory of Dipl.-Ing. Klaus Blachnitzky who died on the Juneau Icefield in 1988 in fulfilment of his work as an academic teacher and researcher.

The authors are indebted to Prof. Maynard M. Miller, Director of the Juneau Icefield Research Program. This work was financially supported by the Foundation for Glacier and Environmental Research, the National Science Foundation, and the Universität der Bundeswehr München.

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Manuscript received 25th October 1991

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