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STRAIN RATE MEASUREMENTS IN A 20 M DEEP FIRN PIT IN A TEMPERATE GLACIER (KESSELWANDFERNER, OETZTAL ALPS, 1967–1978)

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With 6 figures

SUMMARY

The deformation of a 20 m deep firn pit in the accumulation area of Kesselwandferner was surveyed over a period of 11 years. Six or seven surveying markers had been installed at each of 14 levels.

The survey shows that the shear strain rate is independent of depth and the originally circular pit cross section was changed into an ellipse. In the direction of the glacier flow, the diameter was increased, the strain rate being approximately independent of depth. Transverse to the flow, however, the diameter decreased, the strain rate becoming higher as the depth increased. The vertical strain rates responsible for thinning of firn layers decrease with depth.

MESSUNG DER DEFORMATION EINES 20 METER TIEFEN FIRNSCHACHTS IN EINEM TEMPERIERTEN GLETSCHER (KESSELWANDFERNER, 1967—1978)

ZUSAMMENFASSUNG

Zur Messung der Verformung eines 20 m tiefen Firnschachts im Akkumulationsgebiet des Kesselwandferners wurden an der Schachtwand Vermessungspegel eingesetzt. 14 Niveaus in verschiedenen Tiefen wurden über 11 Jahre vermessen. Jedes Niveau wurde durch 6–7 Pegel markiert, wobei der Querschnitt des Schachtes anfangs kreisförmig war.

Ein nahezu lineares Kriechprofil zeigt, daß die Deformationsrate der Scherverformung im wesentlichen unabhängig von der Tiefe ist. In der Richtung der Gletscherbewegung wurde der Durchmesser des Schachtquerschnitts vergrößert, wobei auch hier die Deformationsrate annähernd unabhängig von der Tiefe ist. Quer zur Fließrichtung wurde hingegen der Durchmesser verkürzt, wobei hier die Deformationsrate mit der Tiefe zunimmt. Die vertikale Deformationsrate, die zur Verdünnung der Firnschichten führt, nimmt mit der Tiefe ab.

1. INTRODUCTION

Strain rate measurements on a firn pit were made to gain better information on the movement of the firn of a temperate glacier. The firn pit originally had a depth of 20 m, a diameter of 2 m and an approximately circular cross section.

Six or seven precision surveying markers were installed in the pit walls at each of 14 levels which were surveyed once a year from 1967 to 1978. Stratigraphy and density profiles were taken from an analogous firn pit in the immediate neighborhood (Ambach and Eisner, 1966). The pit is situated in the center of the accumulation area where the water equivalent of the average annual net accumulation for the period 1967 to 1980 amounts to approximately 1,3 m.

In spite of its position in the center of the accumulation area, the pit is not situated in a neutral zone as far as the strain rates are concerned. Detailed surveys of the surface velocity of Kesselwandferner by Schneider (1970, 1975) testify to the existence of longitudinal and transverse strains in that area.

Earlier bore hole and tunnel experiments in ice were evaluated by Nye (1953) according to the general flow law of ice. Further drill hole experiments have been reported e. g. by Hanson and Landauer (1958), Sharp (1963), Gow (1963), Savage and Paterson

(1965), and also by Paterson (1977). All abovementioned field experiments, however, refer to incompressible glacier ice. It is the aim of the present paper to gain new information on the rheological properties of the firn of a temperate glacier from strain rate measurements in a firn pit. Field experiments of this kind are superior to laboratory experiments insofar as in the field experiment the firn and ice structure and the stresses correspond to the natural conditions.

2. DISCUSSION OF RESULTS

Fig. 1 gives a qualitative representation of the pit deformation. The vertical scale appears shortened by the factor 0,87, as an angle of 30° between sight-line and horizontal plane was chosen. The drawing plane is identical with the flow plane. The following deformation effects become evident from fig. 1:

- The profile of relative displacements, i. e. inclination of the pit owing to higher flow velocity in the upper layers. The bottom level was chosen as the point of reference for both the initial profile and the end profile, fig. 1 thus shows differences in displacement (creep profile).
- Progressive immersion of the levels into the firn due to the vertical movement which is composed of the firn compression and the decrease in layer thickness because of tensile stress in the accumulation area. Table 1 reviews the depth of the level at the beginning and at the end of the measurements and the respective density values.
- The deformation of an approximately circular cross section into an elliptical one marked by the gauges arranged hexagonally. Because of the angle of 30° between the sight line and the horizontal plane, the above effect can only be seen in a perspective view.

Fig. 2a gives the cross section deformation for the highest level and the lowest level at the end of the measuring period. As the depths of the levels are not constant during the period of measurements the depth for 1975 was chosen arbitrarily for presentation. Dotted lines are those obtained by subsequent setting of additional gauges. For further evaluation, the cross section was approximated by an ellipse for each level and for each year. The accuracy of this approximation is demonstrated by two examples (Fig. 2b). The quantity $\frac{\sigma}{r}$ is to serve as a measure of the approxi-

Table 1: Depths, densities, and snow loads for individual levels in 1967 and 1978

	depth [m]		density [Mg/m^3]		load [kPa]	
level	1967	1978	1967	1978	1967	1978
11	2,00	18,30	0,650	0,845	10	139
11a	3,63	19,35	0,690	0,850	24	147
10	5,58	20,55	0,730	0,855	37	156
10a	7,16	21,65	0,750	0,860	49	166
9	8,61	22,55	0,770	0,865	60	174
8	9,71	23,50	0,780	0,867	68	182
8a	10,21	23,65	0,785	0,868	73	183
7	11,86	24,85	0,800	0,872	84	191
6	13,58	26,05	0,815	0,874	100	203
5	14,55	26,80	0,820	0,875	108	208
4	15,85	27,78	0,830	0,877	117	216
3	16,65	28,42	0,835	0,878	124	223
2	17,53	29,06	0,840	0,879	133	228
1	19,18	30,26	0,850	0,880	141	237

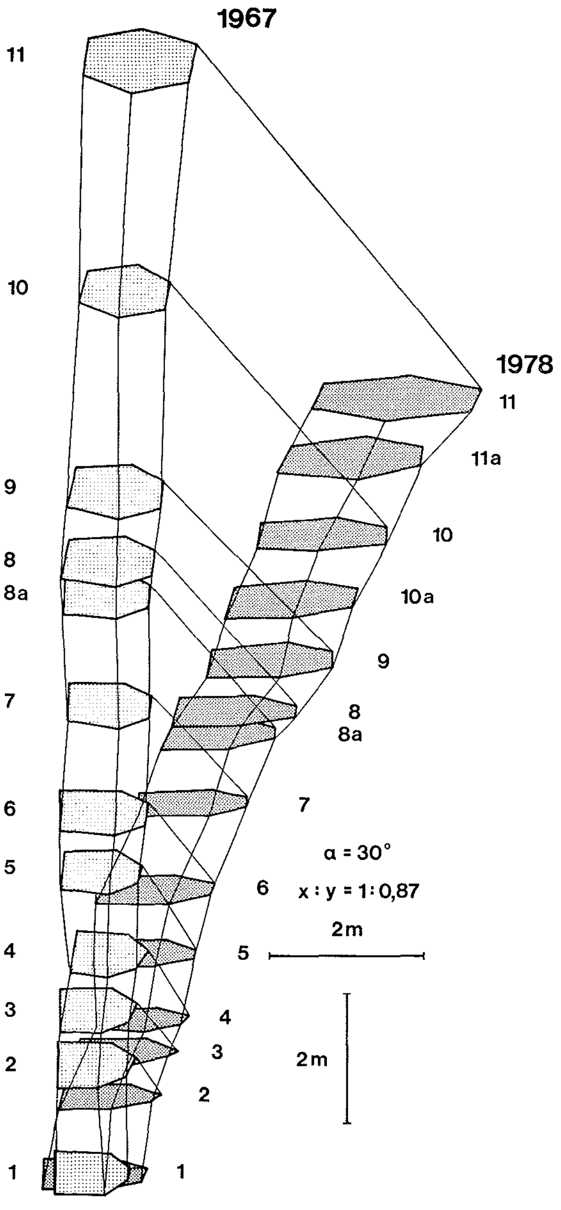

Fig. 1: Position of the markers at the beginning and at the end of the measurement period. The bottom level was made the zero point of the horizontal displacements. For level marking see tab. 1.

mation quality, σ being the standard deviation of the marker position from the ellipse and r being the radius of the initial circle. For the examples given in fig. 2b, σ/r is 1 % in the most favorable case (no. 7) and 7 % in the least favorable case

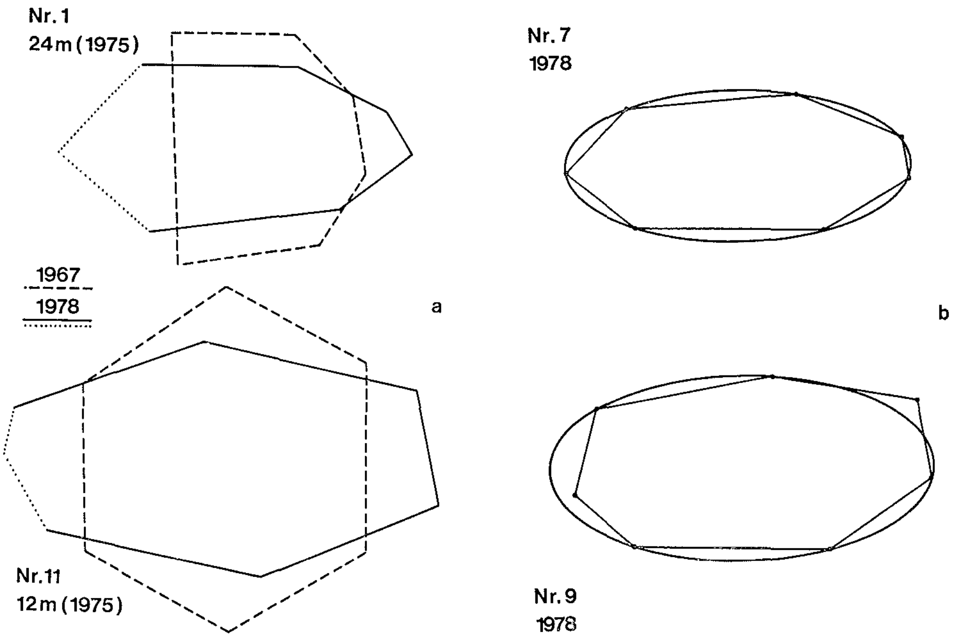

Fig. 2a: Deformation of the circular cross section in the top level (11) and bottom level (1).
b: Examples describing the quality of approximation of a cross section to an ellipse. No. 7: example of good approximation, No. 9: example of poor approximation.

(no. 9). The orientations of the axes of the ellipses determine the directions of the main deformations.

Fig. 3 shows the relative horizontal displacement of the ellipse centres for the entire

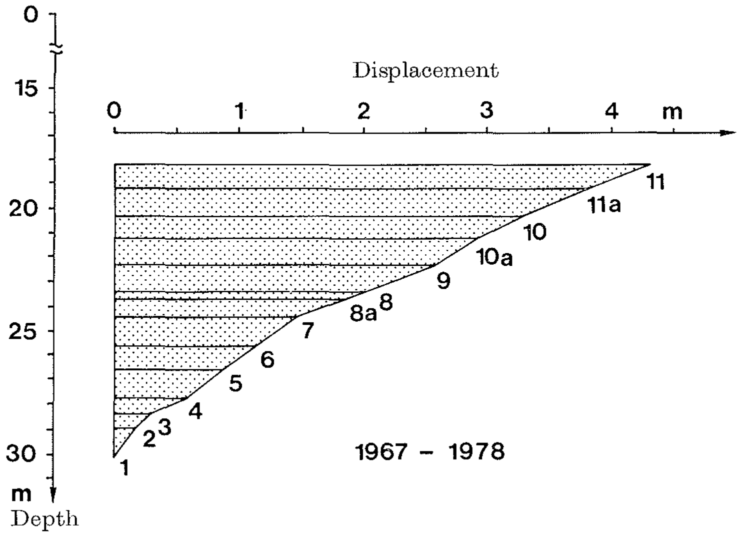

Fig. 3: Relative horizontal displacement as dependent on the depth (creep profile) at the end of measurement period. Reference point is the bottom level.

period of measurement (1967—1978). The lowest level was chosen as the point of reference, the relative displacement being zero. The displacement measurements refer to plummet. The lowest level immerses from 19 to 30 m during the 11 years of measurement. The entire length of the profile shrinks from 17 to 12 m at the same time (Table 1). This loss in thickness is caused by compression of the firn and by thinning of the layers owing to the tensile stress acting in the accumulation area. The profile of relative displacements may very well be approximated by a straight line. The gradient of velocity and the shear strain rate are thus approximately constant and independent of depth.

A linear profile of displacement is typically found in the creep of seasonal snow cover (McClung, 1980). However, measurements on bore holes in the ablation area yield a basically different displacement profile for ice. In this case, i. e., in compact, non-compressible glacier ice, parabolic profiles of displacements with a vertical tangent at the surface were measured in agreement with the flow law of ice (Savage and Paterson, 1963 and 1965).

A physical explanation of linear creep profiles in the snow pack so far has not been given. The interpretation of viscosity increasing with depth describes the linear creep profile only qualitatively without considering physical causes. Going one step further would mean to find out if the viscosity increase is going parallel with both the increasing stress by superimposed layers and the increasing solidification of firn. This permits an interpretation of the linear creep profile owing to metamorphosis (McClung, 1980).

Fig. 4 gives the decrease in layer thickness between the individual levels, ε_h being $\Delta h/h_0$, Δh the change in thickness and h_0 the initial thickness in 1967. The figures in the diagram describe the layers, 1 being the bottom layer between level 1 and 2, 10 the top layer between level 10 and 11. The lower layers (1—5) show less thinning than the upper layers (6—10). The mean value of the strain rate $\dot{\varepsilon}_h$ changes from $- 43 \cdot 10^{-3} a^{-1}$ in the upper layers, to $- 23 \cdot 10^{-3} a^{-1}$ in the lower layers. This diffe-

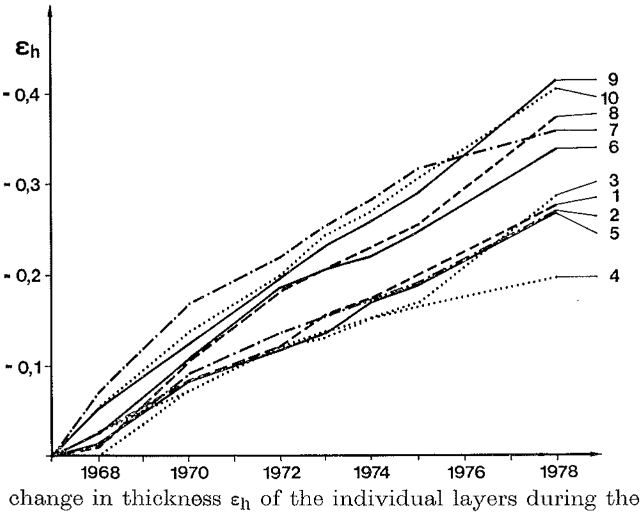

Fig. 4: Relative change in thickness ε_h of the individual layers during the measurement period. The negative sign means a thinning of layers. Layer No. 1, e. g., is the layer between level 1 and level 2 (cf. tab. 1). The levels 8a, 10a and 11a have not been used in this representation, as they were placed at a later time.

rence is due to two effects: the increase of snow load and the decrease of compressibility with depth. The result may be understood as a superposition of both effects.
In first approximation, the results of fig. 4 may be represented in a straight line. A more accurate examination reveals a higher strain rate during the first half of the measurement period.

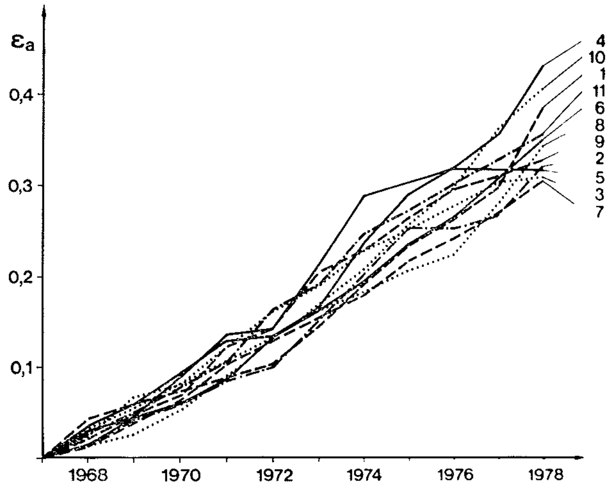

Fig. 5: Strain of the large axis of the ellipse during the measurement period. The positive sign means an elongation of the large axis. For level marking see tab. 1. The levels 8a, 10a and 11a have not been used in this representation, as they were placed at a later time.

Fig. 5 gives the strain of the large axis of the ellipse in all levels during the entire period of measurement, $\varepsilon_a = \Delta a/a_0$, with Δa being the change in the length of axis and a_0 the initial length of 1967. No dependence on depth and time was observed. The diagram shows approximately constant strain rate of about $33 \cdot 10^{-3} a^{-1}$ independent of depth.

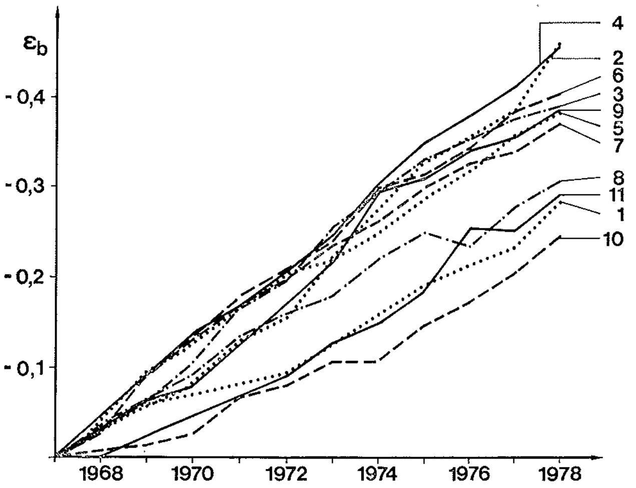

Fig. 6: Strain of the small axis of the ellipse during the measurement period. The negative sign means a contraction of the small axis. For level marking see tab. 1. The levels 8a, 10a and 11a have not been used in this representation, as they were placed at a later time.

Fig. 6 is an analogous representation referring to the small axis of the ellipse (cf. fig. 5), ε_b being a contraction effect. Except in level 1, ε_b was found to depend on the depth in such a way that the amount of the strain rate increases with increasing depth. The averaged strain rate over the measurement period varies from $-22 \cdot 10^{-3}a^{-1}$ in the upper layers to $-30 \cdot 10^{-3}a^{-1}$ in the lower layers. In this connection, level 1 must be looked upon as a fault level, whose lateral creep is inhibited by the pit bottom.

3. CONCLUSIONS

Strain rate measurements show that the firn of a temperate glacier has a shear deformation similar to that of the well settled snow pack. The linear depth profile of the horizontal displacement in contrast to parabolic profiles is measured in incompressible glacier ice. The change of an originally circular cross section into an ellipse is caused on the one hand by tensile stress prevailing in the accumulation area. On the other hand, the pressure of the superimposed firn layers causes the original cross section to contract due to lateral creep of firn. For determining the viscosity of firn, a stress-strain rate relation must be known. As the firn is a compressible medium having a multiaxial state of stresses with superimposed shear stress, the problem can probably be solved in terms of invariants of stress and strain rate tensors (McClung, 1974). The firn may furthermore be considered as an anisotropic body, because of its horizontal stratification. Studies are continued for setting up a suitable stress-strain rate relation describing the rheological properties of the firn.

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