Creep Problems in Soils, Snow and Ice[1])

Problèmes de fluage (rampement) dans les sols, la neige et la glace

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Sommaire

En manière d'introduction on souligne le rôle de premier plan joué par la rhéologie dans les recherches sur le fluage et l'on esquisse une brève comparaison entre les phénomènes de fluage observés dans la couche neigeuse, les sols et les glaciers. Sous la rubrique: essais en laboratoires, différentes méthodes sont passées en revue ainsi que les résultats obtenus dans les récents essais. Une comparaison sommaire est établie, sur la base des courbes de fluage, entre les phénomènes de fluage observés dans des matériaux divers. On souligne entre autre qu'en principe rien ne s'oppose à l'étude de l'état de contrainte dans les corps plastiques au moyen d'échantillons consistant en un matériau apte à fluer. Pour les phénomènes de fluage (rampement) qui se manifestent dans les montagnes, on démontre, en se fondant sur la formation des avalanches, qu'un processus de fluage aboutit progressivement à une rupture ainsi qu'on peut l'observer dans les éboulis et les glissements de terrain. Partant de quelques observations faites en Suisse, on commente les processus de fluage et de glissement dans des sols meubles, dans la roche et enfin dans une coulée rocheuse.

Pour conclure on trace une brève revue rétrospective du développement de la théorie des glaciers au cours de 200 dernières années. Prenant comme exemple le glacier d'Aletsch, on tente un aperçu sommaire englobant la grande variété des phénomènes de rampement, de fluage et de glissement entrant en jeu dans le mouvement des glaciers et l'on constate que la notion de viscosité apparente en facilite l'appréciation. La force érosive du glacier, qui a grandement contribué au modelé des régions alpestres, est étroitement liée au glissement de la glace sur sa base.

Introduction

In the Alps we are always coming across the manifold effects of creep phenomena which appear in the snow cover, in the soil or in the glaciers. They reflect not only the fact that these natural phenomena are ruled by time, but also the general characteristics of the creep and flow process which is closely related with the most diversified fields of materials engineering and of natural sciences. Creep is a process which affects, to some extent, not only all loose aggregates, but also all solids. Research on this process, which has barely started, requires the co-ordination of long-term laboratory tests and field observations.

Unlike elastic deformations, creep means the slow change in shape which takes place continually as a consequence of constant or continually changing shear stresses. In nature the shearing stresses which are an essential condition of creep are primarily a result of the force of gravity. Rheology is a branch of physics which deals with deformation and flow of materials, and is therefore competent for the estimation of the phenomena in question since it has worked out a basis for investigation, theoretical as well as experimental. According to the international rheological nomenclature, the scientific notion "creep" is restricted to cases of temporary deformations which slowly re-form after the removal of the load, whereas lasting deformation is termed "flow".

Although fundamentally the introduction of the rheological terminology is highly desirable for the study of the phenomena investigated here, at present it is almost impossible to distinguish strictly between "creep" and "flow" as defined by the nomenclature mentioned. The term "creep" is so widely used in soil mechanics as well as in geotechnical literature or in the publications on snow and concrete research in the meaning of continuous and permanent deformations that it would be misleading, particularly for the engineer, to replace it by the term "flow". Only the glaciologist does not apply the term of "creep" when speaking of the motion of the glaciers, but terms it "flow" in accordance with the new rheological terminology. In the following article both terms are used as synonymous.

I should like to say a few introductory words to outline some facts and problems concerning the creep process within different materials. Creep or flow processes within the snow cover are particularly distinct and therefore suitable for observation purposes (Fig. 1). The internal deformation that occurs continually within an inclined layer of snow yielding under its own

[1]) Revised and supplemented version.

weight, which is due to the metamorphosis of snow, clearly shows two components: i.e. a settling component which is perpendicular to the surface of the slope, and the creep component proper, caused by shear stresses, which appears as a displacement parallel to the slope. Furthermore there frequently occurs a slow sliding of the whole snow layer along its base.

Creep movements are of great magnitude in the glaciers (Fig. 2). The "flow" of the glacier results not only from the continuous internal deformation of ice, but also from the coordination of creep process proper with slides which chiefly occur at the glacier bed, or less often along discontinuity planes and planes due to shear failures inside the glacier. This demonstrates again the affinity with similar processes observed in soils and in the snow cover.

The following relationship shows that the creep phenomenon should be considered not only as an interesting characteristic of the material, but also as a factor contributing to the creation of loose rocks; by creep-flow and slide of the ice, in turn considerable quantities of morainic material are carried inside the glacier and on its surface. In saying so I have in mind the glaciers of the ice ages which once covered the Swiss Central Plain and gave it a new shape, partly through erosion and partly through the enormous glacial deposits they left. Certain loose rocks owe their origin to the creep motion of the glaciers. On the other hand, *W. Penk* (1924) proved that the upper soil layers, exposed to weathering, creep slowly towards the valley just as a glacier does, even when the inclination of the terrain is slight.

The technical and physical problems thus arising are no less complex than creep itself: for example, the creep movements of natural slopes affect their stability and may endanger the structures built on them. Such structures must either be capable of adaption to these movements or made secure. In the latter case, the question arises as to the magnitude of the creep pressure. The determination of creep pressure is therefore the fundamental problem in avalanche protection works in the areas of release of avalanches, in other words, the question arises how to support the creeping snow layer by resistant structures in order to prevent the release of avalanches (Fig. 2a). The problem is much more difficult in the case of a structure "suspended" in a creeping soil. The structure has to be made stable, as was the case with the bridge built across the river Landquart at Klosters (*Haefeli, Schaerer, Amberg*, 1953) (Fig. 3). The left abutment of the arch had to be braced against the right abutment by means of a horizontal strut of reinforced concrete the size of which had been determined so as to withstand the creep pressure. Once the bridge had been reconstructed, we tried to establish the magnitude of the creep pressure, and its changes with time. This was done on the basis of the measured changes in the length of the horizontal strut. However this is possible only if creep within concrete, that can be considered as an artificial rock, has been taken into consideration. With due regard to the basic preliminary work of

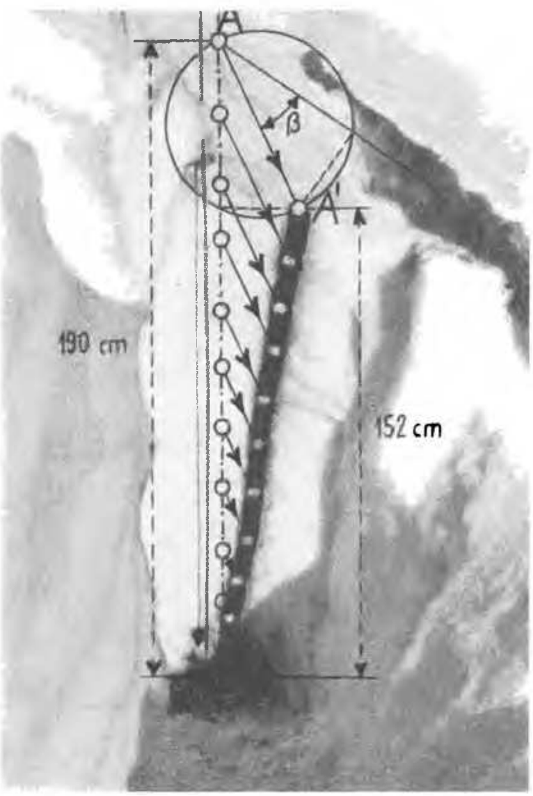

Fig. 1 Creep Profile of the Snow Cover—Test Time 66 Days, 2660 m above Sea Level
Profil représentant le fluage (rampement) dans la couche neigeuse – Durée de l'essai 66 jours, altitude 2660 m au-dessus du niveau de la mer


Fig. 2 The Géant—or Tacul—Glacier and Mont Blanc seen from the Aiguille du Dru
Le glacier du Géant – ou Tacul – et le Mont Blanc vus de l'Aiguille du Dru (photo A. Roch)

Fig. 2a Avalanche Protection Work in Breakaway Zone—Light Metal Snow Bridge
Ouvrage de protection dans la zone d'arrachement – Pont de neige en métal léger (photo Lehner, Sirnach)

the rheologists (*Bingham* and *Reiner*, 1953) it is largely thanks to the recent development in pre-stressed concrete that we have become better acquainted with the creep processes in concrete (*Birkenmaier*, 1952).

Natural rocks are also subject to certain creep processes, the investigation of which is of practical as well as of scientific interest. On the one hand, the evaluation of the pattern of stresses in large concrete dams, which changes with time, con-

Fig. 3 Landquart Bridge (Rhaetian Railway Company) after Reconstruction in 1944
Pont de Landquart (Compagnie des Chemins de Fer Rhétiques) après reconstruction en 1944

Fig. 4 Formation of Folds in the Snow Cover Sliding Slowly on a Grassy Slope—Davos, December 1936
Formation de plis dans la couche neigeuse glissant lentement sur un versant herbeux – Davos, décembre 1936 (photo R. Haefeli)

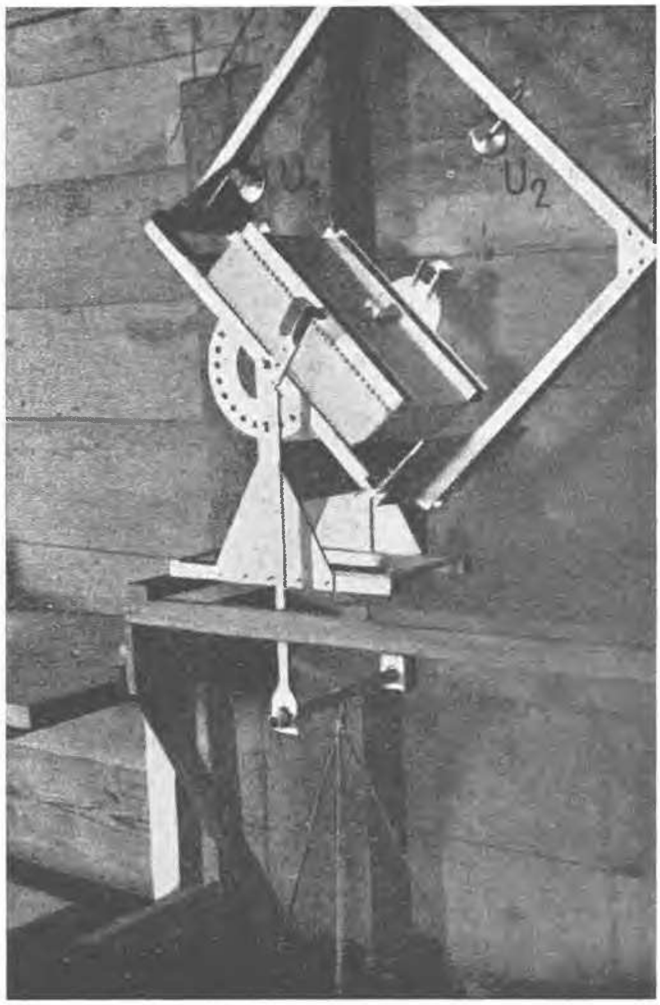

Fig. 5 Device for Creep Measurements Within the Snow Cover (Slope of the Snow Layer 45°, Dial Gauges U_1 and U_2) see Mitteilungen No. 2, Versuchsanstalt für Wasserbau und Erdbau, Eidgenössische Technische Hochschule Zürich
Dispositif pour la mensuration du fluage (rampement) dans la couche neigeuse (inclinaison de la pente 45°, comparateurs U_1 et U_2) cf. Mitteilungen No 2, Versuchsanstalt für Wasserbau und Erdbau, Eidgenössische Technische Hochschule Zürich

fronts the civil engineer with problems in which not only creep within the concrete, but also possible creep processes in highly stressed zones of the rock foundation have to be taken into consideration. On the other hand, it is quite probable that the slow and rupture-free deformations of the earth's crust are partly attributable to creep processes which, for very high temperatures, near melting point, are related to those of glaciers, and for normal temperature, to those of a concrete whose long hardening process is completed. Also the magnificent structure of the Alps, and of other mountain systems all over the world, bring the geologist and the mineralogist closer to creep and flow problems in rocks (*Cadisch*, 1953) which are related to the whole tectonic of mountain formation (*Terzaghi*, 1953; *Lugeon*, 1922). On a small scale, even the snow layer demonstrates how, for temperatures close to the melting point, the combined actions of slide and creep processes can lead to the formation of folds (Fig. 4). Creep processes bring theoretical science as well as practice close to complex and fascinating problems which call for the increased co-operation of geologists, rheologists and engineers if they are to be solved.

Laboratory Tests

The possibility of investigating independently in laboratory tests certain phases of the creep process, or certain influences contributing to this process, should be evaluated in full awareness of the fact that these phases are merely components of the natural process as a whole.

One of the simplest ways to carry out creep tests is to use dry snow with which the most important natural conditions can be relatively easily imitated, and which already creeps intensively under the sample's own weight.

A possible arrangement of a test which permits the observation of the deformation of an inclined snow cover evenly loaded on its surface is exemplified in Fig. 5. The results of such tests show that, with a given inclination of the layer, the creep angle β—i.e. the angle formed between the movement direction of a point on the surface and the latter—as well as the rate of creep, diminish with increasing settlement and solidification of the snow. This process is accompanied by a change in the stress pattern in accordance with known laws (*Haefeli*, 1942).

Considerably more difficult and time-consuming are the creep tests with fine-grained saturated soils such as clay and loam. As a result of an additional liquid phase in a highly dispersed system, the number of the variables increases when compared with dry snow. Therefore it is imperative to distinguish between creep tests in an open system (drained), in which pore water can flow away freely, and tests in a closed system (undrained). Furthermore it should be noted that the degree of water saturation connected with the vapour phase plays an important part. Since all possible combinations are to be found in nature, the field covered by this branch of basic research in soil mechanics extends accordingly. The effect of temperature on the creep process within unfrozen soils, which is still almost unknown, should not be neglected a priori. On the other hand, it is obvious that soil creep in permafrost regions raises problems which can be solved only in research closely linked with soil mechanics, ice mechanics and glaciology (*Terzaghi*, 1952).

The ring-shear principle can be applied in investigating creep processes in clayey soil samples, consolidated and drained (open system), but then the disturbing effects exerted by the lateral friction should be taken into account and reduced as much as possible (*Haefeli*, 1942).

When after consolidation a soil sample is subjected to a continuous shear stress with unchanged vertical stress, the major total principal stress increases, which results firstly in pore water being stressed again, i.e. in a change in the neutral stress. The subsequent stress metamorphosis comprises the relaxation of the pore water pressure and a corresponding change in size and direction of the effective principal stress. As is the case for an inclined snow layer and all open systems,

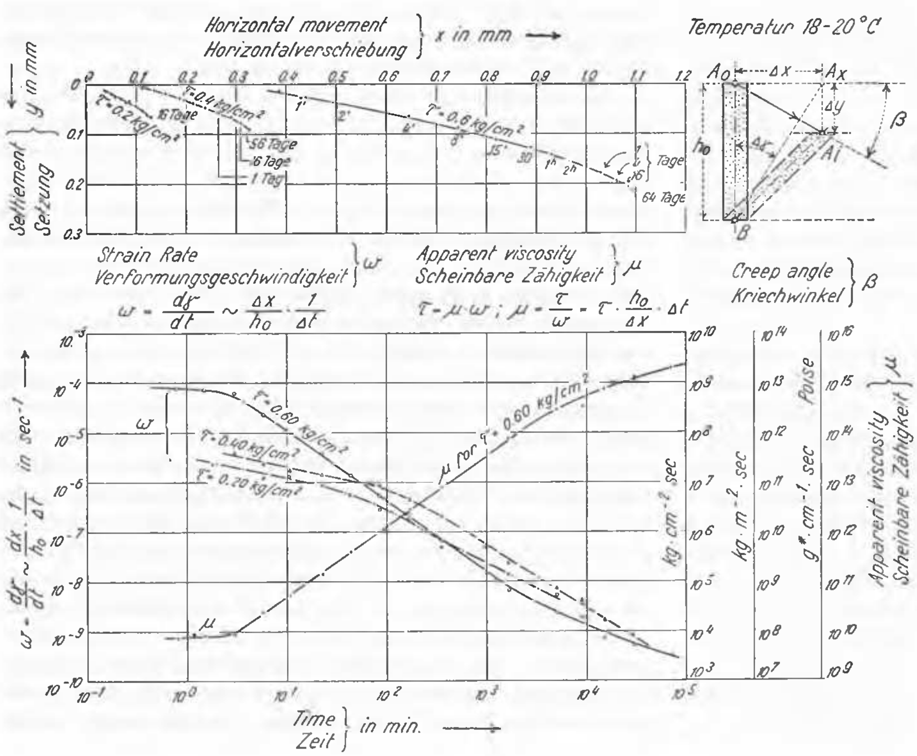

Fig. 6 Creep Tests in Ring-Shear Apparatus
Essais de fluage dans l'appareil de cisaillement à couronne cylindrique

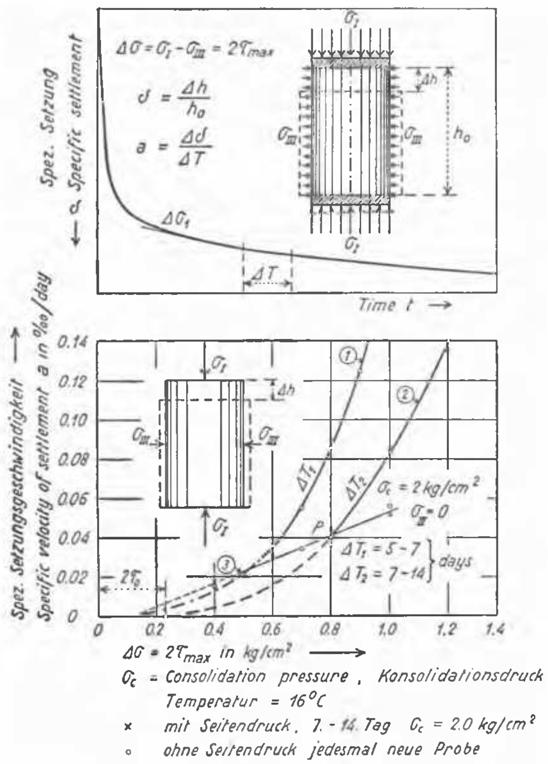

Fig. 6a Creep Tests in Triaxial Apparatus (in Outline)
Essais de fluage dans l'appareil triaxial (schématique)

the creep process is accompanied by settlement (Fig. 6). In plotting the displacement components in a horizontal, respectively in a vertical direction, we obtain the true movement of a point on the surface (creep angle β), whereas from the continuously decreasing inclination of the original vertical line A–B, the angular velocity $\omega = D$, and so the apparent mean viscosity μ of the material, can be approximated by calculation. Accordingly Fig. 6 shows (top) the true creepage path $A_0 — A_i$ of the clay samples No. 4002, consolidated under $\sigma_c = 2$ kg/cm² in the ring-shearing apparatus, which underwent a creep process with different shear stresses τ for 56–60 days. From this representation we see, on the one hand, that the creep curve becomes gradually steeper in the course of a single creep test (increase of the creep angle β during approximately 2 months). When comparing the creep paths thus obtained for different shear stresses ($\tau = 0{,}2 — 0{,}8$ kg/cm²) we see on the other hand that their mean inclination decreases with the shear stress because the horizontal component of the creepage path ($A_0 — A_i$) shows a more substantial increase with τ than its vertical components.

We have shown elsewhere how, on the basis of this exposition, the stress metamorphoses connected with the creep process, i.e. the change in size and direction of the principle stresses, can be approximatively computed (*Haefeli*, 1942). Particularly worth observing is the fact that the apparent viscosity of the saturated clay investigated (No. 4002) strongly increased in the course of a 2 months' creep process (under water) in spite of the relatively slight change in water content. In order to illustrate this fact Fig. 6a (bottom) shows the strain rate, as well as the change in the apparent viscosity versus time for the above mentioned tests in the ring-shear apparatus. So far, it has not been satisfactorily explained to what extent the striking increase in the apparent viscosity calculated from the test data is attributable to thixotropic effects or other influences.

Special attention should be accorded to the fact that in an open system, the normal increase in the rate of skin creep versus shear stress is valid only in the beginning of the creep process when the various samples have the same void ratio. As a result of increasing consolidation during the first period of the creep process, the rate of strain of the sample with the highest shear stress, after some time, is the smallest [cf. μ curve in Fig. 6 (bottom) for different shear stresses]. This fact exemplifies one of the fundamental differences between creep process in open and in closed systems.

We are indebted to *E. C. W. A. Geuze* and *Tan Tjong-Kie* (1953) for considerable improvement in the method of investigating creep processes. They have developed a torsion plastometer which renders it possible to test the resistance to torsional stress of a sample in the form of a hollow cylinder, as we have proposed for creep tests with ice (*Haefeli*, 1948). This experimental set-up which is particularly suitable for constant volume deformations (closed system) renders it possible to create an unvarying and relatively homogeneous state of stress. The state of stress in the triaxial test is less homogeneous but, on the other hand, this test is remarkable because of its simplicity and general applicability. Fig. 6a shows the basic arrangement of such tests in the triaxial cell: after consolidation a cylindrical soil sample enclosed in a rubber sleeve is loaded under a vertical stress σ_I that is smaller than the consolidation pressure σ_c. These tests are carried out with or without lateral pressure σ_{III}. The settlement curve obtained with unconfined lateral expansion and constant volume of the sample provides a criterion for the creep process. The specific rate of settlement (a) can be taken as an indication of the rate of creep. Otherwise the change in volume of the sample has to be measured on the spot, and should be taken into account in plotting the test. Creep—or flow—starts with a certain critical shear stress τ_0 which may amount to a small fraction of the shear strength, and the rate of deformation increases with increasing shearing stress. As illustrated in Fig. 6a, the increase depends on the phase of the creep process under investigation, i.e. on the stress history and on the deformation prior to testing. With increasing water content, the flow curve becomes steeper and the critical shear stress accordingly smaller. At the liquid limit, the material behaves like a viscous liquid ($\tau_0 = 0$).

A saturated sample consolidated under $\sigma_c = 2$ kg/cm², with gradually increasing shear stress τ, showed the relatively pronounced flow curves 1 and 2; the first corresponds to the average rate of settlement during the period ΔT_1 (5th–7th day), the second to the period ΔT_2 (7th–14th day). In another series of experiments carried out with uniform consolidation under $\sigma_c = 2$ kg/cm² a fresh sample was used for each creep test with constant shear stress. These tests, like *Geuze* and *Tan Kjong-Kie*'s (1953), showed an almost rectilineal flow line (3); the extrapolation towards the left side indicates an extraordinarily small critical shear stress τ_0. Subsequently two parallel samples were tested for each shearing strength: one with lateral pressure of 0.75 kg/cm² and the other without. No noticeable effect of the lateral pressure σ_{III} on the rate of flow was observed. We must take into consideration that up to now the stresses were chosen in such a way that no stressing of the pore water took place, the maximum value of the first principal stress during creep being still sufficiently below the consolidation pressure. On the basis of the measured specific rate of settlement a, the determinative angular velocity (strain rate) yields $\omega = 1.5\,a$ for samples of a constant volume, whereas the apparent viscosity may be computed with the formula $\mu = \tau/\omega$ (*Haefeli* and *Schaerer*, 1946). For the point P on the curve 3, we arrived, for example, at the following values, among which the viscosity coefficient η proposed by *Geuze*, corresponding to the gradient of the *Bingham* straight line, is indicated:

Numerical examples: Residual clay 4002.

Plasticity index		$= 34\%$
Consolidation pressure		$= 2$ kg/cm²
$\Delta\sigma$	$= 0.8$ respect. τ	$= 0.4$ kg/cm²
a	$= 0.04\%$ o/day	$= 0.465 \cdot 10^{-9}$ sec⁻¹
ω	$= D = 1.5a$	$= 0.7 \cdot 10^{-9}$ sec⁻¹
μ	$= \tau/\omega$	$= 5.6 \cdot 10^{14}$ Poise
η	$= \tau - \tau_0/\tau \cdot \mu$	$= 4.8 \cdot 10^{14}$ Poise

The apparent viscosity μ of the consolidated sample thus determined is almost identical with the value obtained in the ring-shear-apparatus after the corresponding creep time (see Fig. 6).

Geuze and *Tan Tjong-Kie*'s tests carried out in clay by means of the torsion plastometer indicated that between the critical shear stress τ_0, on the one hand, and a top value τ_2, on the other hand, the strain $D = \omega$ increases linearly with τ. This behaviour which was confirmed in the tests carried out by the Laboratory for Hydraulic Research and Soil Mechanics at the Swiss Federal Institute of Technology (Fig. 6a, curve 3) corresponds for $\tau < \tau_2$ to the so-called "Bingham body" the flow curve of which is shown in Fig. 7 together with other typical curves. Such a comparison reveals the close rheological affinity between viscous liquids, clay and ice. This affinity appears also in the so-called "recovery" of the material after unloading, as shown in *Geuze* and *Tan Tjong-Kie*'s investigations on clay (1953) and, in another form, it is also noticeable in the elasto-plastic behaviour of ice.

Of importance for the stability estimation of natural and artificial slopes, particularly of earth dams, is the question of the effect of the creep process upon the strength of the material in a closed as well as in an open system. It appears from the investigations carried out by *A. Casagrande* and *Wilson* (1950) that this effect is often considerable and that it may be either favourable or unfavourable according to the type of material. It is reassuring to know that for an artificially compacted dam material, a slow load increase causing creep previous to rupture results, as a rule, in an increase of the shearing strength of the material. A clayey subsoil may behave quite differently. Corresponding tests have been carried out at Harvard University since 1948.

For the sake of comparison, the effect of the creep process on the strength of the clay tested (No. 4002) was subsequently investigated. The individual tests yielded the results compiled in Table 1. Regarding these values it should be noted that the slight differences found in the ring-shear apparatus between the shearing strength before and after 2 months' creep are within the range of possible scatter. On the other hand, the triaxial experiments showed a certain increase in the compression strength in the course of the 14 days' creep process. This increase amounted to approximately 20–30% for a maximum shearing stress of 0.5 kg/cm², applied during the creep process (see Table I, max. deviator stress $d_k - \sigma_{III}$).

Triaxial tests are also suitable for investigating creep in ice samples; we shall refer only briefly to this point. The types of ice encountered in nature are polycrystalline solids, the temperature of which is relatively close to the melting point. As emphasized by the late Prof. *P. Niggli*, creep, or flow, in ice is, as a rule, a heat-conditioned deformation which is comparable to those taking place in metals of hexagonal structure,

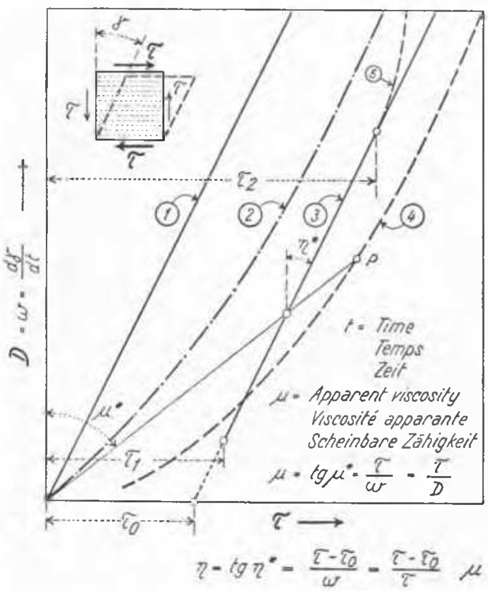

Fig. 7 Typical Flow Curves
Courbes typiques de fluage (rampement)
1 = Newtonian Liquid – Liquide Newtonien
2 = Non-Newtonian Liquid – Liquide non Newtonien
3 = Bingham Body – Corps de Bingham
4 = Ice – Glace
5 = Clay – Argile

such as zinc and magnesium, at high temperatures. The lower the temperature, the stiffer the ice becomes. According to *S. Steinmann* (Internal Note No. 145, Federal Institute for Snow and Avalanche Research, Weissfluhjoch), besides temperature, impurity plays a decisive part since a clear ice behaves more rigidly than a dirty one. Further, experiments carried

Table 1 Effect of Creep on the Shearing Resistance of a Clay

Ring-Shear Tests			*Triaxial Tests*			
Open System (Drained)			*Closed System (Undrained)*			
T	τ	s_k	σ_{III}	T	τ	$d_k - \sigma_{III}$
			0	14	0.2	1.08
16	0.2	1.02	0	14	0.35	1.18
56	0.4	0.95	0	14	0.4	1.17
64	0.6	0.97	0	14	0.5	1.29
			0.75	14	0.2	1.02
			0.75	14	0.3	1.08
			0.75	14	0.4	1.12
			0.75	14	0.5	1.21

Test material: clay 4002 from the talus at the bottom of the Uetliberg, Zurich
Liquid limit = 40.9%; Plastic limit = 16.9%; Plasticity index = 34%
Pore water content = 25%; Consolidation pressure = σ_c = 2 kg/cm²
Water content after shearing ~ 21% (saturated sample)
τ = Shear stress during the creep process in kg/cm²
σ_{III} = Lateral pressure in triaxial apparatus in kg/cm²
σ = Vertical stress in ring-shear apparatus = 2.0 kg/cm²
s = Shear strength (drained) in ring-shear apparatus (approx. 8 h) = 1.03 kg/cm²
s_k = Shear strength after creep in ring-shear apparatus in kg/cm²
d = Resistance to compression (triaxial test, 8′ with σ_{III} = 0.75 kg/cm²); $d - \sigma_{III}$ = 1.0 kg/cm²
d_k = Resistance to compression after creep (triaxial test) in kg/cm²
T = Duration of the creep test in days

Fig. 8 Barn Lifted off by Creep (Glide) within the Snow Cover (Gulmen near Amden, 1953)
Grange soulevée par le rampement de la couche neigeuse (Gulmen près d'Amden, 1953)

out on this subject at the Laboratory of the Federal Institute for Snow and Avalanche Research at Weissfluhjoch, Davos, showed that we ought to distinguish, for monocrystalline as well as for polycrystalline ice, between the "undeformed" and the "deformed" state. As a result of deformation without failure, ice apparently becomes more rigid while a structural stabilization is taking place, especially in polycrystalline ice. The experimental evidence brought by English investigators that creep and flow velocity in ice increases exponentially with shear stress (*Glenn*, 1952; *Perutz*, 1950) was confirmed by the Weissfluhjoch experiments (compare Fig. 7, curve 4). According to other experiences gained up to now it seems that an additional hydrostatic pressure, which influences the melting point, accelerates the rate of deformation, and diminishes the apparent viscosity; nevertheless this effect is one of the numerous and still unsolved questions in the field of creep research (*Renaud*, 1949).

A comparison between creep processes in snow, soil and ice, including also *Winterkorn*'s theory, i.e. that the water film adsorbed by the soil particles presents ice-like properties, due to its high pressure, deserves special attention (*Winterkorn*, 1943; *Tschebotarioff*, 1951). Accordingly increased attention should be devoted to the investigation of the effect exerted by temperature on creep-flow processes in fine-grained soils, such as clay and loam.

The future development of soil mechanics will be closely connected with creep research, for creep plays a part, open or hidden, in almost all soil mechanics phenomena. Creep takes place as long as the critical shear stress τ_0 is exceeded. This applies universally: to the loading tests on a small as well as on a large scale, to the settlements of shallow foundations as well as of pile foundations. Even to day very little is known about the part attributable to creep processes during the consolidation which takes place in the oedometer and in the triaxial apparatus. It is necessary to consider that even the mere fact that two individual grains come nearer to each other, which is a very elementary deformation process in soil mechanics, is rendered possible only provided that a local deformation, partly due to creep, takes place at the contact zone, either in the solid phase or in the viscous water film. So also the slow three-dimensional decrease resulting from a hydrostatic external pressure is partly due to local creep processes between the individual grains. In this case there are no external but only internal shear stresses, i.e. in the contact zone of the grains. Even more, a settlement taking place slowly in a vertical direction only, as e.g. in the oedometer, or in a horizontal soil layer, includes internal creep phenomena. These hidden creep processes which may also play a part in the so-called secondary time effect are closely connected with those changes in the state of stress versus time, which are not controlled by the hydrodynamic stress phenomena (porewater pressure).

The above problem which includes the continuous changes in stress due to creep is not without importance for the future development of earth-pressure theories, for the determination of the stability conditions of earth dams and slopes or the stress distribution under concentrated loads.

For example, the horizontal pressures acting on the vertical planes of symmetry of a central dam core built of plastic material depend to a great extent on the compressibility and on the creep tendency of the embankments on both sides of the impervious core. The more rigid the embankment subjected to horizontal stresses, the higher are the lateral pressures in the plastic core, and thus the shearing stresses in the dam foundation. Similar conditions apply to retaining walls with clayey backfilling where the variation in the earth pressure with time depends on the rigidity of the wall. It is well known that retaining walls founded in loose rocks undergo a noticeable rotational movement in the course of decades.

The considerations mentioned above show that future laboratory research on creep should include also long-duration observations on cohesionless soils such as those used for the construction of embankments. Besides the creep process within weathered and unweathered rocks should be further investigated; this would be of interest from the geological as well as from the technical point of view (*Terzaghi*, 1953). A comparative study of creep processes in completely different materials, such as snow and ice, clay, loose and hard rocks, concrete, bitumen, etc. would provide welcome information.

It has been demonstrated elsewhere that there exists a well-defined relationship between the creep vectors of a two-dimensional creep process and the direction of the principal stresses (*R. Haefeli*, 1942). Therefore, it should be basically possible to investigate the state of stresses within creeping bodies of any shape, as well as its changes in the course of the creep process, by means of tests providing that the critical shear stress of the material under investigation either is zero or is sufficiently small, and that methods are devised which render possible accurate measurement of the creep vectors in the interior of the test sample.

Furthermore, valuable contributions with a view to supplementing laboratory tests could be furnished by field experiments; precise measurements of creep and settlement observed in completed constructions, particularly earth dams, and in the subsoil of concrete dams as well as in natural slopes would be useful. Important in the three-dimensional displacement measurements of individual points is, first of all, the exact determination of the horizontal component, of the creep angle and of possible yearly rhythms.

Creep Processes in the Mountains

The parallel that follows is intended to throw light on the common features in the natural creep processes which—partly combined with slides—take place in snow, soil, rocks and glaciers.

Snow cover

Depending on roughness and temperature conditions of the ground surface, the creep of the snow layer takes place either combined with, or without any sliding movement over the subsoil. The creep pressures exerted on fixed objects are greatly increased when sliding occurs. Fig. 8 shows a small building which has been lifted off its foundations and shifted downhill for 8–10 m by the sliding snow cover.

The natural snow cover, which as a rule consists of layers parallel to the slope with widely varying properties in space and time, is particularly suitable to demonstrate the interplay of creep, state of stresses and stability. The loose intermediate layers, which are of primary importance for the stability of the whole snow cover, are clearly visible in the dynamic penetration diagram of Fig. 9.

The stability conditions become particularly unfavourable if the slope flattens towards the top or if it changes into a ridge. On account of the creep process being impeded at the upper end of the slope, additional longitudinal stresses develop in the wind slabs above the plane of discontinuity. The gradual increase of the tension Z with increasing creep may cause cracks if it is not accompanied by an adequate increase in the tensile strength of the corresponding layers. The fact that tensile strength up to 10 tons/m^2 have been measured at the crack face furnishes evidence that the snow cover is partly anchored on the top.

As a result of the force displacement due to the formation of a tension crack, the shearing resistance is suddenly overcome in the plane of discontinuity parallel to the slope; this is often combined with a structural breakdown of the sliding layer. The compressive strength in the zone of pressure is almost simultaneously overcome, whereupon a clearly visible shear crack appears (Fig. 10). The wind slab avalanche is therefore a striking example of progressive rupture. Furthermore it gives us some indication of the natural interplay between creep process and stress metamorphosis within the snow cover, that gradually leads to the critical state of stresses which, at the slightest disturbance, causes the formation of cracks. The process is very adequately called "the maturing" of the avalanches. This biological term strikingly expresses how an avalanche, like a fruit from the tree, falls when it is fully ripe.

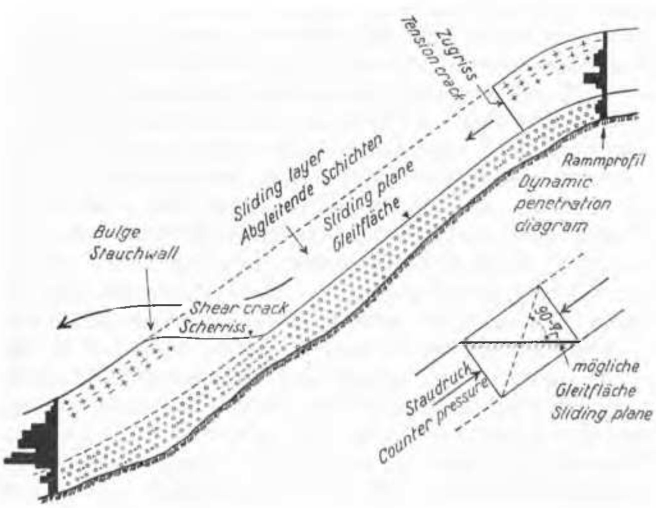

Fig. 9 Graph Representing a Wind-Slab Avalanche (Longitudinal Section)
Schéma représentant une avalanche en planche de neige (coupe longitudinale)

Fig. 10 Breakaway of a Wind-Slab Avalanche (Nüllisgrätli)
Niche d'arrachement d'une avalanche en planche de neige (Nüllisgrätli) – Photo E. Meerkämper, Davos

On this fact are founded not only long-distance launching of avalanches often observed, but also their release by acoustic phenomena and by mortars.

Slopes of loose and massive rocks

Rupture processes similar to those in wind slab avalanches often occur on rock slopes with stratification parallel to the slope. A tragic example is the rock slide which occurred at Arth-Goldau on 2nd September 1806 where a 30 m thick conglomerate (Nagelfluh) layer, inclined at approximately 24°, which lay on marly sandstone with intercalations of a bituminous marl layer, 2–3 m thick, slipped down to the valley. Besides the causes mentioned by *Terzaghi* (1951), the overcoming of the tensile strength of the upper layers of molasse-sandstone in the tension zone may have played a considerable part. The development of tensile stresses in the relatively rigid rock layers can be explained as a tendency to creep exhibited by the intermediate marl layers, as is the case with the formation of the tension zone in wind slabs which lie on loose intermediate layers and are anchored in the upper part. The general view of the rupture zone illustrated in Fig. 11 makes evident the external similarity of rock slides and wind slab avalanches. The volume of the rock mass involved in the Rossberg slide was estimated about 15 million m^3 from the size of the breakaway, which is 320 m in width and approximately 1500 m in length. The total length of the slide path is about 4.5 km and the total slide area about 20 km^2. As far as the climatic conditions are concerned it should be noted that the year 1806 had been preceded by some exceptionally rainy years and that the rainfalls during the months of July and August had been heavy. This is the largest rock slide recorded in Swiss history; it claimed 457 lives, and 111 houses, 2 churches and 200 stables and barns were destroyed (*Alb. Heim*, 1882; *Schweizer Alpenklub*, 1911).

Fig. 11 Breakaway of Goldau Rock Slide—2nd September 1806
Niche d'arrachement de l'éboulement rocheux de Goldau – 2 septembre 1806

Fig. 13 View from Piz Beverin over the Slide and Creep Area of Heinzenberggrat
Vue prise du Piz Beverin sur la zone de glissement, respectivement de fluage (rampement) de Heinzenberggrat (photo Dr H. Jäckli)

In slides on natural slopes of cohesive material, which flatten towards the top, we generally observe bowl-shaped sliding planes (Fig. 12). As according to the rupture theory, the first principal stress forms a known angle α with the plane of rupture, the shape of the sliding plane gives valuable indications about the local stress pattern which started the rupture. We notice that even here at the upper edge of the slope, not only compressive, but also tensile stresses have been effective, while at the foot of the slope relatively flat first principal stresses prevail. The vertical earth cracks often observed at the upper edge of the slope are the results of the combined action of shear and tensile stresses.

The creep process which precedes the slide depends on the original stress pattern, but, on the other hand, it causes a change in the state of stresses with time as well as in the strength of the material. When the shear or tensile strengths are overcome at the weakest point, a sudden displacement of forces takes place with a local loss of cohesion. This process, even under the most favourable conditions, i.e. when the material was completely consolidated before the rupture, may develop local pore water pressures at the foot of the slope. The intensity of the forces displacement resulting from the rupture proceeding from the top downwards is in proportional ratio to the part played by cohesion in the shearing strength. Therefore the danger of progressive rupture is particularly great in highly cohesive materials (*D. W. Taylor*, 1948).

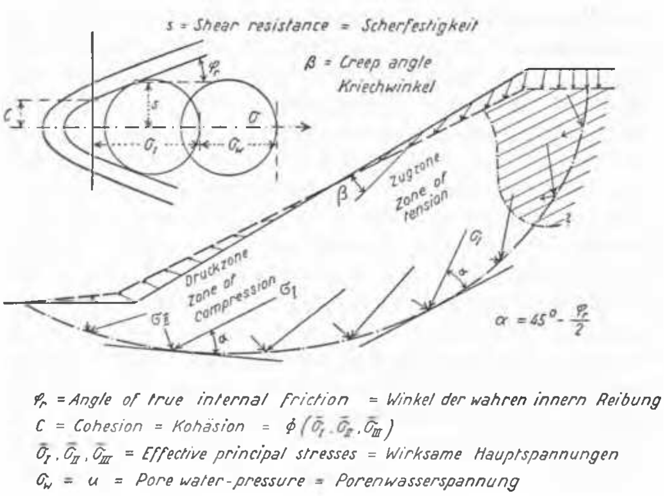

Fig. 12 Shear and Pressure Zones on a Slope with Formation of Slide Planes
Zones de cisaillement et de pression avec formation de plans de glissement

Often, when tension cracks are formed in the sagging area, the slides do not proceed rapidly, but slow movements take place over years, decades and even centuries. They mostly result from a combination of creep and slide processes, similar to those within the snow cover. Fig. 13 shows the sagging zone of a soil movement at the Heinzenberg, described by *H. Jäckli* (1948, 1953), which covers an area of approximately 40 km² consisting of "schistes lustrés". Such creep and slide movements often take place when the strata are parallel to the slope or, as in the mentioned region, when the inclination of the strata is flatter than that of the slope surface. In the latter case erosion at the foot of the slope brings one after the other a series of new sliding planes into action. The surface movements measured in the years 1910–1931 by the Federal Geodetic Survey and the Federal Inspection of Public Works at the southern Heinzenberg, which is exposed to marginal erosion by the powerful Nolla torrent vary on the average between 10 and 26 cm a year at a mean slope of about 25%. These relatively high creep velocities indicate a deep-seated movement which is thought to be a combination of creep and slide processes. The magnitude of the strongly distorted strata at the foot of the slope involved in the movement has been estimated at 50–150 m by the geologist *H. Jäckli*.

It is particularly striking that such creep and sliding processes—with the exception of some velocity fluctuations—often take place with some regularity over several decades. This fact accords on the one hand with our knowledge of the almost constant creep velocity observed in undrained clay samples subjected to constant shear stress; on the other hand this seems to indicate that the loamy water-lubricated layer surfaces combined with the lamellar structure of the "schistes lustrés" facilitates the progress of the movement.

The Heinzenberg slide comprises creep and slide movements of rock masses which consist mainly of distorted rocks. The Klosters slide, to which reference has been made in the introduction, exhibits the slow movement of a loose rock with mixed grain size due to its origin in a post-glacial mountain slide (Fig. 14). Besides minor quantities of clay slates, breccia, cellular dolomite with gypsum and crystalline rocks, the mountain slide material, consists predominantly of dolomite and lies probably on moraines. The order of magnitude of the coefficient of permeability k of the material found round the left abutment of the Landquart Bridge near Klosters is about 10^{-4} cm/sec. The observations covering a span of more than 50 years as well as the measurements taken for some years of the creep movements that endanger different constructions, the more important of which after the Landquart Bridge is the connected loop tunnel, indicate that the movement is rather deep-seated and steady, but relatively slow. The maximum rate of creep at the surface hardly exceeds a few centimeters a year, and diminishes substantially round the left abutment (approximately 0.5 cm a year) (*Mohr* and *Haefeli*, 1947; *Haefeli, Schaerer, Amberg*, 1953; *Skempton*, 1953) (Fig. 14). The deepest point of the tunnel involved in the movement lies at a depth of approximately 60 m under the surface. Its creep velocity was measured under the direction of *F. Kobold* and was found to be about 2 cm a year (1952–53).

Considerably quicker creep movements have been observed in "rock glaciers" which set high mountain morphology very complex soil mechanics and rheological problems. By this we mean considerable masses of detritus material which, although moving at a slower rate, behave in a manner similar to that of the glaciers with which they are often genetically connected (*H. Boesch*, 1951). Fig. 15 shows such a rock glacier with an average inclination of 1 : 4. It is one of the areas put under observation by the Swiss National Park Commission (*Domarzky*, 1951).

According to measurements taken by *E. Chaix* and *J. Domarzky* the creep velocity along the axis of the most rapid flow at the surface amounts to about 100 cm a year. *H. Boesch* (1951) assumes that a rock glacier, as a rule, comes to a standstill when the moisture supply which predominently depends on the melting of dead ice masses stops. The creep process of the lowest zones of the rock glaciers, which are allegedly free of dead ice, sets still many unsolved problems. The transitional phase between soil and glacier movement is probably after all an interplay of various influences. Beside the solifluction of the surface layers, also the occurrence of permafrost (*Terzaghi*, 1952), water and air circulation in relationship with temperature conditions have to be considered.

The examples presented in this chapter illustrate two cases of creep in loose-rock masses (Klosters and the Val dell'Aqua rock glacier), and two others where considerable stratified rock masses were carried by the movement. *Terzaghi* has emphasized that a distinction should be made between two kinds of creep, i.e. the creep movement within the crust of weathered material (skin creep) and the creep movement within the underlying hard rocks (mass creep) (*Terzaghi*, 1953). On the other

Fig. 14 View over the Creep Area below Gotschnagrat, near Klosters (Post-Glacial Slide)
Vue de la région de fluage (rampement) au-dessous de Gotschnagrat près de Klosters (glissement post-glaciaire)

(1) Bridge and Tunnel entrance of the Rhaetian Railway
Pont et tête du tunnel des Chemins de Fer Rhétiques
(2) Slide Area
Zone de glissement
(3) Gotschna Cableway
Funiculaire de Gotschna
(4) Track of the Rhaetian Railway Line
Tracé de la ligne des Chemins de Fer Rhétiques

Fig. 15 Rock Glacier in Val dell'Aqua—Swiss National Park. Aerial Photograph Federal Topographic Service, Berne, 28.9.48. All Rights Reserved
Coulée rocheuse dans le Val dell'Aqua – Parc National Suisse. Photo aérienne du Service Topographique Fédéral, Berne, 27.9.48. Tous droits réservés

hand, we observe in mountains with a thick snow cover that solifluction and skin creep is activated not only by climatic effects such as frost, temperature, weathering, etc., but in the first place by the creep pressure within the snow cover. The forces transmitted from the snow cover to the subsoil attack first the salient points on the soil surface, e.g. the edges of the paths, the blocks, etc.; this often results in an anchoring of the snow cover by the soil obstacle. Thus relatively considerable tangential forces develop which crack the soil surface and cause the melt water to enter the interior of the subsoil. Therefore when observing creep within the upper soil layers of snow-covered mountains influenced by solifluction, it is necessary to take into consideration creep and slide within the snow cover. the same applies to the glacier bed which is subjected to the powerful tangent forces transmitted by the large ice masses. Together with these tangent forces, the erosion power of the glacier depends widely on whether the ice is sliding on the soil or not.

Creep movements in the deep-seated rock masses affect loose as well as hard rocks. A link is formed by the strongly distorted and weathered shales (e.g. the schistes lustrés) whose creep tendency is decisive not only in extensive mountainous regions, but, in connection with the problems concerning erosion and bed load transport, also in the zone consisting of erratical deposits carried by the river as for example in the upper course of the Rhine down to the Lake of Constance. According to *Jäckli* (1953), approximately 2800 km² of the Rhine area in the Grisons, i.e. almost a half, is formed by impermeable rocks with a slight resistance to erosion and a pronounced tendency to slow creep movements. These rocks, which are known suppliers of sedimentary material, consist mainly of Flysch and of "schistes lustrés" whose lamellar structure and considerable clay content occasion differential movements in the creep process. Since the intrusion of moisture into the layer and cleavage planes causes the formation of clay minerals apt to swell and to creep, drainage, particularly in sagging areas, is still one of the most important measures to be taken in the prevention of soil movements.

Creep in massifs of hard rocks constitutes one of the processes which extend over geological periods and therefore escape observation and go beyond human imagination. Glaciers exemplify creep visually, the creep processes progressing in their interior demonstrate the continuous deformation of a polycrystalline solid subjected to shear stresses which relatively seldom attain shearing strength.

If, for example, a zone of the ice mass is subjected to the damming pressure acting along the flow direction of the glacier, the mass, being a body of constant volume, undergoes a corresponding transverse strain which causes a local heaving—in the form of a wave—on the surface of the glacier. If the intensity of the damming pressure is not permanent, but responds to yearly fluctuations as is the case e.g. at the toe of a steep step (*Haefeli*, 1951), a pressure wave develops every year and, with increasing glacier movement, gradually widens and forms a wonderfully curved ogive (Fig. 2). The distance measured in the flow direction of the glacier between the crest of two consecutive waves indicate the average yearly velocity of the glacier surface at this station. The question as to the extent to which (in mountain formation) analogous processes of transverse expansion in rock masses involved in a creep process leading to local heavings will have to be solved by geologists. Such a question may prove of some interest in respect of the slow heaving of "younger" mountain ranges like the Himalayas which is now often discussed.

Glaciers

In the ice covered parts of the earth the circulation of the water is rendered possible only by the flow of the glaciers. Exploration of glaciers was initiated by *J. J. Scheuchzer* (1672–1733) and *M. A. Cappeler* (1685–1769). These investigations were put on to a new track under the influence of *Agassiz*'s classical work on the Unteraar Glacier (1841–46), and led after following many side tracks to the theory of gravity which is still valid to-day (*P. Niggli*, 1946; *R. Haefeli*, 1948; *W. Jost*, 1953). Already *B. de Saussure* (1740–1799) came to the conclusion that the force of gravity was the only driving force activating the movements of the glaciers; *Forbes* is to be thanked for proving the validity of the theory already advanced by *Bordier* in 1773 and supported by *Rendu*, i.e. for proving that ice behaves like a viscous liquid (*Rütimayer*, 1881).

The assumption that ice behaves like a Newtonian liquid of very high viscosity, which is the basis of *Somigliana*'s theory (1921), has led to a simplified but very clear conception of the continuous phase of glaciers' motion. These assumptions have been confirmed in numerous observations of flat ice streams. However, since the more recent laboratory investigations have shown that ice viscosity is not constant in Newton's sense, even this view requires some modification. For example, we could imagine a liquid, the apparent viscosity of which depends —among other factors—on the state of stresses, so that its viscosity changes from point to point. We see from Fig. 7 how the apparent viscosity of the ice ($\mu = \tan \mu^* = \tau/\omega$) diminishes with increasing shear stress. As a result of this dependency the term of viscosity loses its original meaning of a constant of the material. The most recent and promising development pursued in particular in England indicates a sound tendency to attribute the mechanism of the glacier movement to those coefficients which best characterize creep in ice (*Nye*, 1952; *Perutz*, 1947, 1953).

In Switzerland, where of late various glaciological investigations have been performed in connection with technical problems, we have experienced that the concept of "apparent viscosity" is still basically applicable to the solution of practical problems. With due regard to the progress realized within the past years in the field of ice mechanics, we have to admit that apart from the effect of shear stress, the deformability of ice (flow curve) is influenced by numerous factors, which have still not been sufficiently investigated. As long as this state of affairs is unchanged, it seems premature to throw overboard the traditional notion of viscosity which, because of its simplified character, greatly facilitates comparison and survey. For a concrete problem with given stress and temperature, the task consists in estimating rightly the determining value of the apparent viscosity especially by means of tests carried out in the field (*Haefeli* and *Kasser*, 1951; *Nye*, 1953).

In order to furnish information about the magnitude and variation range in temperate glacier ice, the average apparent viscosity μ of the ice of 8 Swiss glaciers profiles was calculated according to *Somigliana*'s formula. This calculation was established on the basis of the velocity measured at the surface, as well as of the maximal profile ascertained by means of seismic investigations as well as the known widths and gradients of the glaciers. Furthermore, since the calculation is based on the assumption that, in the profile under investigation, the glacier does not slide on its base, as may happen in periods of regression, only profiles taken in flat sectors, and as even as possible, were used. The values of apparent viscosity thus obtained are of the order of magnitude of 2×10^{14} Poise, respectively 2 × 10^{12} kg.sec/m² and they show only small fluctuations. The profile of the Zmutt Glacier (altitude 2400 m) showed the following data:

	Approximate maxima	
Measured:	Thickness of ice	= 180 m
	Maximum surface velocity	= 5.36 cm/day
	Mean width of glacier	= 180 m
	Average gradient of glacier	= 8.5%
Computed:	Average bulk density of ice	= 900 kg/m³
Calculated:	Average apparent viscosity μ_m	= 1.7 · 10^{14} Poise

Apart from this, an attempt has been made to determine the viscosity on the basis of the continuous contractions of 3 widened circular profiles (⌀ = 2.2 m) located in a tunnel approximately 1000 m in length excavated in the ice of the Zmutt Glacier by the E.O.S. As expected, the results show a clear decrease in the apparent viscosity with increasing overburden: 7.2 and 2.5 Poise for overburden of 25 m and 43 m respectively. It should be noted that the last μ value is slightly higher than the average apparent viscosity of the whole glacier profile shown above. On the other hand, apparent viscosity values were determined in the ice cap of the Jungfraujoch, which lies in the permafrost zone, where the ice temperature ranges between —0.5 and —2° C; these μ values are nearly 10 times higher than those found in temperate glaciers. We may conclude from the preceding that some mechanical properties of the ice vary in a more or less jerky way as soon as its temperature drops below the pressure-melting point.

In order to facilitate the comparison between creep and flow processes within temperate ice, on the one hand, and clays on the other hand, the following table showing the mean apparent viscosity for some stress ranges may be of interest (see Fig. 7).

When comparing these values it becomes strikingly evident that the apparent viscosity of a temperate glacier ice within the stress range under investigation is of the same order of magnitude as that of the consolidated clay samples used for creep tests by the Laboratory for Hydraulic Research and Soil Mechanics of the Swiss Federal Institute of Technology.

This coincidence which is observed only for a certain consistency of the clay, and is therefore of fortuitous character, may be explained by the ice-like behaviour of the intergranular water film. Such an assumption is borne out by comparison with the flow curves in clay and ice—as illustrated in Fig. 7—may throw some light on the discussion about the real nature of the "true cohesion" of saturated clays.

Since a few creep problems encountered in a complex alpine glacier—similar to the Aletsch Glacier—are to be treated below, I wish to mention first the polar contrast existing between firn and ablation areas. For a continuous and laminar flow, *Finsterwalder* has shown by applying purely kinematic considerations that the ablation area can be regarded as an approximate distorted picture of the firn zone (Fig. 16). The small surface area A of the firn zone is connected with its picture in the ablation zone a by means of stream lines. Actually the continuity of the stream lines is often disturbed by various influences. The firn line which separates the two zones from each other also forms a marked boundary in regard to the movement of the glacier. Above this line the yearly increase of the glacier snow causes the immersion of the stream lines under the surface of the glacier (positive creep angle β), whereas below, the yearly ablation causes the stream lines to emerge (β negative). Besides this it is worth noticing that along the deep-diving stream lines along which in the course of centuries the ice of the firn zone is transported to the extremity of the

Table 2 Apparent viscosity values μ of ice and clay

Case	*Overburden Pressure or Consolidation Pressure in kg/cm²*	τ_{max} *kg/cm²*	*μ-Values in Poise*
Ice:	approx.	approx.	
Unteraar Glacier Pavillon Dollfuss	0–28	0–2	2.0 · 10^{11}
Zmutt Glacier Cross section 2400 m alt.	0–16	0–2	1.7 · 10^{14}
Zmutt tunnel circular section 547	3.9	—	2.5 · 10^{14}
Zmutt tunnel circular section 200	2.2	—	7.2 · 10^{14}
Clay: Sample 4002			
Triaxial test 7th–14th day	2.0	0.4	5.6 · 10^{14}
Ring-shear-apparatus 26 days (Fig. 6)	2.0	0.4	5.0 · 10^{14}

glacier tongue, the phenomenon of metamorphosis takes place: the fine-grained snow changes into the polycrystalline glacier ice which contains grains of the size of a fist.

In addition, the numerous velocity measurements, taken within the surface of the glacier, worth noticing are the measurements taken within the Rhone Glacier over a span of 41 years (*Vermessungen am Rhonegletscher*, 1916). Up to date we pos-

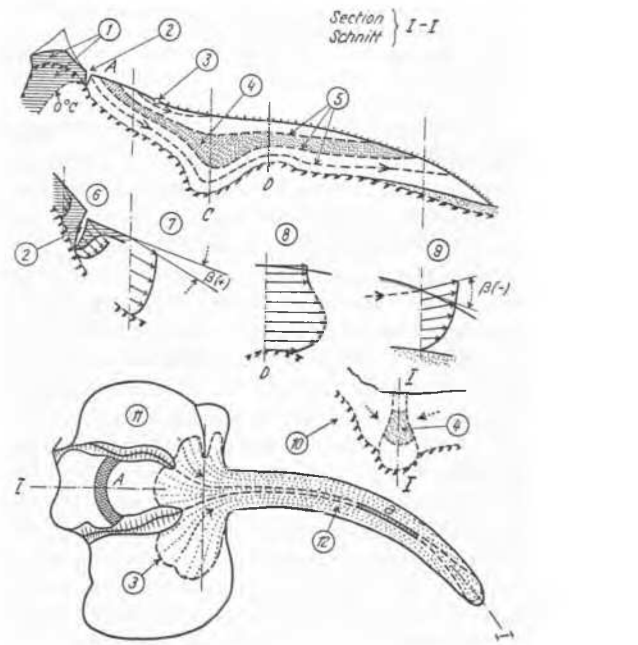

Fig. 16 Composite Glacier of the Type of the Big Aletsch Glacier (Schematic)
Glacier composite du type du grand glacier d'Aletsch (schéma)
(1) Zone of Permafrost – zone de permafrost
(2) "Bergschrund" – Rimaye
(3) Firn Line – Ligne de névé
(4/5) Stream Line – Ligne de courant
(6/9) Creep Profile – Section de rampement
(10) Cross Section at C – Section à C
(11) Firn Zone – Zone de névé
(12) Zone of Ablation – Zone d'ablation

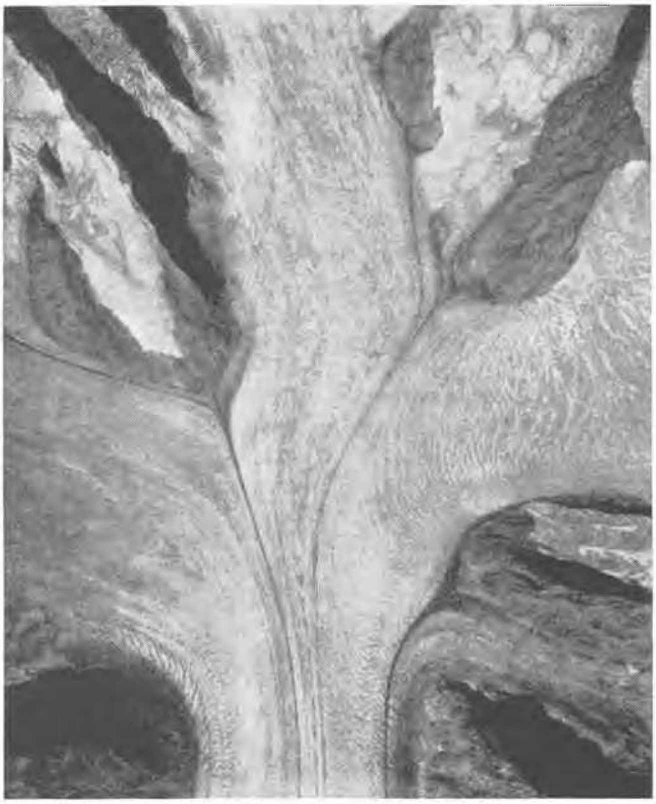

Fig. 17 View over Konkordiaplatz—Confluence of the Big Aletsch Glacier (left), Jungfraufirn (middle) and Ewigschneefeld (right). Aerial Photograph by Federal Topographic Service, Berne, 24.9.47. All Rights Reserved
Vue du Konkordiaplatz – Confluant du grand glacier d'Aletsch (gauche), Jungfraufirn (milieu) et Ewigschneefeld (droite). Vue aérienne de Service Topographique Fédéral, Berne, 24.9.47. Tous droits réservés

sess only a few measurements and observations which might furnish us with conclusive information about the movement conditions within the ice streams. Two almost horizontal tunnels approximately 100 m (Skautihöe Glacier, Norway) and 200 m in length (Mt. Collon Glacier, Switzerland) which reach the rocky subsoil within the zone of ablation provide evidence of a continuous motion taking place within the ice mass, and of a marked sliding on the bed rock (*R. Haefeli*, 1951; *J. C. McCall*, 1952). With the exception of the foundation of some water-filled crevasses, the continuity of the deformation process was exemplified also by the ice tunnels driven at the Jungfraujoch. The latter, however, are all located in the cold ice cap, above the Bergschrund, i.e. in the zone where permafrost has penetrated into the rocky subsoil and effects a relatively stiff and brittle behaviour of the ice firmly frozen at the bed rock.

Downstream from the Bergschrund at the Jungfraujoch, in the section where the ice temperature already reaches melting point at a depth of about 15 m, in spite of the fact that the average yearly air temperature is —8°, *Gerard*, *Perutz* and *Roch* measured for the first time a vertical creep profile about 130 m in depth with a surface velocity of 35 m a year that showed a pronounced increase of the curvature with depth. The conclusion drawn should be emphasized, i.e. that the gradient of velocity does not increase linearly with shear stress, as in a Newtonian liquid, but progressively, as the results yield in creep tests with polycrystalline ice have shown (*Perutz*, 1950).

The junction of the 3 tributary glaciers near Konkordiaplatz is particularly instructive; we see the central ice stream being pushed down by the two rival glaciers on both sides, so that only a narrow strip subsists on the surface (Fig. 17). Measurements of the ice by means of seismic reflections indicated a maximum thickness of nearly 800 m (*Loewe*, *Mothes* and *Sorge*, 1929) compared with 500–550 m at the outlet of Konkordiaplatz (*A. Süsstrunk*, 1947). This indicates the presence of a considerable overdepth which was not brought into being by the geology of the subsoil, but by the locally intensified erosive power of the glacier. In other alpine valleys whose step-like character is due to glacial erosion, the presence of basins was also ascertained at the confluent of two or more glaciers either by seismic soundings or by bore holes.

The formation of the downstream banking-up of the rock, at the narrowest cross section of the glacier basin, which indicates a decrease of the erosive power towards the narrow pass is one of the most fascinating problems of glacial erosion. When movement is impeded by large obstacles, an increased creep pressure develops, e.g. between C and D, and thus facilitates the pressure melting of the temperate ice (Fig. 17). It seems plausible that the ice thus becomes more plastic and that the erosive power of the boulders imbedded in the ice diminishes. This explanation of the roches moutonnées which was first supported by *Carl* (1943–47) may be a fruitful contribution to the discussion on the origin of big rock barriers, and, subsequently, on the part played by glaciers in the formation of alpine marginal lakes. In the study of such problems regarding the movement of the glaciers and their erosive power, special attention should be given to the development of stressed intercrystalline pore water (pore water pressure). Furthermore the possibility of the formation of rupture planes in high pressure zones, as assumed by *J. F. Nye* (1953), should also be taken into consideration.

With regard to the velocity distribution of the ice in the outlet profile of the Konkordia basin, an average surface speed of 165 m a year (maximum rate 206 m a year) was measured in the year 1946–47 (Figs. 17–18). Knowing the maximum depth of the profile mentioned above to be about 500–550 m, and assuming on the other hand a parabolic cross section, an average speed of more than 200 m a year was calculated, i.e. a value substantially higher than the mean speed measured on the surface. This implies that, in this profile, the highest mean velocity at the cross section does not develop at the surface of the glacier, but at a certain depth which has so far not been ascertained (*Haefeli* and *Kasser*, 1951). The occurrence of squeezing is termed "extrusion flow".

During Whitsuntide of 1919 an enormous block called "Konkordia block" started its journey over the glacier from the junction of the central and the right tributary. It has taken the block 33 years to cover about 5 km. In conclusion we hope that during the span of over a century the block will take to reach the tongue of the glacier, research inspired by a new awareness of the organic-like behaviour of the earth will lead to a deeper understanding of the laws which govern creep phenomena in snow, soil and ice.

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References

Bernatzik, W. (1947): Baugrund und Physik. Schweizer Druck- und Verlagshaus, Zürich.

Bingham, E. C., and *Reiner, M.* (1953): The Rheological Properties of Cement and Cement-Mortar-Stone. Physics 4 (88–89), 102.

Birkenmaier, M. (1952): Die Berechnung der Spannungsverluste im vorgespannten Beton. Schweiz. Bauzeitung Bd. 70, Nr. 45.

Boesch, H. (1951): Beiträge zur Kenntnis der Blockströme. Die Alpen, Vol. 27, No. 1.

Burgers, J. M., and *Scott Blair, G. W.* (1949): Report on the Principles of Rheological Nomenclature. Proc. 1st Int. Congr. Rheol., Scheveningen.

Cadisch, J., unter Mitarbeit von *Niggli, E.* (1953): Geologie der Schweizer Alpen. Verlag Wepf, Basel.

Carol, H. (1943): Beobachtung zur Entstehung der Rundhöcker. Die Alpen, H. 6.

Carol, H. (1947): The Formation of "Roches Moutonnées". Journal of Glaciology, Vol. I, pp. 57–63.

Casagrande, A., and *Wilson, D.* (1950): Effect of Rate of Loading on the Strength of Clays and Shales at Constant Water Content. Harvard Soil Mechanics Series, No. 39. Cambridge, Mass.

Domarzky, J. (1951): Blockströme im Kanton Graubünden usw. Dissertation, Universität Zürich.

Geuze, E. C. W. A., and *Tan Tjong-Kie* (1953): Rheological Properties of Clays. D. van Sijn en Zonen, Rotterdam.

Glen, J. W. (1952): Experiments on the Deformation of Ice. Journal of Glaciology, Vol. 2, p. 111.

Haefeli, R. (1942): Spannungs- und Plastizitätserscheinungen der Schneedecke unter besonderer Berücksichtigung der Schneedruckberechnung und verwandter Probleme dcı Erdbauforschung. Schweiz. Archiv für angewandte Wissenschaft und Technik, H. 9–12, 8. Jahrgang, Mitteilung Nr. 2 der Versuchsanstalt für Wasserbau und Erdbau ETH Zürich (1944). See also: Erdbaumechanische Probleme im Lichte der Schneeforschung. Mitteilung Nr. 7 der Versuchsanstalt für Wasserbau und Erdbau ETH Zürich.

Haefeli, R., and *Schaerer, Ch.* (1946): Der Triaxialapparat, ein Instrument der Boden- und Eismechanik zur Prüfung von Verformungs- und Bruchzuständen. Schweiz. Bauzeitung, Bd. 128, und Mitteilungen der Versuchsanstalt für Wasserbau und Erdbau ETH Zürich.

Haefeli, R. (1948): The Development of Snow and Glacier Research in Switzerland. Journal of Glaciology, vol. I, pp. 193–201.

Haefeli, R. (1951): Neuere Entwicklungstendenzen und Probleme des Lawinenverbaus im Anbruchgebiet. Beiheft Nr. 26 zu den Zeitschriften des Schweiz. Forstvereins und Mitteilung Nr. 21 der Versuchsanstalt für Wasserbau und Erdbau ETH Zürich.

Haefeli, R., und *Kasser, P.* (1951): Geschwindigkeitsverhältnisse und Verformungen in einem Eisstollen des Zmuttgletschers. Union Géodésique et Géophysique Internationale. Association Internationale de l'Hydrologie Scientifique. Assemblée générale de Bruxelles. Tome I, pp. 222–236.

Haefeli, R. (1951): Some Observations on Glacier Flow. Journal of Glaciology, vol. 1, p. 496.

Haefeli, R., *Schaerer, Ch.*, and *Amberg, G.* (1953): The Behaviour under the Influence of Soil Creep Pressure of the Concrete Bridge built at Klosters by the Rhaetian Railway Company, Switzerland. Proc. Third Int. Conf. on Soil Mechanics and Foundation Engineering, Switzerland, vol. II, p. 175, and Mitteilung Nr. 26 der Versuchsanstalt für Wasserbau und Erdbau ETH Zürich.

Heim, A. (1882): Über Bergstürze. Neujahrsblatt der Naturforschenden Gesellschaft, Zürich.

Jackli, H. (1948): Die Bodenbewegung im Hinterrheintal und ihre bautechnischen Auswirkungen. Schweiz. Bauzeitung, Jg. 66, Nr. 37.

Jackli, H. (1953): Geologische Eigentümlichkeiten der Geschiebeherde des bündnerischen Rheingebietes. Wasser- und Energiewirtschaft, Nrn. 8 und 9, Zürich.

Jost, W. (1953): Das Grimselgebiet und die Gletscherkunde. Die Alpen, Heft 8.

Lugeon, M. (1922): Sur le balancement des couches. Barrages et géologie. Librairie Rouge, Lausanne.

McCall, J. C. (1952): The Internal Structure of a Crique Glacier. Journal of Glaciology, vol. 2, p. 122.

Mohr, C., and *Haefeli, R.* (1947): Umbau der Landquartbrücke der Rhätischen Bahn in Klosters. Schweiz. Bauzeitung, Jg. 65, pp. 1–12, und Mitteilungen Nr. 12 der Versuchsanstalt für Wasserbau und Erdbau ETH Zürich.

von Moos, A. (1953): Der Baugrund der Schweiz. Schweiz. Bauzeitung, Bd. 71 (Subsoil of Switzerland. Proceedings of the Third Int. Conf. on Soil Mechanics and Foundation Engineering, 1953, Switzerland), und Mitteilungen Nr. 28 der Versuchsanstalt für Wasserbau und Erdbau ETH Zürich.

Fig. 18 Big Aletsch Glacier and View towards Konkordiaplatz
Grand glacier d'Aletsch et vue dans la direction de Konkordiaplatz (photo Swissair)

Niggli, P. (1946): Die Schnee-, Lawinen- und Gletscherkunde in der Schweiz. Mitteilung des Eidg. Institutes für Schnee- und Lawinenforschung, Nr. 1, 1946.

Nye, F. J. (1952): The Mechanics of Glacier Flow. Journal of Glaciology, vol. 2, p. 82.

Nye, F. J. (1953): The Flow of Ice from Measurement in Glacier Tunnels, Laboratory Experiment and the Jungfraufirn Experiment. Proceedings of the Royal Society, A, vol. 219, pp. 477–489.

Penk, W. (1924): Morphologische Analyse.

Perutz, M. F. (1947): Report on Problems Relating to the Flow of Glaciers. The Journal of Glaciology, vol. I, pp. 47–50.

Perutz, M. F. (1950): Direct Measurement of the Velocity Distribution in a Vertical Profile through a Glacier. Journal of Glaciology, vol. 1, p. 382.

Perutz, M. F. (1953): The Flow of Glaciers. Nature, vol. 172, p. 929.

Reiner, M. (1949): Twelve Lectures on Theoretical Rheology. North-Holland Publishing Company, Amsterdam.

Renaud, A. (1949): A Contribution to the Study of the Glacier Grain. Journal of Glaciology, vol. I, No. 6, pp. 320–24.

Rütimeyer, L. (1881): Zur Geschichte der Gletscherstudien. Jahrbuch des Schweizer Alpenklubs, 1880–81, pp. 379–418.

Schweizer Alpenklub (1911): Geologische Wanderungen durch die Schweiz, mit einer Einführung von Dr. *J. Weber*, I. Bd., pp. 122–29.

Seligman, G. (1941): The Structure of a Temperate Glacier. Geographical Journal, vol. 97, p. 295.

Skempton, A. W. (1953): Earth Pressure, Retaining Walls, Tunnels and Strutted Excavations. General Report. Proceedings of the Third Int. Conference on Soil Mechanics and Foundation Engineering, vol. II, pp. 358–61.

Somigliana, C. (1921): Sulla profondita dei ghiacciai. Rediconti della R. accademia nazionale dei Linciei, vol. 30.

Staub, R. (1924): Der Bau der Alpen. Beiträge zur geologischen Karte der Schweiz, Nr. 52, Bern.

Steinmann, S. (1953): Interner Bericht Nr. 145 Eidgenössisches Institut für Schnee- und Lawinenforschung Weissfluhjoch bei Davos, Schweiz.

Taylor, D. W. (1948): Fundamentals of Soil Mechanics. John Wiley & Son, New York,

Terzaghi, K. (1951): Mechanism of Landslides. Harvard Soil Mechanics Series, No. 36. Cambridge, Mass.

Terzaghi, K. (1952): Permafrost. Harvard Soil Mechanics Series No. 37, Cambridge, Mass..

Terzaghi, K. (1953): Discussion, Session 7, Third Int. Conference on Soil Mechanics and Foundation Engineering, Switzerland, vol. III, p. 205.

Tschebotarioff, G. P. (1951): Soil Mechanics Foundations and Earth Structures. McGraw-Hill Book Co. Inc., New York.

Vermessungen am Rhonegletscher 1874–1915 (1916). Herausgegeben von der Gletscherkommission der Schweizerischen Naturforschenden Gesellschaft.

Winterkorn, H. (1943): The Conditions of Water in Porous Systems. Soil Science, pp. 109–115.