Translation of two Swiss articles on permafrost in the Alps

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TRANSLATION OF TWO SWISS ARTICLES ON PERMAFROST IN THE ALPS

TRANSLATED BY

D. A. SINCLAIR

THIS IS THE TWO HUNDRED AND ELEVENTH OF THE SERIES OF TRANSLATIONS PREPARED FOR THE DIVISION OF BUILDING RESEARCH

OTTAWA

1973

PREFACE

The Division of Building Research has been carrying out investigations on the distribution of permafrost in Canada for many years as part of its program to gain a better understanding of this phenomenon in relation to northern construction problems. In recent years there has been increasing interest in the distribution and occurrence of permafrost at high elevations in the Western Cordillera of British Columbia and Alberta with the growth in that region of activities such as mining and road construction. Little information is available on alpine permafrost in Canada but some work has been carried on in other countries, notably Switzerland, where the investigations described in these two papers were made. The observations on the relationship of permafrost occurrence to elevation and climate in the Swiss Alps is of considerable interest to Canadian permafrost investigators for comparison with Canadian conditions. Other foreign language papers on alpine permafrost will be translated in the future. The Division of Building Research is grateful to Mr. D.A. Sinclair for translating these papers and to Dr. R.J.E. Brown of this Division who checked the translations.

Ottawa
September 1973

N.B. Hutcheon
Director

NATIONAL RESEARCH COUNCIL OF CANADA

Technical Translation 1657

TRANSLATION OF TWO SWISS ARTICLES ON PERMAFROST IN THE ALPS

Translated by: D. A. Sinclair, Translations Section, National Science Library

PERMAFROST IN THE UPPER SUBNIVAL STEP OF THE ALPS

(Permafrost in der oberen subnivalen Stufe
der Alpen)

D. Barsch

Geographica Helvetica, 24 (1): 10-12, 1969

PERMAFROST IN THE UPPER SUBNIVAL STEP OF THE ALPS

To the best of our knowledge the question of the occurrence of recent permafrost in the Alps has not yet been fully clarified. During our investigations in the Jura (D. Barsch, 1967) we encountered various phenomena which could be satisfactorily explained only by assuming the existence of Würm (glaciation) permafrost. For the Jura, the "periglacial lakes" (D. Barsch, 1968) in particular, which were formed in the Würm by karst depressions blocked by permafrost, testified to the existence of continuous Würm permafrost just below the snow line at that time. In the upper subnival step of the Jura of that time it would correspond to the recent "continuous permafrost zone" described by the American geologists in Alaska. For obvious reasons we therefore expected to encounter permafrost in the present subnival step of the Alps as well. So far, we have learned of two examples of this, which we wish to publish in a current report. We hope that this will encourage others to look for additional indications. It would appear advisable to pursue the problems associated with the recent occurrence of permafrost in the Alps under the aegis of a rather broad group of research workers.

During the building of the upper terminal and the half-way station of the Corvatsch railroad (Upper Engadine) and during excavation for certain of the column footings of the railroad, crevasse fillings of ice were discovered*. According to a letter to me from the railroad administration, what was involved, especially at the upper terminal and at a few column foundations, was a mixture of rock and ice. At the upper terminal ice was found right down to the bedrock at around 15 m depth. During excavation for the half-way station, which, of course, had already been carried out in spring

* These conditions were first brought to my attention by Dr. V. Trommsdorff (Mineralogical-petrographical Institute of the University of Basel). The phenomena were confirmed in a letter written to me by the railroad administration. The Director of the railroad, Mr. Rohrer gave me the address of the Building Supervisor, Mr. Camadeni, who gave me a description of the conditions particularly at the half-way station. I should like to thank all those mentioned for their information.

(March to May), ice lenses and frozen detritus were found to a depth of about 4 m. Although we do not have any accurate photographs, there can no longer be any doubt of the existence of permafrost in the vicinity of the upper terminal, and in the half-way station area the occurrence of the permafrost is very probable.

The upper terminal of the Corvatsch railroad is situated to the north of the peak of that name (3451 m) at an altitude of 3304 m, while the half-way station is at an altitude of 2699 m. The recent tree line would be between 2200 and 2400 m (F. Holtmeier, 1967) and the recent snow line at approximately 3000 m. The position of the local snow line in the Upper Engadine, of course, depends strongly on the topographical conditions. The ridge on which the upper terminal is constructed, is bare every year despite its high altitude. At this station, therefore, we are on the boundary between the nival and subnival zones. Here, in accordance with the special conditions, the occurrence of permafrost is altogether logical. Frost occurs throughout the year at this altitude and a negative temperature average may be expected even for the summer months. Moreover, as observations in Alaska and Siberia indicate, permafrost becomes very thick wherever absence of a snow cover favours the penetration of the frost into the ground. Even more interesting is the probable occurrence of permafrost in the region of the half-way station of the Corvatsch railway, since this region is definitely below the snow line in the upper part of the subnival step of the Alps. The fact that permafrost is generally possible at this elevation is shown by the rock glacier that has developed only a few hundred meters to the southwest of the station between 2730 and 2880 m altitude. According to our investigations in Macun (see below) rock glaciers consist almost entirely of frozen detritus, and only the top layer of boulders consists of unfrozen material. We conclude from this that the occurrence of permafrost in the vicinity of the half-way station of the Corvatsch railway is not improbable.

Another example of recent permafrost is from the Lower Engadine. In the course of a research program of the Geographical Institute of the University of Basel, we have been studying the rock glaciers in the Macun cirque (south of Lavin, Lower Engadine) since 1965. With a party of students, rock glaciers Macun 1 and Macun 2 were charted in detail, and with the aid of an expert surveyor, M. Maurer, the movement of the glacier was determined for the periods 1965-1967, and 1967-1968. A preliminary report on the results has been in print for some time (Zeitschrift für Geomorphologie). Our studies of the motion processes of the rock glaciers could not have been completed if further details concerning the internal structure of rock glaciers had not been collected. With the generous support of the Swiss National Fund for the Advancement of Scientific Research, which we also wish to thank at this point, it was possible to get the necessary information. Through the firm of Geotest AG,Berne (Dr. A. Schneider) as well as our own working party of students, we subjected the carefully surveyed rock glacier Macun 1, the external motion patterns of which were well known, to an explosion seismic investigation. Even the preliminary investigation showed that the entire rock glacier, with the exception of the uppermost layer of boulders, reacts as a rigid mass. The compression waves in the rock glacier showed the same velocity as in ice. Excavations in the upper part of the rock glacier along the lateral motion faces showed, in addition, the intermittent presence there of solidly frozen material at a depth of about 1 m. Fine material and coarser fragments constitute a mass with the hardness, roughly, of bone, intermingled with thin ice lenses acting as a cement. Generally speaking, the ice appears only in thin films on the coarser fragments. Large ice lenses are very rare.

On the surface of the rock glacier flowing melt water from snow could be observed in various places (in August!). At these points we cleared away the larger boulders and found that the water was flowing over bottom ice and was thus unable to seep away. All rock fragments are frozen solidly to the bed of the trough. As far as we know, this is the first time it has been definitely shown that the interior of the active rock glacier comprises a body of solidly frozen detritus which becomes plastic in its lower part owing to its intrinsic weight and the weight of the boulder layer. This frozen body of detritus is responsible for the flow process.

Elevation	Station	Period
3579	Jungfraujoch	From 1938
3488	Plateau Rosa (Testa Grigia)	From 1953
2667	Weißfluhjoch	From 1947
2479	Grand St-Bernard	From 1818
2237	Julier Hospiz	1864—1910
2096	St. Gotthard	From 1903
1968	Buffalora	From 1917
1853	St. Moritz II	1932—1953

These stations, which are situated approximately at the elevations of 2600 to 3000 m, show distinctly positive mean temperatures only during four months of the year. The maximum monthly mean temperature on the Weissfluhjoch is 4.7°C (in August), on the Grand St. Bernard 6.8°C (August). In Macun the rock glacier Macun 1 occupies a range of elevations between 2600 and 2720 m. The tree line here should be 2200-2300 m, and the snow line at about 2950-3000m. The rock glacier, i.e., the zones of frozen detritus, clearly lie below the snow line in the upper part of the subnival step. We regard the rock glacier, therefore, as belonging to the periglacial rather than the glacial category; the frozen detritus essential to its motion can therefore be regarded as a special permafrost phenomenon. From our two examples it is evident that we can expect to find permafrost in the upper part of the subnival step in the Alps. We do not yet know the extent of this phenomenon in the Alps, but it should appear more frequently than hitherto known. It has not yet been possible to correlate it to individual zones depending on the intensity of the formation (continuous, discontinuous, sporadic). Nor has it yet been determined whether there is any so-called "dry permafrost" in the Alps. This term refers to waterless or ice-free rock parts which show temperatures below the freezing point throughout the entire year. Some enlightenment might be possible from systematic observations of all new constructuon in the Alps, or from the evaluation of the observations collected on the occasion of earlier construction work, which are often filed locally.

As far as the climatic conditions are concerned, concerning which we can give only few details for the Swiss Alps owing to the sparse network of stations, the existence of permafrost in the region of the upper subnival step in the Engadine also appears possible. After M. Schüepp (1960), I have assembled the following data, all relating to the period 1901-1940:

Winter	Spring	Summer	Autumn	Year
—14.1	—10.5	—2.4	—7.1	—8.5
—12.2	— 8.6	0.1	—5.0	—6.4
— 8.9	— 4.9	3.8	—1.3	—2.8
— 8.2	— 3.6	5.8	—0.6	—1.7
— 8.1	— 1.9	7.3	0.1	—0.7
— 6.9	— 1.8	7.0	0.7	—0.2
— 9.7	— 0.8	9.0	0.7	—0.2
— 6.1	1.5	10.3	2.8	2.1

Frosts can occur during all seasons. The influence of negative temperatures predominates. It follows that the thermal conditions are present for the formation of permafrost in the range of altitudes of the upper subnival step in the region of the Engadines

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Rock glacier in Macun (Lower Engadine). Photo by J. Rohner

TREATISE ON THE PERMAFROST PROBLEM IN THE ALPS

(Beitrag zum Permafrostproblem in den Alpen)

G. Furrer and P. Fitze

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TREATISE ON THE PERMAFROST PROBLEM IN THE ALPS

1. Definitions

Today, with the areas of human habitation being pushed beyond the cold boundary, the problem of permafrost is becoming increasingly important. The regions in which permafrost is currently the subject of intensive investigation are the higher latitudes on the one hand, and the high mountain ranges on the other.

The present paper is devoted to the still relatively unknown alpine permafrost. The work is based on arctic permafrost, about which we are better informed.

Sumgin (1937, in Kakela 1965) defines permafrost or "permanently (perennially*) frozen ground" as a layer of soil (at a certain depth below the natural surface of the soil) which remains at negative temperatures for two or more years without interruption. Muller (1947, in Kakela 1965) supports Sumgin's definition, but adds (p.7): "Permanently (perennially*) frozen ground is defined exclusively on the basis of temperature, irrespective of texture, degree of induration, water content or lithologic character." Bryan (1946) proposed the term "pergelisol" in place of permafrost, and "mollisol" for the active layer, but this does not appear to have established itself in the literature. Like Muller, Black (1951, in Kakela 1965) defines permafrost as purely a temperature phenomenon which can occur in either natural or artificial material. Black and Muller's definitions show clearly that permafrost has nothing to do with whether ice is present or not. If no ice is present we then have the so-called "dry permafrost" (Muller, 1945, in Péwé 1966). Péwé (1966) defines permafrost as a layer of soil in which the temperatures are below zero for at least two years. This layer may even contain salt or brackish water, so that it is not necessarily frozen. Contrary to all these definitions are those of the Russians Parkhomenko and Sidenko (both in Kakela 1965), according to whom frozen water is the principal criterion.

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* Translator

2. Permafrost in the High Northern Latitudes

2.1. Structure and thickness of permafrost

The permafrost is a layer of frozen soil that may be from a few to hundreds of meters in thickness. In our view the term "frozen" should apply only to the temperature. Above the permafrost is a zone which thaws during the summer (the "active" or thaw layer). The frozen mass itself does not consist wholly of frozen material; frozen sections may alternate with unfrozen ones (taliks). Beneath rivers or lakes the influence of the water is so great (Johnston and Brown 1964, Péwé 1966) that the surface of the perennially frozen soil ("permafrost table") is very deep, or, in the discontinuous zone (see 2.2), may be absent altogether.

The thickness of the perennially frozen soil in northern Siberia, according to Black, is about 600 m. For Spitzbergen, values of 300 m are cited, and for the Canadian Arctic 50-150 m. Such figures are often merely estimates and represent minima.

2.2. Zonal classification of permafrost phenomena

Black (1951), as well as Brown and Johnston (1964), divide the permafrost into a continouous, a discontinuous and a sporadic zone. The thickness of the active layer increases in the same order. In the first zone it is 0.1 to 1.8 m, in the second 0.3 to 3.0 m, and in the third 0.6 to 5.2 m. In the sporadic zone, according to Black, the permafrost is either of a relict character or has come about through especially favourable conditions. Bone (1962) also distinguishes three zones: a continuous northern zone of the Arctic Circle, a discontinuous zone between the Arctic Circle and 62° N, and a relict zone between 62 and 60$\frac{1}{2}^{\circ}$ N. Pihlainen (1962) defines the following three zones: a continuous zone in the tundra, a continuous zone in the forested region, and a discontinuous zone.

From these and other examples it is clear that as an extreme northerly element we find a continuous permafrost zone where - horizontally regarded - an uninterrupted layer of permafrost is found at a shallow depth. To the south this merges into a discontinuous zone in which unfrozen sections are intermingled with the frozen mass. Farther south again we strike the sporadic zone in which the frozen soil is encountered only in isolation. For the present we leave aside the question of whether this frozen soil is relict or recent.

2.3. Ice and temperatures in the permafrost

Ice in the soil can take on various forms. Black (1951) describes six types: thin ice films, ice granules, crevice and crack fillings, coatings of various thicknesses, ice wedges, and irregular masses of ice. According to Schmid (1955) ice can form a film over individual grains of soil (this is the case primarily in coarse-grained soils), or it can run through the soil in the form of layers or lenses.

Data on the temperature in permafrost vary widely in the literature. The differences are so great that no generalization is possible. According to Cook (1958) and Péwé (1966), it appears well established that the temperature fluctuation due to seasonal changes in the air temperature is no longer present at a depth of 15 to 20 m. According to Annersten (1963), the temperatures decrease down to this depth, below which they rise again. According to Nichols (1956), the temperature in the upper layer is -0.5 to -2.0° C. Schostakowitsch (1927) reports a temperature of -1.2° C at a depth of 8.5 m in Siberia. According to Péwé (1966), the temperatures at depths of 15 to 20 m are -5° C in continuous permafrost and between 0.0° and -5° C at the same depth in the discontinuous zone. More general statements on the permafrost temperature in northern Siberia give figures from 0 to -12° C (Nichols and Yehle 1961, Black 1951).

2.4. Conditions of permafrost formation

Unlike the temperatures, the conditions described in the literature for the formation or maintenance of permafrost do not differ very widely. The most important factors affecting the permafrost are the air temperature, the snow conditions and the vegetation conditions.

Temperature

According to Black, the mean annual air temperature (MAAT) in permafrost regions would be 0 to -3° C, but could be higher, of course, if other factors are very favourable to the development of permafrost. Decisive ones, according to Black, are long, cold winters together with short, cool cummers, i.e., factors which favour a negative heat balance in the soil, wherein, of course, is to be found the ultimate cause of permafrost formation. Nichols (1956) gives a MAAT of -2.6° C for a permafrost location in the discontinuous zone. According to Kaiser (1960), the present perennially frozen soil is bounded in the direction of the equator in Siberia by the -2° annual isotherm. If higher temperatures occur at a permafrost location it will be a relict formation. According to Kudr'avtsev (1954 in Kost'yaev 1966), permafrost is a zonal-climatic phenomenon, the MAAT boundary of which is located at -3.0° C. Pihlainen (1962) sets the southern boundary of the permafrost between -1.1 and -3.9° C MAAT. According to Redozubov (1954 in Péwé 1966), to be sure, this boundary is situated at MAAT of 0° C.

Snow

Opinions expressed in the literature on this factor are fairly uniform. When we take into consideration the insulating properties of snow it becomes clear that the formation of new permafrost is rendered more difficult. On the other hand, according to Brown and Johnston (1964), the thawing process is also obstructed, an important consideration in connection with relict permafrost. Snow has a much higher albedo than bare ground, which very probably prevents or retards the thawing of snow-covered frozen ground. According to Annersten (1963), permafrost can no longer form beneath a snow cover thickness of more than 45 cm. Viereck (1965) mentions a permafrost site with 0.5 to 1.5 m snow in winter. For Ives (1960a, 1960b, 1962), not only snow, but also wind direction and slope direction (windward or lee) are also decisive factors.

Vegetation

Vegetation is the third factor of great importance. We find frequent references to the differences of heat conductivity between dry, wet and frozen vegetation: dry vegetation in summer prevents the heating of the soil, while wet or frozen vegetation in winter promotes the dissipation of heat from the soil. According to Annersten (1962), the vegetation appears to be the factor with the least effect among those so far mentioned. According to the same author (1963), the vegetation raises the soil temperature slightly. Bonnlander (1958) showed the effect of permafrost very clearly by measuring a permafrost thickness of 35 to 80 m in the tundra, 15 to 35 m in the transitional zone between tundra and forest, and none at all beneath the forest.

These three principal factors are joined by several others.

Annersten (1962, 1963) mentions the exposure; according to him, slopes with northern exposure are about one degree colder than slopes with southern exposure. According to Furrer (1959 and 1965), a deeper thawed layer must be expected on southern exposed slopes than on northern. Péwé (1966) believes that no permafrost will be found on comparatively steep slopes with southern exposure. Bonnlander (1958) mentions a correlation between permafrost and topography. According to him, permafrost is encountered mainly on higher ground, less in depressions. Besides exposure and topography we find microclimate, microrelief, drainage and soil composition mentioned as factors.

These statements clearly indicate how many different factors may be involved at any one site. They also show how difficult it is to derive any generally valid regularities from the description alone.

2.5. Determining the boundaries of the permafrost and its age

Although there is no generally recognized method of determining the extent of the permafrost, we shall recount here a few attempts to do so.

One possibility is based on the annual isotherm, already discussed under 2.4. Evidently a certain approximation to the "true" boundary can be arrived at in this way.

According to Schostakowitsch (1927), the criterion for the presence of permafrost is the quotient of the mean air temperature of the winter months divided by the January snow depth (in cm). If the quotient exceeds -0.5, we can no longer expect to find permafrost. To be sure, this formula was contested by Sumgin (1929) on the grounds that there were too many exceptions.

According to Grigor'ev (1930 in Frenzel 1967), the diffusion of the permafrost can be given by the formula:

$$G = \frac{t_{neg}}{S\, t_{pos}\, N_{pos}},$$

where t_{neg} is the sum of the negative monthly mean temperatures (in $^{\circ}$C), S the mean depth of the snow cover in cm for the months of thickest snow cover, and N_{pos} the sum of the mean precipitation quantities in mm for the months with positive mean temperatures. However, it is not quite clear exactly how S and N_{pos} are to be defined.

Pihlainen (1962) determined the limits of the various permafrost zones by correlating the thaw index (= sum of all positive daily mean temperatures) and the MAAT (see 3.5). However, both Pihlainen and the present authors use the practically equivalent sum of the monthly mean temperature multiplied by the number of days.

All these are approximate methods. One difficult problem for us in this connection is the application of the climatic data from the Arctic to the Alps. We must always bear in mind that, for example, when the MAAT's are the same both in the Arctic and the Alps, the conditions are nonetheless fundamentally different. Whereas in the Arctic a typical seasonal climate prevails, the alpine regions of the middle latitudes are in the transition zone between a seasonal and a daily climate that becomes dominant, of course, only in the mountain ranges of the tropics. In Section 3 we shall attempt the transfer of the Arctic data to the Alps.

Another problem in determining boundaries lies in the fact that the permafrost will not necessarily have been formed under present-day conditions. It may be a relict form (e.g., from the Pleistocene or the Little Ice Age between 1600 and 1850). Opinions differ on this question.

According to Black (1951), sporadic and discontinuous permafrost is relict, whereas continuous permafrost may be recently formed. Bone (1962) holds the same view. True "contemporary permafrost", as far as he is concerned, exists only in the continuous zone and occasionally also in the discontinuous. Farther south only relict permafrost will be found, in process of reduction. According to Bryan (1946) and Taber (1943 in Nichols 1956), permafrost is a relict form, to be placed, according to Taber, in the early Pleistocene. For Williams (1959) and Ives (1962), permafrost below the forest boundary, at least, must be regarded as relict, formed, according to Ives, under different climatic and vegetation conditions from those of today. Kaiser (1960), who identifies the permafrost boundary with the -2^{o} annual isotherm, speaks of relict occurrences when findings extend to the 0^{o} yearly isotherm. According to Schostakowitsch (1927), Nichols (1956) and Ives(1960b), the present-day climate is sufficient to form or maintain permafrost. Mackay (1967) succeeded in proving recent permafrost formation in the Mackenzie Delta (Northern Canada).

3. Permafrost in the Swiss Alps

The following references to permafrost have been found in the literature on the Swiss Alps.

Campell (1954, p.113) writes: "In our regions permafrost can normally extend down to about 2400 m and on sunny slopes above 2600 m above sea level, wherever water-retaining clay layers are present."

A concrete example is mentioned by Furrer (1955) from the Fimber region at about 2600 m above sea level.

Jäckli (1957, p. 20 ff.) writes that, according to Lütschg (1947), the mean annual temperature of the soil in the Graubünden goes below 0^{o} at a depth of 1.20 m only at 2650 m above sea level, and that above this altitude we can expect to find permafrost even on sunny slopes.

An astonishing altitude statement was made by Richard (1961, p. 83 ff.). He observed subsurface ice in July at 850 m above sea level and noted a year-round occurrence of ice at 1020 m above sea level.

Two additional concrete examples of permafrost are given by Elsasser (1968) from the Fuorela da Fàller region (2830 m above sea level) and Barsch (1968) on the Corvatsch railroad (3300 m, and in some places even 2700 m above sea level).

Our studies have revealed a large number of other permafrost sites, so that those mentioned above must be regarded only as isolated examples.

3.1. Permafrost on the Fuorela da Fàller (Point 765,200/148,000 on the new map, Bivio sheet, No. 1256)

The permafrost found by Elsasser (1968) is situated at 2830 m above Juf in Avers. As the name suggests, this is a typical anticline, which should favour the presence of permafrost since it is probable that little snow is retained in the anticline, or the snow cover is not very thick. This factor has already been mentioned in connection with the arctic permafrost, and here it appears to be very important.

In the middle of August, 1969 the highest part of the anticline was completely bare of snow, but a little below it, snow was still lying on the south-southeast slope. We dug a ditch 1.3 m thick on the bare part. The temperature measurements that were carried out immediately gave positive values down to 70 cm. At 75 cm the temperature was already -0.5° C, and at a greater depth it went still lower. This showed that in August the permafrost table was situated at a depth of 70 cm. The soil structure changed at this depth also (Figure 1). Whereas the active layer consisted of loose gravelly soil, the soil beneath was frozen hard, and between 70 and 105 cm it was bestrewn with transparent ice lamellae 2-4 mm in thickness. An example is sketched in Figure 2. Below 110 cm no more ice was found. The soil grew softer and sandier, but the temperatures remained negative. We therefore had "dry permafrost". This is clear from the two water-content determinations (Figure 1). The structural change was probably due to the change in material.

Measuring the soil temperatures at the same location in spring and autumn Elsasser (1968) obtained readings of -4° C at a depth of 60 cm.

With regard to the formation of ice in the permafrost in the form of lamellae, it should be mentioned that this is by no means the only form found in the Alps. We have received an excellent picture from the Gebr. Gruner Engineering Office showing an ice lens about 60 cm thick (Plate 1). This was found during construction of the Schilthorn railroad at 3000 m. It has also been reported to us that sometimes the permafrost ice fills all the gaps in coarse gravelly soil, i.e., it acts as a pore and crack filler.

It is clear, therefore, that the permafrost in our Alps is not a uniform phenomenon. Depending on the location, we find "dry permafrost", ice lamellae, pore ice or ice lenses.

3.2. Permafrost in the Totälpi

At this site, discovered by Freund on the Rothorn (765,200/179,200, 2810 m, Filisur sheet , No. 1216) the frozen soil was checked over a period of two years. A peculiarity of this site, according to Freund, is the fact that it has a very thick snow cover that does not melt away completely until late summer. However, it is possible that the perennial patch of snow (Figure 3), at the base of which ice has formed in the course of time, acts as a cold centre and thus creates permafrost (or at least conserves it) which cannot be compared with other occurrences. An indication of this cooling effect of the snow is given by the fact that temperature measurements about 40 m away from the patch of snow, carried down to a depth of 1.2 m, showed no sign of permafrost over a period of two years. There was only a temporary deep penetration of frost from the surface down, and no indication of a deeper cold centre could be deduced with any certainty. This frost could conceivably be an azonally intensified permafrost which can develop only through the cooling effect of the snow.

A further indication of the effect of cooling by the snow was obtained from excavations. The position of the permafrost table was determined on September 19, 1969 (Figure 3). Beneath the snow it reached the surface of the soil. Then, the farther we proceeded from the snow the deeper was the permafrost table. On October 27, after a succession of fine days, the permafrost table receded still further, except in the area near the margin of the snow, where it rose towards the surface. Here, in the vicinity of the snow, therefore, a negative heat balance for the soil had developed, although farther away from it the balance remained positive. Moreover, the top 5 cm of soil was frozen.

This location shows that even at this altitude permafrost does not necessarily occur if there is too thick a snow cover in winter and spring, but that a cold centre can lead to the formation or at least the maintenance of permafrost in an otherwise unfavourable situation.

3.3. The Jungfraujoch ice cap

Its situation at an altitude of around 3450 m interests us especially in relation to permafrost temperatures. The following data are derived from a work by Häfeli (1961) and from special borings carried out by the PTT (1958).

It was assumed that the ice-rock interface was situated in the permafrost zone by reason of the fact that all the glacier crevasses were filled with melt water that evidently was unable to escape underground. When we bored down to this interface around 30 m below the surface of the ice, we measured temperatures here between -1 and -3° C. However, this did not tell us whether we had the "usual" permafrost temperatures here under the ice or were confronted with a special case.

These values, taken together with data already on hand, show that even in relation to the temperature the alpine permafrost is not a uniform phenomenon. The values vary, depending on location, between -¼ and -4° C. These differences are not surprising, however, but we must bear in mind that most of the values mentioned refer to the top layer of permafrost, and the latter - as is evident from the American and Canadian literature - lies in the zone of daily or seasonal variations.

3.4. Thickness of the permafrost

There have been very few measurements of thickness, but three figures have been determined for altitudes from 2800 to 3000 m showing thicknesses of 8,11 and 35 m respectively. The lower boundary of the permafrost was not reached in any of these three locations, and one assumption has been made that the thickness in the third instance may be as great as 200 m.

3.5. Extent and lower altitude limit of permafrost in the Swiss Alps

Determining the extent of the permafrost remains a difficult problem. It is scarcely possible without systematic investigations at various altitudes, but we shall nevertheless try here to determine a probable lower altitude limit for the occurrence of permafrost, using the methods applied in the Arctic together with the findings already made in the Alps. First of all, therefore, we shall note the altitude data on permafrost discoveries in three regions.*

(a) Graubünden

Besides the locations already mentioned, discoveries are known at the following altitudes: 2300, 2400, 2600, 2700, 2800, 3050, 3200, 3300 m above sea level.

* At this point we wish to thank all engineers and the Division of Military Airfields for their information. It is obvious that in many instances we had to rely on information from local sources.

Discoveries above 2700 m are not exceptional. Permafrost at 2400 and even 2300 m, however, is a rarity, and it cannot be assumed that we may expect the regular appearance of permafrost at these altitudes.

(b) The Berne Highland

From this region discoveries have been reported to us at the following altitudes: 2900, 2900, 2950, 3000, 3450 m above sea level.

Schönholzer (correspondence), who has considerable experience in this area, believes that permafrost can be expected above 2600 m, but not below 2500 m.

(c) Wallis

The known occurrences are at altitudes of 2900, 2950, 3000, 3000, 3050 and 3300 m above sea level.

The permafrost at 3050 m here is interesting. It is situated in the embankment of the Gornergrat railroad. The embankment was built in 1896, so that the permafrost can certainly be regarded as a recent formation.

The three methods of determining the permafrost boundaries discussed in 2.5 were tested for five stations in Graubünden (Weissfluhjoch, 2670 m; Arosa, 1820 m; Davos, 1560 m; Splügen, 1460 m; Disentis, 1170 m). These are the only Graubünden stations for which we have temperature and snow depth data (except for Engadine).

Schostakowitsch's method (1927) (cf. 2.5) yields nonsensical values for our stations. Weissfluhjoch, for example, would not be in the permafrost zone; actually it has the same quotient as Arosa. Currently, therefore, this method is unsuitable for the part of the Alps we studying.

Grigor'ev's method (1930) was found, unfortunately, only in Frenzel's work(1967). As described there it is ambiguous and, depending on the interpretation, the lower boundary of the permafrost in our region would be around 3200 m or 1300 m, i.e., at altitudes that do not agree with the discoveries that have been made.

As a third method we may consider that of Pihlainen (1962). He plots the thaw index (cf. 2.5) on the abscissa against the MAAT on the ordinate of a system of coordinates. Permafrost occurences are then entered accordingly (continuous and discontinuous permafrost) and are separated by a straight line from observation points at which no permafrost was found. A second straight line separates the continuous from the discontinuous permafrost. We calculated the equations for these two lines as follows:

$$(1) \quad MAAT + \frac{T}{780} = 0, \qquad (2) \quad MAAT + \frac{T}{270} = 0,$$

where MAAT is the mean annual air temperature and T is the thaw index. In the case of an occurrence where (1) is greater than zero it is unlikely to be permafrost, otherwise it will be. If (2) is greater than zero it will be discontinuous, otherwise continuous permafrost.

Let us now try to apply these equations to the Swiss conditions. MAAT and T were determined from the climatic records of the MZA (Schüepp, 1960), whence we determined the altitudes for which the above equations are satisfied. For Graubünden (not counting Engadine), Engadine and Wallis these limiting values and the corresponding MAAT were calculated as follows:

	Lr. bound. discont.		Lr. bound. cont.	
Region	Alt.	MAAT	Alt.	MAAT
Graubünden	2350 m	−1,1° C	2550 m	−2,2° C
Engadine	2250 m	−1,4° C	2400 m	−2,3° C
Wallis	2400 m	−1,3° C	2550 m	−2,2° C

Two important facts emerge from this:

1. The MAAT at the lower boundary of the continuous permafrost agrees well with the value of -2^{o} C generally mentioned to date. (Note that these values lie below the climatic snow boundary which, according to Escher (1969), is situated at -5.5^{o} C MAAT.)
2. All permafrost discoveries known to us in these regions are situated above the lower boundary of the discontinuous permafrost.

Nevertheless it is by no means true that we must always expect to find permafrost above approximately 2500 m, for the influence of the exposure or the snow cover is too great. In our experience permafrost will be encountered above about 2500 m only under favourable local conditions, and will hardly be found at all below about 2300 m. A truly continuous permafrost zone is present in our Alps, if at all, only in the very highest regions.

To sum up what we have learned about the distribution of permafrost in the Alps, we can say that above around 2300 m isolated occurrences can be found (above approximately the -1^{o} annual isotherm). Above around 2500 m there is a high probability of permafrost wherever the local factors are favourable, as is the case above the -2^{o} annual isotherm.

4. Würm Permafrost in the Zürich Plain

Referring to permafrost in the glacier regions of the North, Poser (1948) has shown that in the terrain in front of an advancing glacier perennially frozen soil forms, but "the development of a climate producing the recession of the ice would, at the time of the start of recession, have progressed so far that not only would the formation of new perennially frozen soil be stopped, even its retention would no longer be possible" (p. 56). In the region of alpine glaciation conditions may have been different. Thus, Trümpy (1963) attributes the Tomahügel at Reichenau (confluence of the Vorder Rhine and the Hinter Rhine) to a rock slide in the late Würm, the debris from which slid apart over a perennially frozen soil. This extremely remarkable indication of permafrost after the recession of the ice masses in the alpine valley of the Vorder Rhine suggests that it is a definite possibility in the valley bottoms of the Alps at the end of the Ice Age.

Little is known as yet about the existence of Ice Age perennially frozen soils in the Swiss Midland. There are, however, Ice Age hanging valleys with concave cross sections and no valley floor, or elongated, dry synclinal ravines in the Zürich plain (Leeman, 1957) which can be readily explained by assuming intensive solifluction over permafrost. Soil forms of climatic origin testify to the existence of perennial frost, for example, fossil ice wedges and patterned ground on young Pleistocene gravelly surfaces.

"Both recent ice wedges and cryoturbated forms", aside from certain exceptions, presuppose permafrost. They serve as keys to it. Their fossil occurrence, therefore, justifies the assumption of a Pleistocene perennially frozen soil (Brüning, 1966, p. 81).

The presence of ice wedges and patterned soils on young Pleistocene gravelly surfaces has been conclusively demonstrated in the Rafzerfeld by Bachmann (1966). Other ice wedges have been noted at Henggart and Embrach. Ice wedges are items that appear near the surface and sometimes grow narrower in steps downwards (Plate 2). In the mentioned examples they have an overall depth of about 1 m. They can be dozens of meters long (horizontally). The fill corresponds to the capping material and is clearly differentiated from the mother rock (gravel). The latter shows distinct deformations in the vicinity of the edges of the ice wedges ("stratigraphic constrictions") (Figure 2). Recent ice wedges found in the Arctic are available for comparison. They are formed when the soil heaves at low temperatures. Melt water, unable to seep through the permafrost, freezes in the cracks. In the Rafzerfeld more or less perpendicularly intersecting ice wedges were found (Bachmann, L966), indicating a polygonal division of the soil. According to Brüning (1966), when the climate improves, the soil on the surface thaws first, sparing the ice wedges. When the ice wedge melts later it is replaced by capping material, and is thus fossilized. According to Hantke's map (1967), the ice wedge occurrences known to date in the Würm gravels that have been explored are situated in the vicinity of the area of maximum Würm glaciation. Hence, permafrost can be assumed to have existed in the Zürich plain in the high Würm period. In the Rafzerfeld the network of ice wedges is associated with patterned soils which, according to Leeman (1957), belong to the High to Late Glacial Era. Thus, there was probably permafrost at that time as well. On lower-lying "erosion terraces" in the vicinity of low-terrace gravels and late Würm deposits no forms indicating a late Würm permafrost have as yet been found.

The former permafrost in the Zürich plain would indicate a mean annual temperature about 12-14^{o} C cooler than the present (Furrer, 1966).

The basic importance of the permafrost is that is had a decisive effect on the morphological processes during the ice ages, while Büdel (1969 p. 25 ff.) has drawn attention to the decisive effect of the ice crust (the top 0.5 m of the perennially frozen soil) on the erosion processes.

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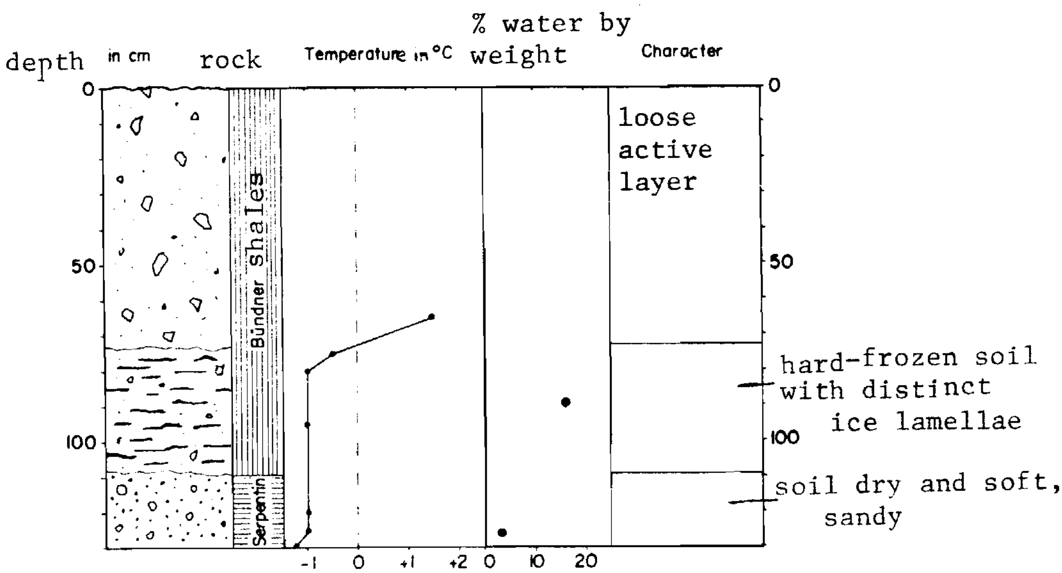

Figure 1

Permafrost on the Fuorela da Fäller (2830 m) on August 12, 1969

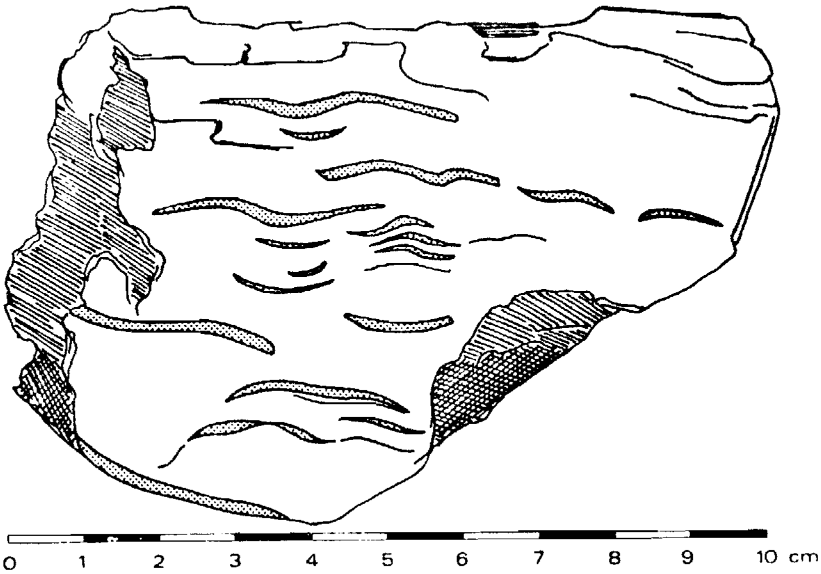

Figure 2

Sketch of a hand-site specimen of permafrost with ice lamellae (dotted shading)

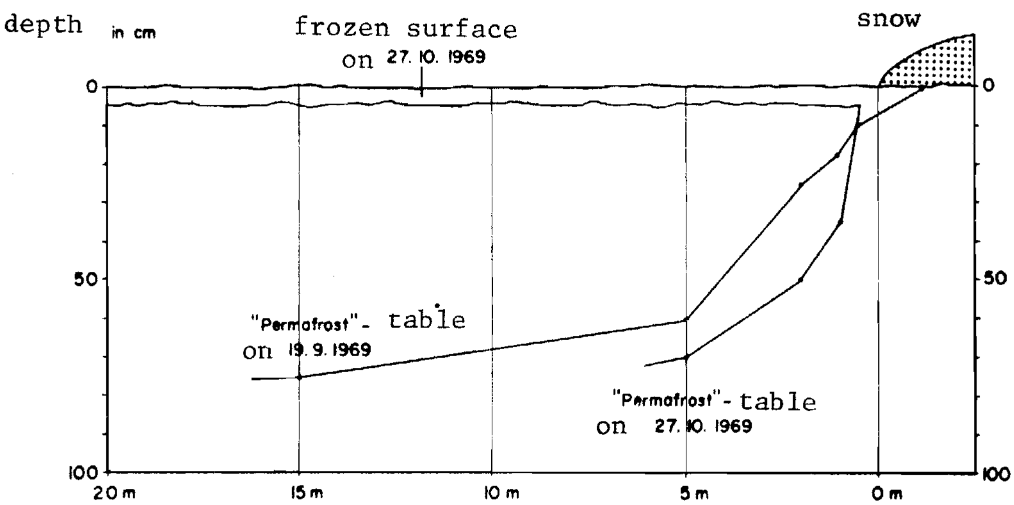

Figure 3

"Permafrost" in the Totälpi (2810 m), after Freund

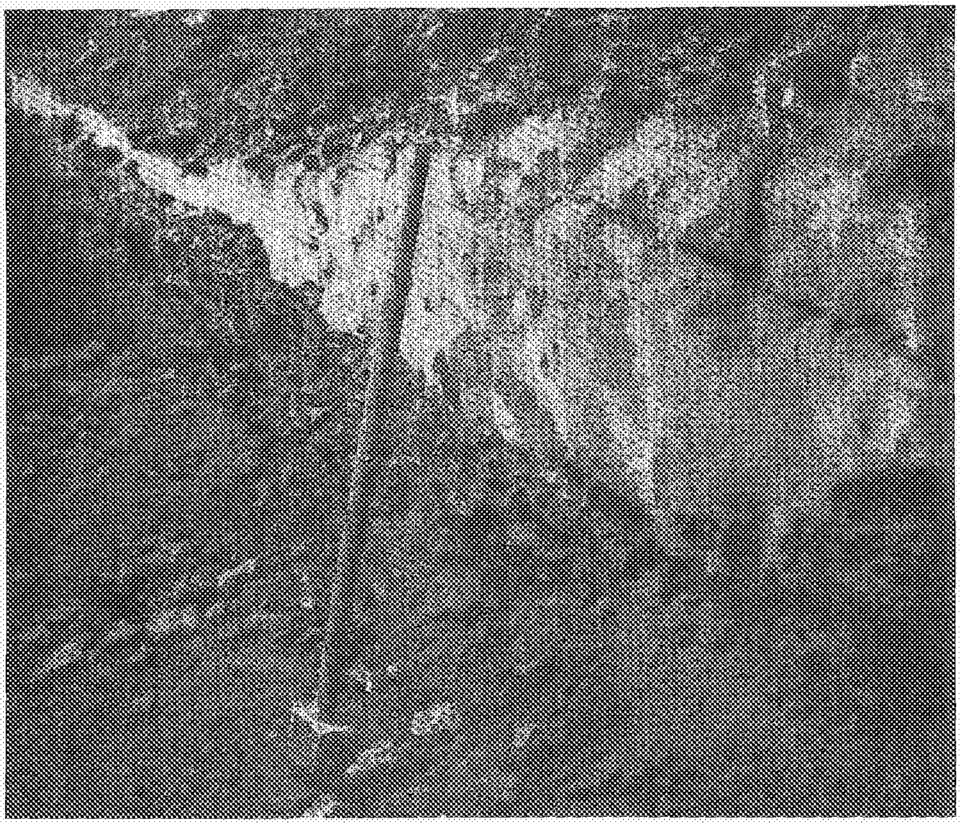

Plate 1

Ice lens at a depth of about 5 m (Schilthorn peak station, 3000 m), by kind permission of Gebr. Gruner, Engineering Office, Basel

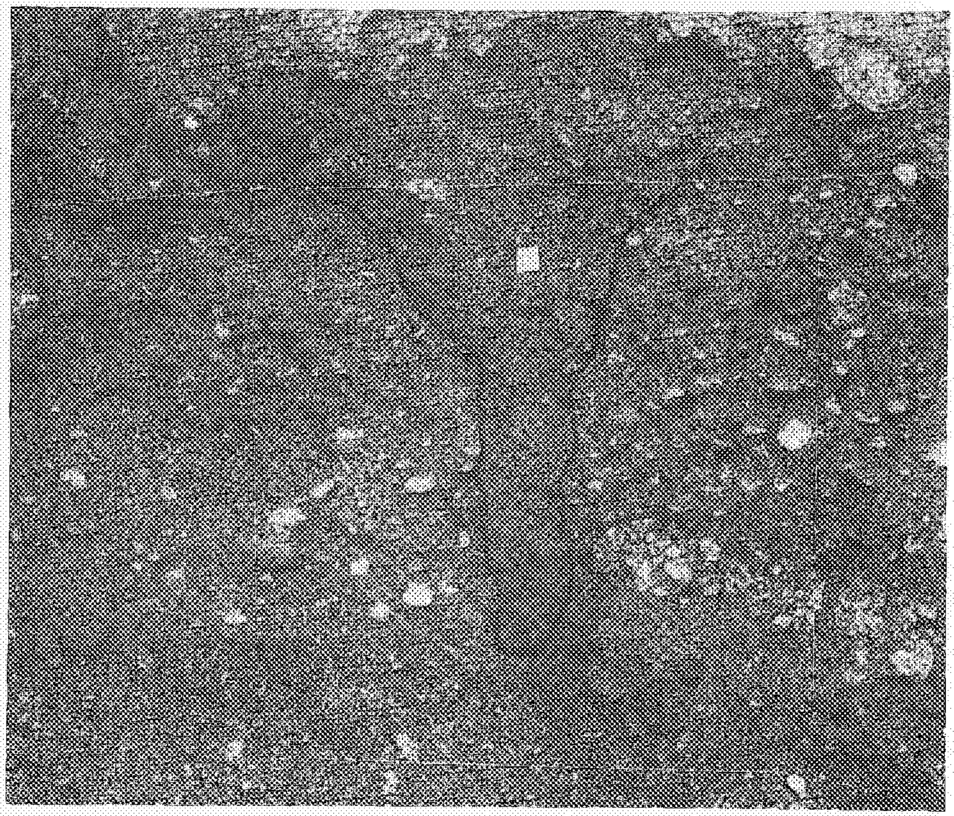

Plate 2

Ice wedge in the Rafzerfeld. Grid size 1 m (Photo F. Bachmann)