ANALYSIS OF A 20 m. FIRN PIT ON THE KESSELWANDFERNER (ÖTZTAL ALPS)*

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Abstract. The firn stratification in the accumulation area of an alpine glacier was studied in a 20 m. deep, vertical pit dug in the summer of 1963 on the Kesselwandferner (3,240 m. above sea-level in the Ötztal Alps). The firn is traversed by ice layers up to 25 cm. in thickness which have been formed by the damming up and freezing of melt water. Firn density increases with depth. At a depth of 13 m. (8 yr. old firn) the density reaches 0·80 g./cm.³ as a mean value of one annual net accumulation. Excluding the ice layers, the firn reaches a density of 0·82 g./cm.³ in a 10 yr. old layer at a depth of 16 m. The firn stratification in relation to seasons was studied by analyses of the pollen content in the lower part of the pit, beginning with the horizon "late summer 1954". The late summer horizons obtained from the firn stratification were confirmed by the pollen analyses.

Résumé. *Analyse d'un puits de 20 m dans le névé du Kesselwandferner (Alpes d'Ötztal).* La stratification du névé dans la zône d'accumulation d'un glacier alpin a été étudiée dans un puits vertical de 20 m de profondeur creusé pendant l'été 1963 au Kesselwandferner (3 240 m au-dessus du niveau de la mer dans les Alpes d' Ötztal). Le névé est traversé de couches de glace ayant jusqu'à 25 cm d'épaisseur qui ont été formées par la retenue et le gel des eaux de fonte. A une profondeur de 13 m (névé de huit ans) la densité atteint 0,8 g/cm³ valeur moyenne pour une accumulation nette annuelle. En excluant les couches de glace, le névé atteint une densité de 0,82 g/cm³ dans une couche de 10 ans à 16 m de profondeur. La stratification du névé par rapport aux saisons a été étudiée par l'analyse du pollen contenu dans les parties plus basses du puits, à partir de l'horizon "fin de l'été 1954". Les horizons de fin d'été connus à partir de la stratification du névé ont été confirmés par l'analyse de leur contenu en pollen.

Zusammenfassung. *Analyse eines 20 m tiefen Firnschachts am Kesselwandferner (Ötztaler Alpen).* In einem 20 m tiefen, senkrechten Firnschacht, der im Sommer 1963 am Kesselwandferner (Ötztaler Alpen) in 3240 m Seehöhe gegraben wurde, wird die Stratigraphie im Akkumulationsgebiet eines Alpengletschers studiert. Die Firnschichten sind mit bis zu 25 cm dicken Eisschichten durchzogen, die sich durch Stauung von Schmelzwasser und Frieren gebildet haben. Die Firndichte nimmt mit der Tiefe zu und erreicht in 13 m Tiefe (8 Jahre alter Firn) als Mittelwert einer Jahresrücklage den Wert 0,80 g/cm³. Bei Ausschluss der Eislamellen erreicht der Firn in der 10 Jahre alten Schicht (16 m Tiefe) die Dichte 0,82 g/cm³. Die jahreszeitliche Firnstratigraphie wurde im tieferen Teil des Schachtes ab Horizont "Herbst 1954" pollenanalytisch untersucht. Die aus der Firnstratigraphie abgelesenen Herbsthorizonte wurden durch die Pollenanalyse bestätigt.

Introduction

In the summer of 1963 a firn pit was dug to a depth of 20 m. on the Kesselwandferner (3,240 m. above sea-level in the Ötztal Alps). The aim of this investigation was to study the firn stratification in relation to the annual net accumulation of previous years. Firn samples were taken from all layers and pollen analyses were carried out on some of them. These samples will be examined later for radioactivity resulting from atmospheric fall-out.

Area of Investigation

The site of the firn pit has been designated L58 by Hoinkes and Rudolph (1962, fig. 1). Since the International Geophysical Year (1957–58) the Kesselwandferner has been included in the mass budget programme which was started in 1952 (Hoinkes and Rudolph, 1962). This pit is still accessible and can be used for further studies.

In 1956 H. C. Hoinkes dug an 11 m. deep firn pit at approximately the same place in order to study the stratigraphy of the annual net accumulation (Hoinkes, 1957). At the end of every budget year since 1958, the water-equivalent of the annual net accumulation of the past budget year has been determined by measuring the density profile at that locality. However, for various reasons this series of measurements is incomplete. By using the 20 m. deep pit it was possible to complete the series of studies.

* Dedicated to Gerald Seligman on the occasion of his graduation to the degree of Dr. Phil. *honoris causa* in the Universität Innsbruck.

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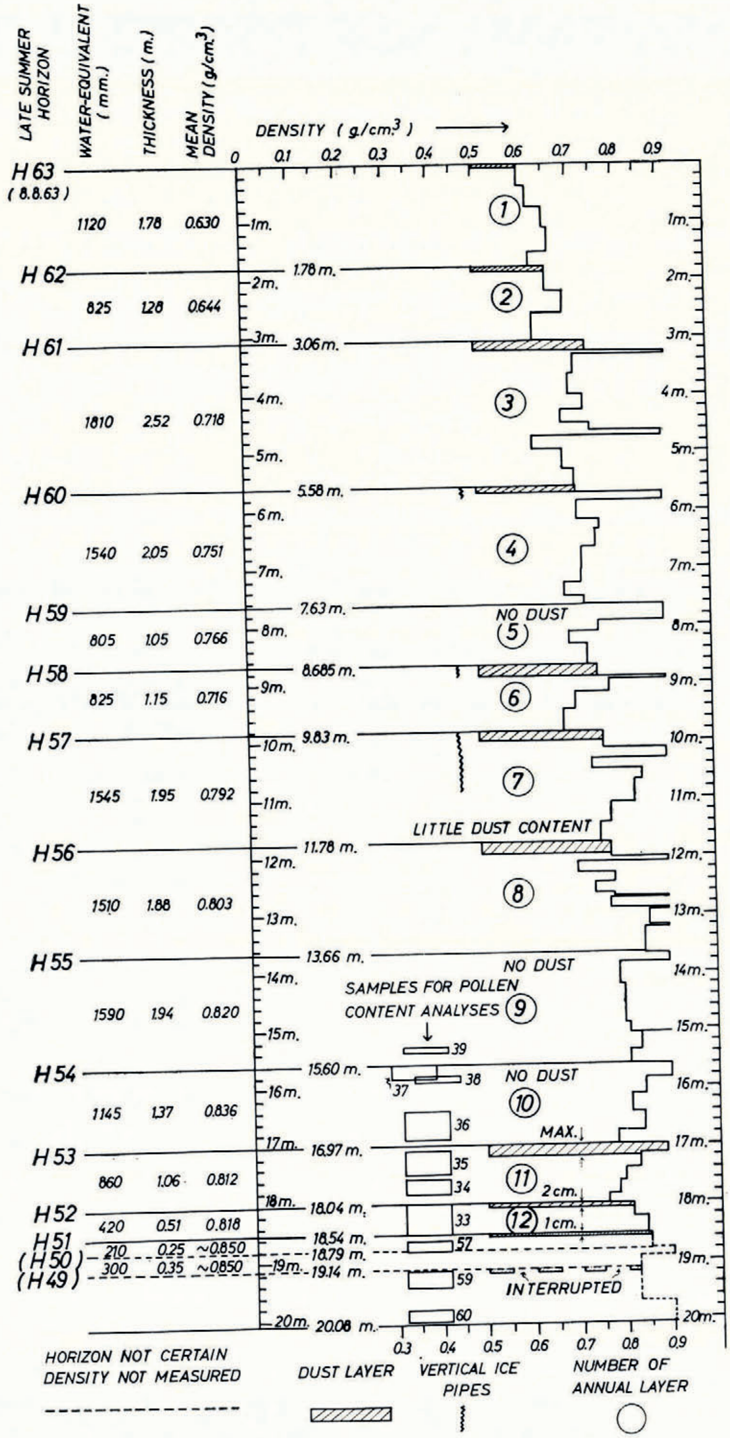

Fig. 1. Density profile of the 20 m. pit at locality L58 (Kesselwandferner, 3,240 m. a.s.l.)

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Determination of the Horizons of the Annual Layers

Identification of the late summer horizons was comparatively easy, because the approximate water-equivalents of the respective accumulation layers were already known from density-profile measurements made during the autumn controls. A dust layer on top of an ice layer which reached a maximum thickness of 25 cm. was the best means of identifying the late summer horizon. However, in some instances, either the dust layer or the ice layer was absent.

It is not difficult to understand the origin of the characteristics of the annual horizons. The dust layer forms during the ablation period by the deposition of dust from the rock faces surrounding the firn. The ice layer forms when the free water in the firn freezes at the end of the ablation period. Measurements made by Ambach (1963, p. 103) confirm that in the firn layer near the surface the amount of free water is especially large. In the following year, the ice layer thus formed results in slight damming up of melt water derived from younger firn layers. It is therefore possible that when freezing occurs during the subsequent autumn the ice layer may rise, allowing the depth-hoar of the superimposed annual layer (Hoinkes, 1957) to become solidified. This process could continue until such time as the ice layer being investigated has reached a depth below the range of the winter cold.

For an individual case (the horizon for the "late summer of 1954"), the determination of the annual horizon by dust- and ice-layer analysis was doubtful. Even though there was a distinct ice layer (25 cm. thick), a dust layer was not visible. As a result of pollen analyses carried out by S. Bortenschlager, this ice layer could be clearly recognized as the horizon for the "late summer of 1954".

Firn Stratification and Density Profile

After digging down to a depth of 20 m., the density profile was determined with the aid of a snow sampler (50 cm.^{2} cross-section) provided with a drill bit. On an average a 20 cm. thick firn layer was weighed by using a steelyard. The sample was chosen in such a way that the density was as homogeneous as possible. However, thick ice layers were split up and in this case, for calculation of the water-equivalent, their density was assumed to be 0·9 g./cm.^{3}. Density measurements could be made as far down as the horizon for the "late summer of 1951". The snow sampler used was unsuitable for sampling the deeper ice layers for density measurements. Below the horizon for the "late summer of 1951" no further horizon could be clearly identified by density measurements and only stratification was studied in these layers.

Because the previous year's firn layer was considerably disturbed by digging, density measurements were commenced at the horizon for the "late summer of 1962". However, the density profile of the previous year's accumulation was studied in an undisturbed area adjacent to the main pit.

Figure 1 shows the density profile obtained by sampling. Ice layers that could not be cut by the snow sampler are shown as a single layer with a density of 0·9 g./cm.^{3}. Thin ice layers could be cut easily with the snow sampler and they were also weighed. The dust layers were especially prominent in the profile. Vertical intrusions in the form of small ice pipes were detected in some of the layers and they are indicated as vertical wavy lines (e.g. "horizon 1960"). The density values below the horizon for the "late summer of 1951" are only estimated from the ice structure. In the profile above this horizon ten ice layers are thicker than 4 cm. and five are thicker than 10 cm.

After calculation of the water-equivalent of the annual net accumulation, the increase in mean density with depth was determined. The ice layers were included in this calculation. Figure 2 shows the mean density of the annual net accumulation plotted against depth. It cannot be expected that any definite law of densification is obeyed, because the mean density depends on the number and thickness of the ice layers present in the profile. Densification is not only due to compression but also to the formation of ice layers (Ambach, 1961). After

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8 yr. (at a depth of approximately 13 m.), the density becomes greater than 0·80 g./cm.³. The transition from firn to ice is a continuous process. According to Seligman (1941) it does not entail a change of density and grain-size. As soon as the air bubbles and capillaries in the packed firn begin to coalesce, the firn becomes impermeable glacier ice. The transition occurs at a density of 0·82–0·84 g./cm.³. This means that the lowermost layers in the pit would have to be regarded as ice. This is confirmed by a further observation. At the bottom of the pit, at a depth of 20 m., a water layer (40 cm.) developed and consequently digging could not be continued. Deeper layers were clearly already completely impermeable and therefore the transition from firn to impermeable glacier ice takes place at a depth of 15–20 m. If the ice layers are not considered, the firn in the 10 yr. old layer (16 m. depth) has a density of 0·82 g./cm.³. However, in the 11 yr. old accumulation layer below there are layers with a lower density (0·76 g./cm.³). Since no porosity measurements were made, the transition from firn to glacier ice can only be discussed in terms of a comparison of densities.

Water-equivalents

Figure 1 shows the water-equivalents, thicknesses of layers and the average firn densities. Table I gives both the water-equivalents determined and a comparison with water-equivalents determined during the annual autumn controls for the annual net accumulation as far back as the horizon for the "late summer of 1956".

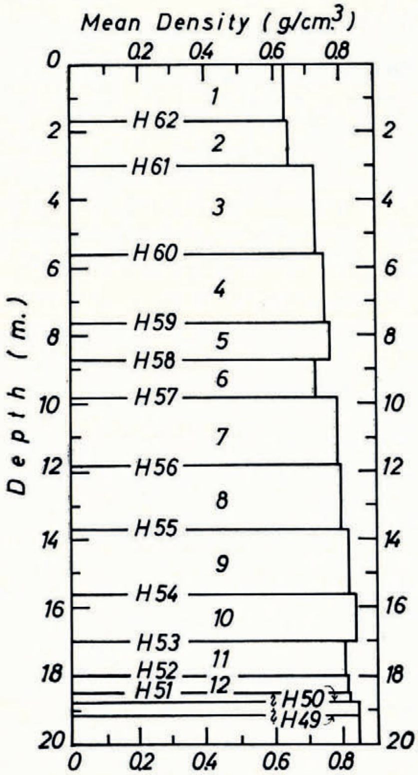

Fig. 2. Mean density of annual net accumulation plotted against depth for locality L58 (Kesselwandferner, 3,240 m. a.s.l.)

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TABLE I. WATER-EQUIVALENTS AT L58 (KESSELWANDFERNER, 3,240 m. a.s.l.)

Layer number	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Budget year	1962–63	1961–62	1960–61	1959–60	1958–59	1957–58	1956–57
Net accumulation (mm. water-equivalent)	1,120[a]	825	1,810	1,540	805	825	1,545
Depth (m.); lower part of layer	1·78	3·06	5·58	7·63	8·69	9·83	11·78
Mean density of annual net accumulation (g./cm.^{3})	0·630	0·644	0·718	0·751	0·766	0·716	0·792
Net accumulation; autumn control* (mm. water-equivalent)	1,220	790	1,900	1,755[c]	735	855	1,680
Date of autumn control	1.10.1963	20.9.1962	2.10.1961	18.10.1961	1.10.1959	2.10.1958	25.8.1958

Layer number	*8*	*9*	*10*	*11*	*12*	*13*	*14*
Budget year	1955–56	1954–55	1953–54	1952–53	1951–52	1950–51	1949–50
Net accumulation (mm. water-equivalent)	1,510	1,590	1,145	860	420	210[b]	300[b]
Depth (m.); lower part of layer	13·69	15·60	16·97	18·04	18·54	18·79	19·14
Mean density of annual net accumulation (g./cm.^{3})	0·803	0·820	0·836	0·812	0·818	0·85[b]	0·85[b]
Net accumulation; autumn control* (mm. water-equivalent)	1,750[c]	—	—	—	—	—	—
Date of autumn control	24.8.1956	—	—	—	—	—	—

[a] Measurement made on 8 August 1963.
[b] Density estimated, horizon uncertain.
[c] Value uncertain.
* Professor H. C. Hoinkes kindly provided these unpublished data for comparison purposes.

The accumulation for the budget year 1962–63 can be given with close approximation. The density profile measured during the autumn control (on 1 October 1963) contained 45 cm. of fresh snow which had accumulated after the middle of August. In this case the dust horizon marked the end of the long period of fine weather in the summer of 1963, i.e. about mid-August. Therefore, a dust horizon does not necessarily indicate the end of the budget year with respect to the whole glacier.

For the purpose of comparison, the water-equivalents of the pit and those of the autumn controls are shown in Figure 3. The 1962–63 accumulation was therefore not taken into consideration for the reason given above. The data for the annual net accumulation which could not be determined at exactly the end of the budget year, i.e. 1959–60 and 1955–56, were completed by the results obtained from the pit. The water-equivalents derived from the pit and those measured during the autumn controls agree quite satisfactorily. The total water-equivalent from the late summer of 1955 until the late summer of 1962, as determined in the pit, amounts to 8,860 mm. water, and the sum of the measurements during the autumn controls is 8,960 mm. water. The difference between the two sets of measurements is only 100 mm. water (1·2 per cent).

Since the layers in the 1963 and 1956 pits partly overlap, a comparison is also possible for the overlap zone. The water-equivalents of the net accumulation during those years are generally small. Due to local differences in the net accumulation, the respective horizons are displaced as regards their depths and therefore a positive identification of horizons and their correlation between the two pits is not possible.

The identification of the horizons "late summer of 1950" and "late summer of 1949" is vague in the 1963 pit, as they were determined only by pollen analyses and they were not positively confirmed stratigraphically. However, a 13 cm. thick ice layer, which lacks definite impurities, could be identified as the horizon for the "late summer of 1950". A partly brownish ice band was identified as the horizon for the "late summer of 1949".

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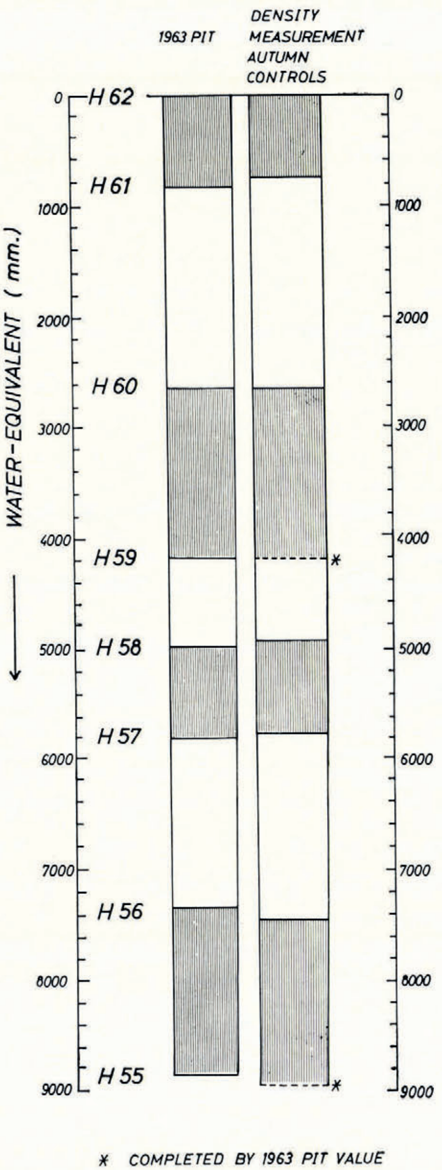

Fig. 3. Comparison of the totals of water-equivalents for annual net accumulation taken from the 1963 pit and from density measurements during annual autumn controls at locality L58 (Kesselwandferner, 3,240 m. a.s.l.)

Analysis of Pollen Content in Relation to the Firn Stratigraphy

Pollen analyses of firn samples were carried out by S. Bortenschlager (Botanisches Institut der Universität Innsbruck) in order to control the lower late summer horizons beginning with that for the "late summer of 1954". Figure 1 gives the numbers and locations of the samples studied and Table II shows the results of the pollen analyses.

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TABLE II. RESULTS OF THE ANALYSES OF THE POLLEN CONTENT OF THE SAMPLES. VALUES ARE GIVEN IN PERCENTAGES
(for samples with a very small pollen content the number of pollen grains obtained is given in brackets)

Sample	Pollen and spores												Relative pollen and spore contents	Relative mineral dust content	Conclusion
39	*Abies*	1·2	Gramineae	8	*Chenopodium*	2·3	Compositae liguliflorae	2·3					small	medium	
	Picea	14	Cerealia	1·2	*Plantago*	2·3									
	Pinus	37	Cyperaceae	3·5	*Rumex*	2·3	*Dryopteris*	1·2							
	Quercus	1·2	*Calluna*	1·2	Rosaceae	1·2	*Lycopodium*	1·2							
	Corylus	2·3	*Artemisia*	2·3	*Centaurea*	1·2	*Ephedra* cf. *altissima*	1·2							
38	*Abies*	0·3	*Betula*	4·2	Gramineae	3·8	*Castanea*	1·2	Compositae tubuliflorae	0·7	Rubiaceae	0·3	medium	medium	Late summer horizon between samples 39 and 37
	Picea	15	*Alnus*	8·5	Cerealia	0·7	*Vaccinium*	4·5	Compositae liguliflorae	1					
	Pinus	43	*Corylus*	10	Cyperaceae	0·7	*Thalictrum*	0·3	*Plantago*	0·3					
	Larix	0·7	*Salix*	0·3	*Calluna*	0·3	Umbelliferae	0·7	*Chenopodium*	0·3					
	Ulmus	1			*Juniperus*	1	*Centaurea cyanus*	0·3	Caryophyllaceae	0·3					
							Ranunculus	0·3							
37	*Abies*	0·2	*Quercus*	0·2	*Artemisia*	0·7	*Rumex*	0·2					very large	large	
	Picea	2·6	*Salix*	0·2	*Calluna*	0·2	Compositae tubiliflorae	0·7							
	Pinus	82	*Castanea*	0·6	*Filipendula*	0·2	*Dryopteris*	0·4							
	Betula	1·1	Gramineae	4	*Chenopodium*	0·4	*Ephedra* cf. *altissima*	0·2							
	Alnus	3·1	Cyperaceae	0·4	Umbelliferae	0·2									
	Corylus	1·1													
36	*Picea*	(8)	Gramineae	(1)									very small	very small	
	Pinus	(8)	*Vaccinium*	(1)											
	Ulmus	(1)	Compositae tubuliflorae	(1)											
35	*Picea*	9	*Corylus*	4	*Vaccinium*	1	Compositae liguliflorae	1					small	medium	Late summer horizon between samples 36 and 35
	Pinus	63	*Fraxinus*	1	Umbelliferae	2·3	*Botrychium*	1							
	Betula	1	Gramineae	6	*Rumex*	2·3									
	Alnus	2	*Artemisia*	1	*Plantago*	2·3									
	Castanea	1													
34	*Pinus*	(9)											very small	very small	Late summer horizon between samples 34 and 33
	Gramineae	(2)													
	Artemisia	(1)													
	Chenopodium	(2)													
	Helianthemum	(1)													
33	*Picea*	13	*Acer*	0·3	Gramineae	2·8	*Vaccinium*	0·8	Caryophyllaceae	0·3	Compositae tubuliflorae	0·5	large	large	Thickness of sample 33 approximately corresponds to one annual layer
	Pinus	65	*Carpinus*	0·3	Cerealia	0·3	*Chenopodium*	1	*Rumex*	0·3					
	Betula	3·8	*Fraxinus*	0·5	Cyperaceae	0·3	*Helianthemum*	0·5	*Polygonum*, cf. *bistorta*	0·3					
	Alnus	2·5	*Ulmus*	0·3	*Artemisia*	1·3	*Plantago*	0·5	*Ranunculus*	0·3					
	Corylus	1·8	*Fagus*	0·3	*Calluna*	0·8	Rosaceae	0·8	Umbelliferae	0·3					
57	*Picea*	10	*Castanea*	1·5	*Calluna*	1·9	Caryophyllaceae	0·3	Compositae	1·9			large	large	Late summer horizon in sample 57
	Pinus	56	*Fagus*	1·2	Rosaceae	0·3	*Plantago*	1·5	tubuliflorae	1·9					
	Betula	2·2	Gramineae	2·2	*Chenopodium*	1·9	*Rumex*	0·6	*Dryopteris*	3·7					
	Alnus	3·1	Cerealia	0·3	Umbelliferae	0·9	*Ranunculus*	0·6	*Ephedra* cf. *altissima*	0·3					
	Corylus	1·5	*Artemisia*	7·1	*Campanula*	0·9	*Filipendula*	0·3							
59	*Abies*	0·2	*Corylus*	8·1	Gramineae	7	*Campanula*	0·2	*Rumex*	0·6	*Pteridium*	0·2	large	large	Late summer horizon immediately above sample 59
	Picea	8·5	*Salix*	0·8	Cerealia	0·2	*Chenopodium*	0·8	*Rhamnus*	0·2					
	Pinus	34	*Juglans*	0·2	*Artemisia*	1·9	Umbelliferae	1·1	*Ranunculus*	0·2					
	Betula	8·7	*Castanea*	0·6	*Juniperus*	0·9	*Helianthemum*	0·2	Compositae tubuliflorae	0·8					
	Alnus	20			*Vaccinium*	0·4	*Plantago*	0·6	*Dryopteris*	0·4					
60	*Abies*	1	*Ulmus*	1	*Saxifraga*	1	Umbelliferae	1					small	medium	No conclusion possible, as distance between samples 59 and 60 is too great
	Picea	7	Gramineae	4	Rosaceae	1	Compositae tubuliflorae	1							
	Pinus	49	Cerealia	1	*Plantago*	2	*Dryopteris*	2							
	Betula	13	*Artemisia*	2	*Helianthemum*	1									
	Alnus	6	*Calluna*	2	*Rumex*	1									

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Horizon for the "late summer of 1954"

In order to control the horizon for the "late summer of 1954", a sample (39) from a firn layer just above this horizon and two further samples (37, 38) from a firn layer just below this horizon were studied. The upper sample (39) contained mainly autumn pollen and no spring pollen, but the two samples taken from below this horizon (37, 38) contained mainly spring and summer pollen. Therefore, the ice layer at a depth of 15·80 m. was confirmed as the horizon for the "late summer of 1954".

Horizon for the "late summer of 1953"

To control the horizon for the "late summer of 1953", a sample (36) which had been taken between 10 and 60 cm. above this horizon was studied. This layer could be regarded as a winter layer, because of its small amount of pollen and dust. Only a few displaced pollen grains were found. A further sample (35) taken from a depth of between 10 and 50 cm. below the horizon for the "late summer of 1953" was also analysed. This layer could be identified as a spring layer because of its anemogamous tree pollen content. The horizon for the "late summer of 1953" which had already been recognized from the firn stratification was therefore confirmed by pollen analysis.

Horizon for the "late summer of 1952"

Sample 34 was taken from a depth of between 15 and 65 cm. above the horizon for the "late summer of 1952". The result obtained by pollen analysis proved that this was a winter layer, which agreed with the stratigraphic analysis.

Horizon for the "late summer of 1951"

Between the horizons for the "late summer of 1952" and the "late summer of 1951" a sample (33) which covered the whole of what was presumed to be the annual net accumulation was studied. In addition to spring pollen it also contained summer and autumn pollen. Therefore, the horizon for the "late summer of 1951" was confirmed by pollen analysis. The large amount of dust in the sample also confirmed this interpretation.

Horizon for the "late summer of 1950"

A sample (57) taken from 10–30 cm. below the horizon for the "late summer of 1951" contained both summer and autumn pollen. On the basis of the stratigraphic analysis of firn at this depth, an ice layer without a distinct dust content could be recognized at 18·80 m. But when a microscopic examination was carried out a particularly large number of dust particles was found in the sample. Consequently, the upper margin of the ice layer, at a depth of 18·80 m., was interpreted as the horizon for the "late summer of 1950".

Horizon for the "late summer of 1949"

Sample 59, taken from between 40 and 70 cm. below the horizon for the "late summer of 1950", lay beneath a partly brownish ice band. Pollen analysis confirmed that this layer had been formed between spring and late summer. Microscopic analysis revealed a high percentage of dust. Therefore, the brownish ice band can be regarded as being the horizon for the "late summer of 1949".

Sample 60 was taken from the lowest compacted ice layer at a depth of 20 m. The pollen and dust content of the sample was small and only a few late summer and spring pollen grains were found. On the basis of these findings this ice layer was regarded as a winter accumulation. However, the identification of the horizon below this was uncertain, since the distance between samples 59 and 60 is too great.

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Attempted Ice-fabric Analysis

F. Purtscheller and G. Eisbacher (Institut für Mineralogie und Petrographie der Universität Innsbruck) attempted to study the ice fabric microscopically. Precisely orientated preparations were necessary for this experiment in order to obtain a statistical orientation of the optic axes (*c*-axes) of the individual crystals. The crystals (1–3 mm.) in the samples were too small to follow exactly the method of preparation described by Bader and Rigsby (Rigsby, 1960). The prevailing local temperature caused rapid melting to such a degree that it was impossible to measure the number of grains in the field necessary for statistical purposes, especially since the grain-size was already small in relation to the thickness of the section. As far as could be observed, the porosity of a sample of normal firn from a depth of 20 m. is still so high that greater preferred orientation of the individual crystal optic axes is not likely to exist.

Technical Data

The cross-section of the pit (2 m. in diameter) was approximately circular and it was dug with the aid of a spade, a shovel and a pick-axe. It was only possible to use a pneumatic drill for a short time and not much time was gained from the use of this device. A tripod made of iron rods was positioned over the pit and the spoil was pulled up with the aid of a double pulley. After the studies had been completed the pit was covered and it will probably be preserved for future experiments. Transport of the apparatus and cargo to and from the pit was carried out by a Piper Supercub aeroplane provided by the Austrian Ministry of the Interior.

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