Manuscript received 27.5 1959.

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* Plates XIV and XV and
Maps I—III are in a pocket in the back cover.

Preface

Before I pass on to the dry, matter-of-fact chapters which follow I may be permitted to begin with a declaration of love for Spitsbergen and more particularly for Tempelfjorden and Tempelfjellet. The four of us who formed the little expeditionary group from Uppsala University to Tempelfjorden in 1954 were doubtless all equally grateful for the experience of seeing this iridescent and beautiful landscape. It is a combination of Polar sea and Arctic mountain into a unity of infinite, free expanses of sea, of mountain and of glacier. I do not believe there exists a fresher, freer and fairer range of natural scenery.

From a practical point of view there are both advantages and disadvantages in choosing remote areas for investigation. One of the disadvantages in this case has been that I have not had an opportunity of going back to Tempelfjorden later, in order to fill up the gaps which my material naturally has after so short a time in the field as a full four weeks.

There are perhaps two authors especially, who by their writings have stimulated me in my now completed labours. One is B. Högbom by his fundamental study (1914) of frost weathering of rocks on Spitsbergen. The other is J. Büdel, who in 1948 drew up the guiding lines of a climate-morphological classification and descriptive account of the cold regions which has been fruitful for research. That I have afterwards in essential points come to conclusions other than those of the authors mentioned and of earlier investigators does not imply that the value of their contribution is diminished. They were pioneers who smoothed the way for continued research.

Professor Filip Hjulström gave the initiative impulse to the Spitsbergen expedition. It was through his support that it came into existence. His stimulating and experienced guidance has been of decisive importance for the arrangement and reporting of my material.

My comrades, Docent Å. Holm and Fil. lic. T. Roos, Zoologiska institutionen, Uppsala, and Mr. H.-E. Dahl, Narvik, have the credit of an expedition successful in all respects and characterized by an extraordinarily good comradeship. 2

Dr. A. Orvin and Mr. B. Luncke, director and engineer respectively of the Norwegian Polar Institute, Oslo, have supplied and allowed me to use maps and aerial photographs of fundamental importance for my thesis. Dr. Orvin has with great goodwill had the report printed and included in the Institute's series of "Skrifter"

Professors G. Hoppe and S. Rudberg, Docent Å. Sundborg and other teachers and colleagues from Geografiska institutionen in Uppsala have given me many valuable points of view and suggestions.

Mrs. E. H. de Geer has kindly allowed me to use picture material from the G. de Geer collections.

I have had a great advantage in being able to call upon the services of the staff of Geografiska institutionen to set in order a part of the material in a state ready for printing. Mr. Tiit and Mr. Ludvigsen, the cartographers, skilfully executed the text figures and Mr. Eriksson, the photographer, excellent prints and enlargements of photographs, which has been of specially great importance for this thesis.

Fair copies of the Maps Nos. I-III were drawn by Mr. Evensen, of the Norwegian Polar Institute. The thesis was translated into English by Neil Tomkinson, B.A.

Financial contributions for the field work have been received from the following funds and institutions:

Andréefonden (Swedish Geographical Society),
Bjurzons, Liljevalchs, Sederholms fonder (Univ. of Uppsala),
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To my wife and to all private persons and institutions who have helped me with my work on this thesis I extend my warmest thanks.

Anders Rapp.

Geografiska institutionen,
University of Uppsala,
March, 1959.

Introduction

1.1 PURPOSE OF THE INVESTIGATION

The land forms in nature are subject to a breaking down, the purpose of which is to obliterate the irregularities. The breaking down works by different means and at a different rate depending on the type of slope, the rock, the climate and the vegetation.

The study of the forms and development of the slopes within different geological and climatic environments is a central and topical subject in geomorphology. One of the main courses in the study of slopes concerns intensive studies in the field in small typical localities (Macar, Birot, 1955, p. 14 f.). This investigation has rather the character of such an intensive study in an Arctic locality. It is the author's intention to present in a future report similar studies from more southerly climatic environments for comparison.

It is considered that denudation works exceptionally rapidly on Spitsbergen, principally through intensive frost-weathering and solifluction (Högbom, 1914; Dege, 1949; Büdel, 1948 and 1953; and others) in the land areas which lie outside the glaciers and which lack close vegetation (the frost-shatter zone[1]). "Die Frostschuttzone zeigt unter allen klimamorphologischen Zonen der Erde die grösste Abtragungsintensität." (Büdel, 1948, p. 40.) "Von den gewaltigen Trogtalformen, die das Inlandeis einst auch auf Spitzbergen . . . geschaffen hatte, ist fast nur noch die stark geradlinige Erstreckung aller grossen Täler übrig geblieben." (Op. cit., p. 47.)

With regard to the points of view quoted above, the author considered that on Spitsbergen if anywhere it should be possible to calculate the rate of recent denudation[2], *inter alia,* by comparing pictures of suitable talus slopes and their cliffs, photographed at intervals of several decades. The purpose of the investigation can in short be formulated thus: to

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[1] "Frostschuttzone" according to Büdel, 1948, p. 31.

[2] Denudation (here in a wide sense) = the combined effects of weathering and transport (Holmes, 1945, p. 24).

describe the shapes of the talus formations and their transport processes in a typical locality on Spitsbergen with supposedly rapid recent denudation. The description aims principally at an attempt at *reconstruction of the morphological development of these talus formations and the mountain walls belonging to them.*

1.2 TALUS SLOPES, THEIR FORM AND DEVELOPMENT A SHORT GENERAL PRESENTATION

A talus slope (or scree slope) consists of rock débris which has fallen down more or less continuously[1] from a weathering mountain wall[2] (scarp) and formed an accumulation whose surface slopes about 30-40° and has a straight or slightly curved lateral profile.[3] The material is usually angular stones and boulders, which often lie assorted according to size with the smaller particles at the top and the larger boulders at the base of the talus slope.[4] This so-called fall-sorting is caused by the fact that the larger boulders, owing to their greater kinetic energy (according to the formula $e = mv^2/2$, where e = kinetic energy, m = mass and v = velocity) and their greater radius, can roll further down than the small particles in a rock-fall.

Certain mountain walls weather and retreat more or less uniformly over the whole of the free wall surface. They can suitably be called *simple walls*. They undergo *uniform retreat*. It would, however, seem to be more usual for the wall to retreat unequally through the formation of rock-fall chutes[5] or funnels, which dissect the wall all the more. This type

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[1] In very large, instantaneous rockslides there are formed not talus but rockslide tongues (Heim, 1932, p. 106; Kolderup, 1955, p. 211; Rapp, 1957, p. 182).

[2] Mountain wall = steep, rocky slope, from which the weathered particles move by a free or a bounding fall (after Lehmann, 1933, p. 83). The inclination is about 40—90°.

[3] Many authors have measured and discussed the so-called maximum talus angle (angle of repose) and its dependence on the kind of rock, the particle size and the shape of the particles (see Piwowar, 1903; Stiny, 1926; Burkhalow, 1945; Malauric, 1949).

[4] This sorting has been described by a very large number of observers. Behre (1933, p. 624 f.) describes a sorting in reverse, with coarse at the top and fine at the base, and interprets this as "normal" for talus. Bryan (1934, p. 655) makes a conclusive criticism of Behre, but despite this the latter author's erroneous generalization has been made the basis of the description of talus formations in handbooks by Sharpe (1938, p. 32) and Lobeck (1939, pp. 81 and 92).

[5] Rock-fall chute (shortened to "chute" (Blackwelder, 1942, p. 328, and Baulig, 1956, p. 70)) = a gully or wide cleft in a steep, rocky slope, through which débris is moving by free or bounding fall (German "Steinschlagrinne"). Rock-fall funnel (shortened to "funnel") = a half-funnel-shaped excavation in a rock wall, wide above, narrow below, through which débris is moving by rock-falls (German "Steinschlagtrichter"). Large "funnels" are classified as cirques.

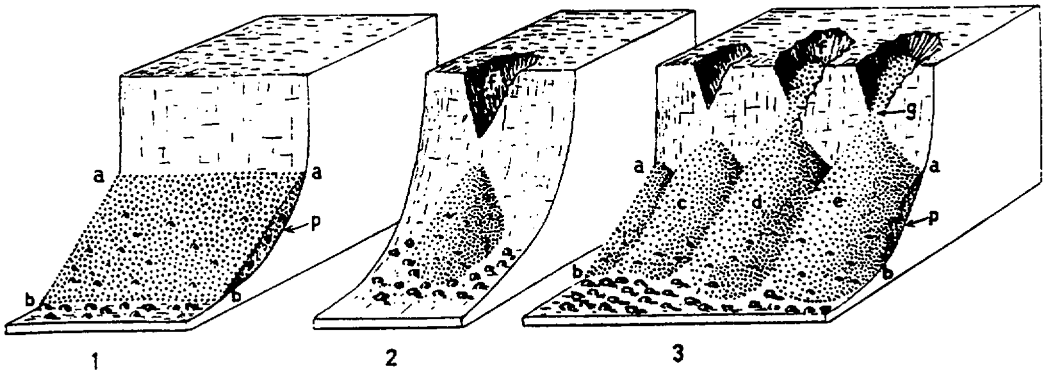

Fig. 1. The basic shapes of the talus formations. 1, Simple talus slope alongside a simple mountain wall. 2, A talus cone. 3, Compound talus slope alongside a dissected wall with rock-fall funnels.

a-a, talus crest. b-b, talus base with a base fringe of boulders in front of it. c, talus cone with a sheer top contour, as distinguished from d and e, which are proximally extended cones (hour-glass shaped). f, rock-fall funnel. g, funnel gorge (mouth of the funnel).

The talus accumulation is called by the comprehensive name of "talus mantle" irrespective of the forms. In a proximally extended talus cone the part which lies below the funnel gorge is called the "cone mantle".

can most simply be designated *dissected walls* and the corresponding retreat *dissection retreat.* Mount Templet's walls (Plate I) afford fine examples of regular dissection retreat.

Alongside a simple mountain wall is formed a *simple talus slope* (Fig. 1:1), alongside a wall with rock-fall chutes are formed *talus cones,* one in front of each chute. If the talus cones grow together laterally, they form a *compound talus slope* (cf. Bargmann, 1895, p. 70, and Poser, 1954, p. 143).

Many observations show that the talus material usually lies as a relatively thin layer of some few metres' thickness on top of a substratum of solid rock with approximately the same inclination as the talus surface. Morawetz (1933, p. 36) reports a thickness of 1-3 m, Malaurie (1950, p. 15) 2-5 m, and Young (1956, p. 125) 2-8 m in descriptions of talus formations from different environments. Even greater thicknesses have been reported, for example, by Fromme (1955, p. 39) up to 25 m and by Rapp (1957, p. 197) up to 35 m, but not even these maximum values amount to more than about $^1/_{10}$ of the height of the talus slope in question.

From a dynamic point of view the talus slopes can be designated as a first re-loading place for the weathered material on its way from the mountain wall to the sea or the lake. The movement of material in and from a talus slope can suitably be divided into the following stages:

Supply	Fall of débris from the wall down to the surface of the talus. It is terminated by the primary deposition of the particles.
Shifting	The movement of the material down the talus slope after the primary deposition.
Removal	Movement of the material away from the talus slope.

Supply usually occurs through smaller rock-falls from the wall and is terminated by the boulders and stones bouncing and rolling a short distance on their edges, before they remain lying on or below the talus surface.

Shifting and removal take place through processes which can work at a lower inclination than about 30—35°, for example, talus-creep, slides, snow avalanches, running water, etc. (see Rapp, 1957, p. 179 f.). Through the shifting and removal of the material the talus formation is levelled out, takes on a more and more concave profile (see Fig. 2) and may be transformed, for example, into an alluvial cone.[6]

In principle the development of a talus slope is conceived of in the following way (cf. Lehmann, 1933; Bakker, 1952; and others). A steep mountain wall weathers. The debris forms a talus slope at the foot of the mountain. According as the talus slope is supplied with more material, it increases in height with inclination preserved and an almost straight profile. The wall retreats and finally comes to be entirely covered with débris. On the retreat of the wall there is formed a more level slope of solid rock, which is covered over by the talus slope and which has about the same declivity. The new mountain slope, which forms the substratum of the talus slope is called by Lehmann (1933) a "rock nucleus" (German "Felskern"), by W. Penck (1924) "Haldenhang", by Howard (1942, p. 27) "subtalus buttress" and by Twidale (1959, p. 65) "sub-debris slope". Another term for it is "Richter's denudation slope" (Bakker 1952), here shortened to "Richter's slope" (Fig. 2).

The talus phase outlined above is an important element in the development of the slope from mountain wall to level surface. Our knowledge is still small as concerns, for example, which transport processes direct the slope's retreat in the talus phase and later (see Fig. 2). Above all we know very little about how rapidly the development goes on. It is these problems, *inter alia,* which are to be elucidated in this thesis.

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[6] In the question of talus in an Arctic environment solifluction is considered to be a removal process of the greatest significance (Högbom, 1914; Jahn, 1947; Büdel, 1948; Dege, 1949; Malaurie, 1950) but practically no measurements of its rate and capacity have been reported.

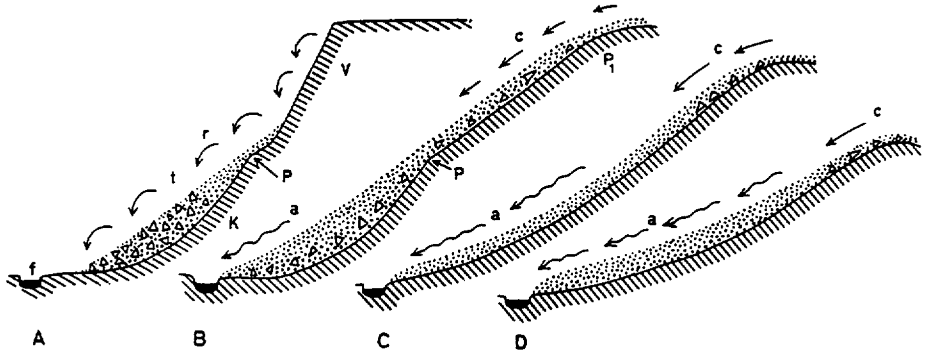

Fig. 2. Sketch showing the principles of slope development, modified by the author after Derruau (1956, p. 59); the later phases are according to the theories of Baulig and Birot.

A. The mountain wall (V) retreats on account of smaller falls (r). The talus slope (t) grows. Beneath it lies the rock core (K), which here is assumed to have been formed by earlier glacial erosion and has therefore been drawn concave. In the upper part of the rock core a "Richter's slope (P) has begun to be formed on the retreat of the wall.

B. The talus phase is finished. The slope gets a convex-concave equilibrium profile on account of weathering and creep (c) at the top and wash (a) (Baulig, 1940) or creep + congestion at the bottom (Birot, 1949, p. 20). The material is removed by a river (f) at the base. P-P_1, the "Richter's slope".

C, D. The slope is lowered. Wash (a) predominates more and more over creep (Baulig, 1940).

1.3 METHODS

1.31 Morphology

In order to be able to establish as accurately as possible the form[1] of the talus cones investigated, the author used the following methods.

(a) Measurement of profiles and isolated gradient values on certain talus cones in the field with the following instruments:

A specially constructed clinometer, consisting of a 20 cm long vertical pendulum of brass fastened to a protractor and protected by a wooden frame (20 × 22 cm) and a celluloid panel. The clinometer was fastened with screws to a collapsible square frame of four laths, 100 cm long (see Plate IX). Measurement of the inclination is made by placing the frame with the clinometer on the ground in the direction of the line of fall and the deflection of the pendulum is read. The accuracy of the reading is about ¼°. A series of gradient values is measured on a profile along a steel measuring tape on the ground. The profile can afterwards be reconstructed on graph paper with the help of a protractor.

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[1] Accurate mapping is, of course, the best method of establishing the forms of the slopes. On account of shortage of time, a complete mapping was not included in the programme for the field work on Spitsbergen in 1954. See Chapter 1.33 below.

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The method is relatively rapid and gives very good accuracy when two men work together. Then the talus surface should be relatively even and the interval between the measuring points short (about 5 m or less).

The profiles measured in this way give a more correct picture of the small variations in the inclination of the talus surface than Maps Nos. I-III. The total length and height of the profiles deviates from those shown on the maps by less than 1 %.

A steel measuring tape, 50 m long, graduated in centimetres, for measuring the length of the profile and the measuring interval.

A "Silva" compass clinometer was used for measuring isolated gradient values.

A "Meridian" levelling clinometer was used for measuring mean gradients along the profile of, for example, a whole talus cone. It can also be used with advantage to measure rapidly profiles on slopes, for example, by two men walking up the slope in the line of fall. The man behind reads the angle of elevation to the man in front at regular intervals, for example, every 5th, 10th or 20th metre.

A barometer of Paulin aneroid type for checking the vertical distance between base and apex in the profile measurement.

(b) Measurement of the profile of talus slopes on large-scale maps (1:2000). See Chapter 1.33 below.

(c) Photographing of the formations. Both plain and stereoscopic pictures. Camera: "Rolleiflex" 6 × 6 cm. See Chapter 5.2 below.

(d) Detail study of talus material and surface forms.

1.32 Development

(a) Making an inventory of fresh fallen débris on remaining, annual snow patches. Inventory and description of all directly observed falls, slides and other transport processes on the talus slopes (see, for example, Rapp, 1957, p. 187).

(b) Detail study of the forms on the talus slopes which yield information as to the kind and rate of material turnover (the profile at the talus base, slide tongues, bump holes, etc.). Examination of the vegetation and its evidence as to the material turnover (see, for example, Friedel, 1935).

(c) Marking of test surfaces on the talus crest for later determination of the quantity of debris which was deposited within the test surface (Rapp, 1957, p. 187).

(d) Determination of shifting movements on the talus slope by markings (colour, poles, etc.) and continuous measurements (Michaud, 1950; Rapp, 1957).

(e) Comparisons between photographs of the same sections of slopc

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taken at long intervals of time; a particularly useful method. See Chapter 5.2 below.

(f) Calculation of the total supply of debris which came from the mountain walls in post-glacial times by measuring on detailed maps and comparing the volume of debris in the talus cone with the volume of the related rock-fall funnel on the wall. Regard must, of course, be had to the removal of material which has taken place from the cone. See Chapter 6.2 below.

(g) For slope investigations of a similar kind, which are to be carried out in inhabited regions, important information as to rock-falls etc. can, of course, often be gathered from interviews with the local people and examination of newspaper items (cf. Nussbaum, 1957).

(h) Particularly plentiful information as to landslide frequency etc. can be obtained in the cases where unprotected traffic routes run alongside talus slopes or mountain walls and reports of the rock-falls have been recorded (cf. Matznetter, 1956, and Balk, 1939, p. 332). It is desirable that this type of material should be examined and exploited to a greater extent than hitherto. Such investigations would probably be one of the best means of achieving a more certain estimate of the kind and capacity of the denudation processes in different parts of the world.

(i) Calculation of the recent breaking down which takes place in mountain walls alongside glaciers, guided by the quantities of surface moraine which the glacier carries away. See Chapter 3.1 below.

1.33 The map material used

Maps Nos. I-III in the pocket in the back cover were drawn on the basis of terrestrial stereoscopic photography and base-line measurement carried out by the late A. Koller, of the Norwegian Polar Institute, Oslo. They have not been published previously. Nos. I and II have in the original a scale of 1:2000, No. III a scale of 1:4000. The originals of these extraordinarily detailed and well-made maps came to the knowledge of the author for the first time in September, 1954 (consequently after his return from Spitsbergen) through the agency of Mr. B. Luncke at the Norwegian Polar Institute. The author is greatly indebted to Mr. Luncke and the Polar Institute for permission to make use of and publish these maps, which are extremely valuable for this thesis.

It was possible to check the reliability of Map No. I, thanks to the measurements the author made in the field in 1954 with a view to the construction of his own sketch map of the area and also to the profile measurements which were made. Base-line measurements made with a steel measuring tape at the foot of the talus cones and also up in the spirifer funnels show complete agreement with the map. Total agreement seems likewise to prevail between the map and a number of contours measured in the field above cones T5 and T6 with the aid of measuring tape, compass, "Meridian" pendulum and barometer. The agreement applies both to the length of the contours and to their curvature above the cone. This is essential for the calculation of volume which is carried out in Chapter 6.

The map in Fig. 4 is largely a copy of that in Harland's report (1952, p. 327). The part at Langtunafjell is copied from an original on a scale of 1:200,000 at the Norwegian Polar Institute.

CHAPTER 2

Description of the Area Investigated and a Short Discussion of its Frost-weathering Climate

2.1 THE CHOICE OF LOCALITY

The situation of the area investigated is clear from the maps in Figs. 3 and 4. The most important of the localities investigated is Mount Templet's south-eastern slope towards Bjonahamna (78° 20′ N, 16° 30′ E) at the mouth of Tempelfjorden (Plate I). The other localities discussed (Langtunafjell at Tunabreen, Bjonadalen, Mount Templet at Gipsdalen, etc.) were studied for comparison.

Bearing in mind the purpose of the investigation formulated in Chapter 1.1, the chosen area of investigation is very suitable for the following reasons, amongst others:

(1) Like the whole of the inner Isfjord area, it has large and well-formed talus cones, which were presumed to be of rapid, recent development.

(2) Since the end of the nineteenth century the area has several times been visited by scientists, who have, *inter alia,* photographed the talus formations, for which reason there are good possibilities of determining by picture comparisons the recent developments. This applies particularly to the talus slope at Bjonahamna (see Chapter 5.2 below).

(3) At Bjonahamna the talus cones lie along a level shore with a series of undisturbed, raised strand lines, which go right in to the talus base. This implies that the talus cones have not been subjected to appreciable removal of material in solid form since they were raised up above the reach of the waves. These cones are therefore well suited to an analysis of the material turnover.

2.2 GENERAL DESCRIPTION OF LANDSCAPE

The landscape around the inner Isfjord is characterized by tableland bounded by straight lines with steep sides and flat tops or level ridges which reach 500—1000 m above sea-level (see Groom and Sweeting, 1958).

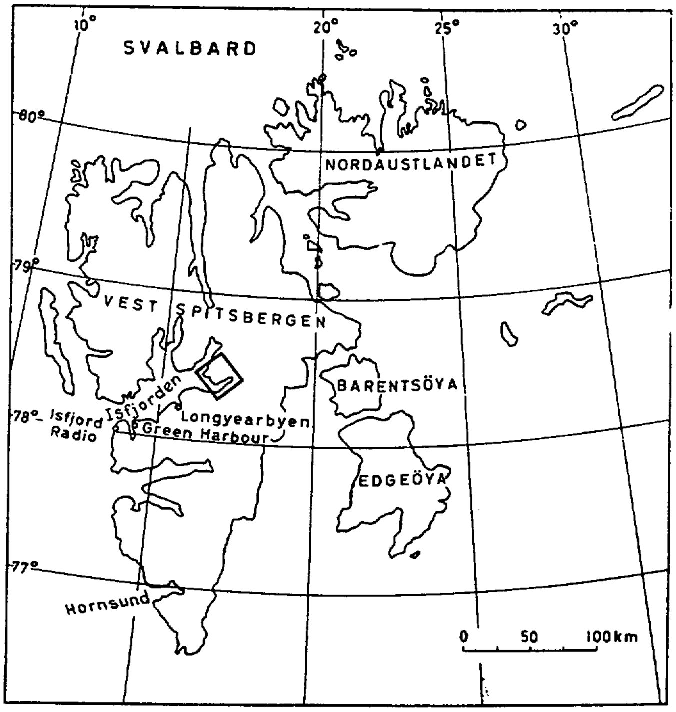

Fig. 3. Map of Spitsbergen. The area of investigation at Tempelfjorden is marked by a rectangle.

The mountain walls are throughout strongly weathered and very regularly dissected by rock-fall chutes,[1] rock-fall funnels[1] and cirques and at the bottom surrounded by great talus belts and alluvial cones.

The plateaux are partly covered by perennial snowfields or glaciers, from which valley glaciers in several places force their way down in side valleys towards the shores of the fjord. East of Tempelfjorden the valleys are filled up with transection glaciers, from which only the mountain ridges stick up. The snow bands in the rock-fall chutes on the nunataks, together with the bare ridges of the mountain-sides, often form characteristic zebra-like stripes of black and white, which at a distance disclose that the walls have undergone regular dissection retreat (the type may be called "zebra mountains"; see Plate III). Inmost in Tempelfjorden

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[1] In other words "features linking the original snow gullies with a fully matured corrie" (McCabe, 1939, p. 459). The term "snow gullies" is perhaps less distinct and of more limited use than "rock-fall chute". "Funnel" is a form in size and shape situated between "chute" and "corrie" (cirque).

Fig. 4. Map of the surroundings of Tempelfjorden. The place-names are in Norwegian. Br. = breen (glacier), fj. = fjell (mountain). Contour interval 100 m. Grey areas denote glaciers, the dotted bands surface moraine.

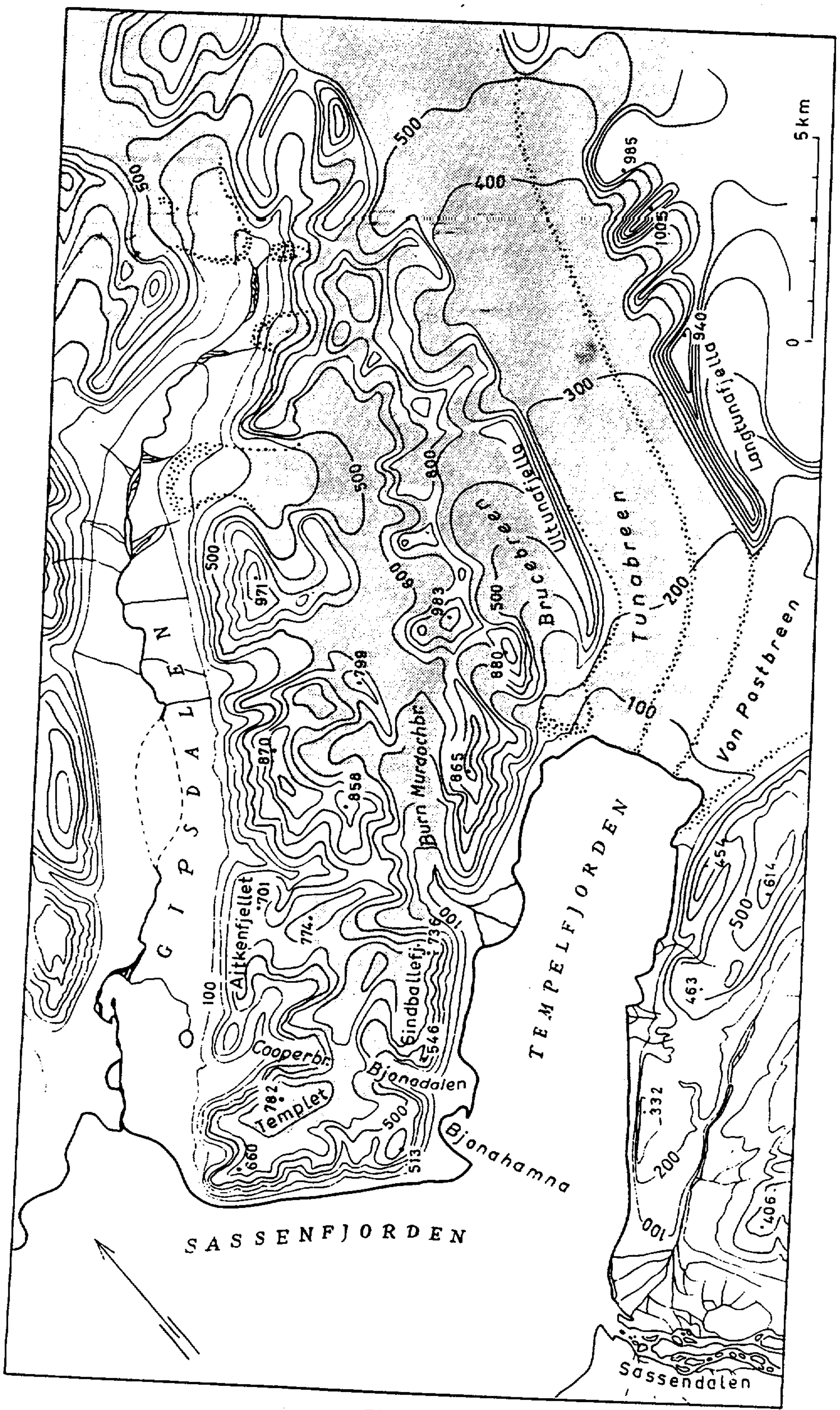
0
5 km
Langtunafjella
940
1005
985
Von Postbreen
Tunabreen
100
200
300
400
500
Ultunafjella
Brucebreen
880
500
983
600
865
Burn Murdochbr.
798
500
971
870
858
TEMPELFJORDEN
GIPSDALEN
Aitkenfjellet
701
774
736
100
Sindballefj.
546
Cooperbr.
Bjonadalen
Templet
782
660
500
513
Bjonahamna
SASSENFJORDEN
454
614
500
463
332
200
100
406
Sassendalen

Fig. 4.

emerges Tunabreen and von Postbreen with a steep front about 4 km in width and a maximum height of 50—60 m above the water.

There are also certain ice-free main valleys, e. g. Sassendalen and Gipsdalen (Fig. 4).

Trees and shrubs are entirely lacking. Herbs, grass, moss and lichens occur here and there but form continuous carpets only in favourable positions.

2.3 BEDROCK

The mountains round Tempelfjorden are built up of almost horizontal layers of sedimentary rocks from the Upper Carboniferous and Permian. A geological map of the area from the north shore of Tempelfjorden to the west shore of Billefjorden on a scale of 1:100,000 is to be found in Gee, Harland & McWhae (1953, Pl. I). In this report, to which the author refers in what follows by the initials GHM, there are also included descriptions of bedrock profiles from the area.

From Fig. 5 it is clear that the spirifer limestone can be regarded as the lowest stage in the Lower Permian (according to Orvin, 1940, Pl. II).

GHM (1953, p. 312) to a large extent divide up the bedrock north of Tempelfjorden in the following way:

Brachiopod cherts		Lower Permian ?
Cyathophyllum limestones	Upper Gypsiferous Series Wordiekammen Limestones	Upper Carboniferous
Campbellryggen groups	Passage beds = Pyramiden conglomerates	Early Upper Carboniferous?

The mountain walls have a staircase formation and at Bjonahamna it is possible to distinguish three major steps between the talus slope and the highest plateau of Templet. The three walls which form these steps are here called "the cyathophyllum cliff (shortened to "the c-cliff"), "the spirifer cliff", and "the productus cliff" after the names of fossils that are found represented in them. They appear most clearly above cone T1 in the south corner of Templet (Map No. I) and are designated by "C", "1" and "4" in Fig. 5.

In the profile in Fig. 5 the bedrock substratum of the talus slope is probably partly composed of thick gypsum layers. These, of course, are visible at corresponding levels on the talus slope of Sindballefjell towards Tempelfjorden (Map No. II, rock projections about 160 m above sea-level). At Bjonahamna the c-cliff is strongly dissected and remains as a series of projections between the upper part of the talus cones. These

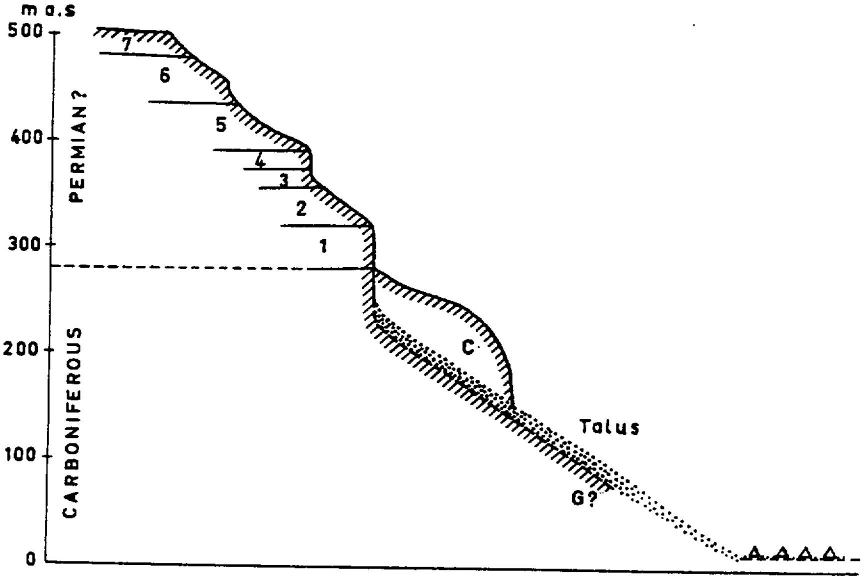

Fig. 5. Stratigraphy of Templet at Bjonahamna according to Nathorst (1910, p. 341) supplemented slightly. The strata dip about 3—4° towards the south, i. e., to the right in the figure.

7 }
6 } Black and yellow cherts
5 }
4 White chert
3 Yellow sandstone
2 Black and yellow cherts and limestones
1 Spirifer limestone
C Cyathophyllum limestones with gypsum beds (G).

(4 to 7: Brachiopod cherts (GHM, 1953, p. 342))

projections are made up of "porcellaneous and sandy limestones with thin-bedded sandstone and shales" (GHM, 1953, p. 344). On the upper part of the c-cliff are embodied several thin gypsum layers (see Plate XIV and others). The c-cliff is mostly so strongly weathered and split that loose fragments of rock can be picked up from the cliff without difficulty in many places (Plate II (a)). It weathers to sharp-edged fragments from pebbles to small boulders in size.

The spirifer cliff is about 40—50 m high and stands out clearly along the sides of the different mountains north of Tempelfjorden and Sassenfjorden, east of Billefjorden to the Cape Ekholm area and west of Billefjorden on Skansen and the surrounding mountains (GHM, Pl. V and VI, letter "A"). It consists of "resistant cherty limestone with an abundant brachiopod fauna — mainly Productus and Spirifer" (GHM, p. 345). The cliff is vertical, in most cases smooth and whole (Plate VIII (b)). It weathers into rectangular boulders 1—2 m large or larger. Many of the large boulders at the foot of the talus slope are of spirifer limestone.

Higher up the spirifer cliff lies a series of "cherts" of varying resistance alternating with thin layers of sandstones and limestones. This part of the cliff is strongly dissected and difficult of access, for which reason it has not been as well investigated as the parts mentioned above. The productus cliff is in the southern corner of Mount Templet about 40 m high and begins about 380 m above sea-level. It consists in its upper part of a white "chert" with green sandstone balls. Beneath it lies a loose, yellow sandstone, large boulders of which are to be found down at the bottom on the fringe of the talus slope (Nathorst, 1910, p. 411). Another brownish-red sandstone seems to form "caps" of more resistant material on the top of the many pillars on the cliff near the plateau. As to the morphology of the cliffs, see Chapter 4.1.

2.4 THE CLIMATE AND ITS FLUCTUATIONS IN POST-GLACIAL[1] TIMES

2.41 The statement of the problem

It was pointed out above that the mountain sides within the Tempelfjord area are very strongly weathered and broken down. For the most part this would seem to have occurred through frost bursting, to judge by the cold climate. The effect of the frost-weathering is probably in principle dependent in the first place on the following three factors: (a) the resistance of the bedrock, (b) the frost changes and (c) the water supply. The first of these factors has been reviewed to some extent in Chapter 2.3, where it was pointed out that many of the rock elements, of which Mount Templet and nearby mountains are built, are strongly split and easily weathered. In the following section the factors (b) and (c) are to be elucidated. The significance of the climate for the effect of frost-weathering is, however, a little-known and much-discussed complex of problems, for which reason it is first appropriate to review the framing of the problem to some extent and simplify it.

The opinion as to a rapid, recent denudation on Spitsbergen is not based on observations or measurements of the present rate of the processes. "Der totale Betrag der Denudation durch den Frost lässt sich natürlich schwierig fixieren, wie auch ein bestimmtes Mass der Geschwindigkeit" (Högbom, 1914, p. 288). Instead it is the great denudation and accumulation forms which have been considered to point to a rapid breaking down. "Dafür legen die tief ausgeschnittenen Skulpturformen der Bergwände Zeugnis ab, wie auch die Talusanhäufungen und die

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[1] The term "post-glacial" is used here and later with a localized meaning. The areas which have been freed from ice are accordingly in a post-glacial phase, those which are covered or surrounded by glacier ice are in a glacial phase.

Steindeltas" (op. cit., p. 288). It is reasonable to draw the conclusion which Högbom and many other authors have done and which can simply be formulated thus: large rock-fall chutes and talus slopes = rapid post-glacial and rapid recent denudation. This should in its turn depend on the fact that "the frost-weathering is very extensive on account of a very severe climate and generally a scarcely resistant bedrock" (op. cit., p. 270).

The above reasoning can be summarized thus:

1. The great talus formations on Spitsbergen are an observed fact, the rapid, recent breaking down is an unverified hypothesis as an explanation of the formations.

2. The supposedly rapid, recent breaking down on Spitsbergen is considered in its turn to depend on a concurrence of easily weathered bedrock and a climate very favourable for frost-weathering.

The following examination and discussion of the climate is directed towards elucidating to some extent the question: what climatic factor may be thought to be specially favourable for frost weathering on Spitsbergen?

2.42 Air temperature, precipitation, frost changes

Fig. 6 gives a general picture of the variation of the air temperature and the precipitation during the year. The values refer to the Green Harbour station, the period is 1912—1925 (Mortensen, 1928). They are thus partly relatively old (cf. Fig. 9, Chapter 2.43), partly representative of a climate probably somewhat more maritime than that of the Tempelfjorden district. Later annual series are, however, interrupted by transfers to other stations (Longyearbyen, Isfjord Radio) and by a longer interruption during the second world war. Isfjord Radio has a decidedly maritime situation. The values quoted in Fig. 6 were consequently chosen because Green Harbour has the longest continuous series of observations on Spitsbergen and because its situation does not differ as much from the Tempelfjorden district as Isfjord Radio.

Fig. 7 (same locality and period as Fig. 6) illustrates the number of days of frost change[1] on an average per month, and also the magnitude of the temperature amplitude, likewise on an average.

From Figs. 6 and 7 the following, amongst other things, is clear. In the Isfjord area the mean temperature of the coldest month reaches about —18° C (March), and that of the warmest month about + 5° C (July) during the period 1912-1925. In later years the mean temperature in March varied between —7.7° and —17.1° at Isfjord Radio during

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[1] Days of frost change ("fc-day") = periods of 24 hours when the highest temperatures lie above 0° C and the lowest below 0° C. The number of "fc-days" per year indicates one side of the frost-changing climate (see below, Chapter 2.421).

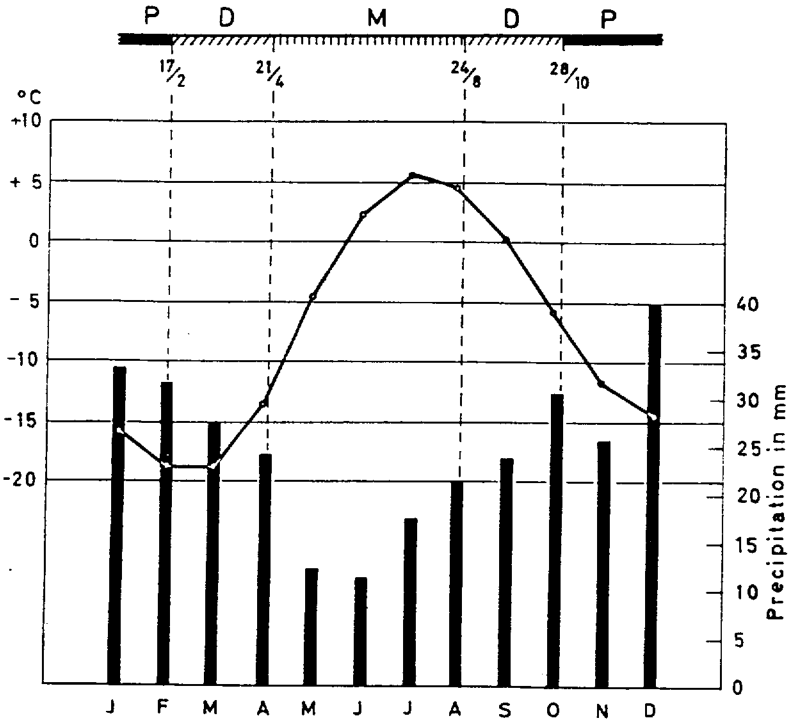

Fig. 6. Air temperature (curve) and precipitation (piles) given as monthly mean values for Green Harbour (78° 2′, 14° 14′ E) from 1912 to 1925. The elevation of the sun on 21/4 at 12.00 hours is 23.5°, on 21/6 at 12.00 it is 35.5° and on the same date at 24.00 12° (after Mortensen, 1928, p. 613). P = Polar night, D = Day sun, M =Midnight sun period.

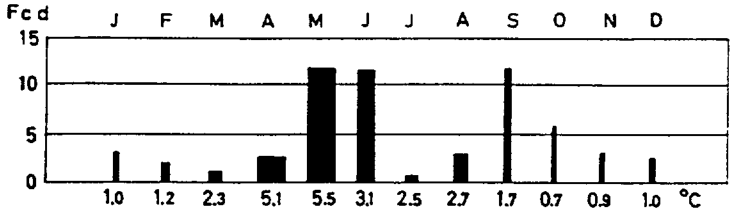

Fig. 7. Number of 24-hour periods of frost change, frost change days, (the height of the piles) and temperature amplitude (width of the piles) in monthly mean values. Same station and period as the previous figure. (Op. cit. p. 627.)

the period 1947—1954 (Norwegian Meteorological Yearbook). The precipitation is as low as about 300 mm per year and has a maximum in December of 40 mm.

The days of frost change were comparatively few (59 per year) and they have moreover a small daily amplitude (maximum in May of 5.5°).[1]

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[1] Cf., for example, corresponding values for Equatorial mountains (El Misti in the Andes). 337 days of frost change per year and the daily amplitude of the temperature was greatest in October at 11.8° C. Both frequency and amplitude are far greater than on Spitsbergen (Troll, 1944, p. 605).

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Frost change occurred throughout the year, but the majority of days ot frost change fell in May, June and September. The frost change in May and June operates with a greater temperature amplitude and meets with a ground surface to a large extent damper than the September frost.

It is consequently probable that the type of frost bursting which is caused by the "daily" frost cycles mentioned here are most strongly active in May and June.

Mortensen (1928, p. 624) considers that the frost changes in May and in part of June are without morphological effect on account of the fact that the snow covering would protect the ground then. Against this it may be objected that the snow only covers the ground in patches. Amongst other things, the mountain walls important in this connection lie for the most part bare already in March. See, for example, the photograph in Berset (1953, pp. 225, 129).

At Tempelfjorden the daily amplitude of the air temperature seems to be about as small as at Green Harbour to judge by the measurements which were carried out during the period the author worked at Bjonahamna in 1954. The measurements were made with thermographs of the Lambrecht type. For the whole observation period (12/7 to 1/8) the following mean values were measured, 1.85 m above the ground.

	Daily mean values		
	Max. temp.	Min. temp.	Daily amplitude
Bjonahamna, talus base, 12 m above sea-level	+ 8.3°	+ 5.7°	2.6°
Bjonahamna, talus crest, 180 m above sea-level	+ 8.6°	+ 4.9°	3.7°

The temperature amplitude was consequently somewhat greater up on the talus slope than down at the base, but small at both measuring places. Greater amplitude was obtained during periods of 24 hours with strong incoming radiation by day and outgoing radiation by night. Fig. 8 reproduces the progress of the temperature during such a period of six days with clear to dim weather.

The minimum temperature during these nights of strong radiation was never lower than + 2° at a height of 20 cm above ground (t_c, t_d in Fig. 8). Further away from the shore slight frost was recorded along the shaded glacier fronts (Cooperbreen) on the same occasion.[1] A thin ice crust had been formed on small pools of water there. On the other hand, ground frost did not occur on any occasion on the slopes at Bjonahamna during the period 12/7 to 2/8 at levels below 300 m above sea level.

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[1] Detailed studies on freezing close to snow patches are described by McCabe (1939, p. 453 f.).

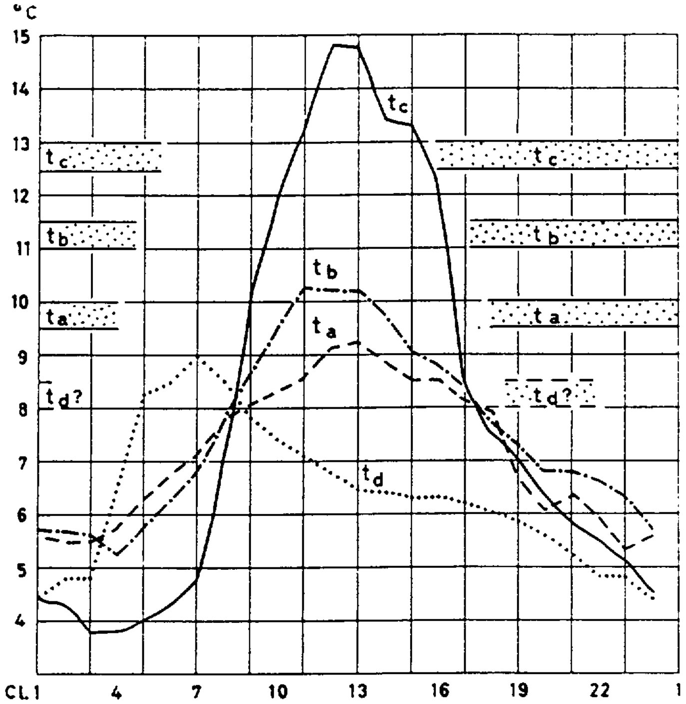

Fig. 8. The variation of the diurnal air temperature at four different points at Bjonahamna. Mean values for six, 24-hour periods from 27/7/54 to 1/8/54. Dotted band marks the time when the respective thermograph was in the shade of the surrounding terrain.

t_a, 12 m above sea-level, 1.85 m above ground. Temp. amplitude 3.7° C.
t_b, 180 m above sea-level, 1.85 m above ground. South-facing talus crest. Temperature amplitude 4.9° C.
t_c, 290 m above sea-level, 0.2 m above ground. South-facing talus crest. Temperature amplitude 11° C.
t_d, 330 m above sea-level, 0.2 m above ground. North-facing talus crest. Temperature amplitude 5.3° C.

The maximum temperature at t_b reached about 15°, whilst at the same time the highest surface temperature measured on the rocks at t_b was + 28° C (measured with a thermistor shaded by a 1 mm thick stone slab).

2.421 Discussion

The afore-mentioned circumstance that Spitsbergen's "air climate" has few and weak daily oscillations of temperature around zero has been observed by and has perplexed several authors who start from the hypothesis that the Arctic climate is extremely favourable to frost-weathering. Dege (1950, p. 276) criticises the use of the number of frost changes, which is based on measurements of the air temperature. "The conditions in the microclimatic area are decisive for the number of frost changes. Then Arctis, and not only the tropical mountains, particularly in June and

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at the beginning of July shows a large number of frost changes . . . I recall that we observed up to 5 such changes in one hour."

Dege's observation is important, but the circumstance that the frost changes are more numerous at the ground surface than in the air applies generally and is probably not particularly characteristic of Arctis. As a rule it has not been overlooked either by the authors who have discussed frost change. This is usually exemplified by Meinardus' measurements from Kerguelen:

> Days of frost change per year in air, 120; days of frost change per year at ground surface, 238; frost changes per year 5 cm below the ground surface, 0 (according to Troll, 1944, p. 623).

From the values quoted it appears, amongst other things, that these recurring small spells of frost are not able to penetrate to any appreciable extent into the ground.

As regards the short frost changes the following can accordingly be said: (1) they are probably no more common in the Arctic than in other climates with frost, and (2) they probably do not have any appreciable weathering effect, as they are very superficial.

Mortensen (1928, p. 624) writes: "The number of days of frost change is so small on Spitsbergen that their significance for weathering must be small." Mortensen suggests that the explanation of the supposedly severe weathering may lie in the temperature variations which occur in the winter when the ground is frozen. These could cause bursting through the ice particles in the rock reacting like a foreign body with a different thermal expansion coefficient than the bedrock (Op. cit., p. 626).

But if bursting were to occur on the penetration of the cold waves into already frozen bedrock, a release of many rock-falls ought to occur immediately. All experience shows, however, that only few rock-falls occur during winter; the majority occur in spring and autumn. Furthermore, the frequency and amplitude of temperature variations in winter are probably not specially great on Spitsbergen in comparison with, for example, the mountains of northern Scandinavia.

Högbom (1914, p. 267) considers that the more rigorous the climate (rigorous climate = low mean temperature?), the more powerfully the frost works. On Spitsbergen frost weathering should in the main occur in summer on the upper surface of the frozen ground principally in the early summer, when the frozen ground is superficial. Then freezing and thawing could occur in the upper surface of the frozen ground as a consequence of small changes in the air temperature (daily or shorter fluctuations, for example, from sun to shadow (Högbom, p. 268)) without this necessarily sinking below 0° C.

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Against Högbom's hypothesis cited above, Frödin (1914, p. 218 f.) has already directed a conclusive criticism, based upon measurements. Besides, it can be objected quite generally that since the daily range of air temperature is so small on Spitsbergen, the pre-requisite conditions there must be particularly slight for such a frost change in the ground.

However, it seems possible to develop Högbom's hypothesis in the following way. In areas with a thick layer of frozen ground the surface of the frozen ground during a part of the early summer will remain a little way below the actual ground surface and prevent the melt water from sinking in a vertical direction. If there then occurs a new frost period of several days, which is able to freeze down all the previously thawed layer, extensive pre-requisite conditions for frost bursting will probably be found when the water freezes over which is shut in between the underlying old and the overlying new frozen-ground zone. The effect can be expected to be strongest on level ground with slow drainage.

The above discussion has given several examples to show that the question of the mechanism and causes of frost weathering is complicated and deserves a closer study in the field. For the continued discussion it may, in the author's opinion, be appropriate to distinguish between the following types of frost cycles,[1] divided up according to duration.[2]

(a) Short frost cycle. Several cycles possible in one day. For example, see Dege above.

(b) Daily frost cycle. Longer than the foregoing. Freezing at night, thawing the following day. Has highest frequency and amplitude on mountains at low latitudes (Troll, 1944; Cailleux & Taylor, 1954, p. 24).

The two types (a) and (b) are both probably limited to the shallowest layer of the ground and therefore have relatively unimportant frost-weathering effect, at least in the cases where the amplitude is small. It is possible that these types of frost cycles cause what Tricart (1953, p. 2; 1956, p. 285) calls "microgelivation", pulverising of the rock into fine material (sand, sandy soil) through frost bursting along invisible cracks. The following types of frost cycles should to a still greater degree cause "macrogelivation", bursting along visible cracks and production of boulders and stones.

(c) Frost cycle of several days. Freezing in a cold period of several days' duration.

(d) Annual frost cycle. Freezing in the winter, thawing the following summer. Reaches a considerable depth in the soil in the "frost-shatter zone" in higher latitudes; on the other hand, not in low latitudes and not in markedly maritime climates either (Cailleux & Taylor, 1954, pp. 15, 16).

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[1] By frost cycle is here meant a freezing and afterwards a following thaw.

[2] A similar discussion is given by Williams (1959, p. 12).

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(e) Frost cycle of several years. Permanently frozen ground during a cold climatic period of several years. Thawing during any particularly warm summer (op. cit., p. 15). It is possible, for example, that the warm summers in the 1930's on Spitsbergen brought with them thawing of ground layers which had been frozen for several years previously.

2.422 Summary

The climate in the Isfjord area on Spitsbergen is characterized, *inter alia,* by a comparatively small number of days of frost change (Troll, 1944, Plate I), relatively small daily temperature amplitude, relatively large annual temperature amplitude and low precipitation figures. In comparison with mountain localities within the "frost-shatter zone" and the tundra zone in lower latitudes, the climatic conditions for frost weathering through short or daily frost cycles on Spitsbergen should therefore be small. McCabe (1939, p. 455) also considers the recent snow-patch erosion on Spitsbergen as slower than on Iceland, partly because of the climate (more and stronger daily frost cycles and more melt-water on Iceland).

The frost weathering is therefore probably caused in the first place by frost cycles of longer duration than the "daily". From the observational material available there is not clearly apparent any certain climatic factor which would place the type of climate prevailing on Spitsbergen in an exceptional position as extremely favourable for frost weathering, compared with more southerly mountain regions. The permanently frozen ground may, however, be thought to give rise to specially favourable conditions for frost bursting. The problem remains to be solved.

To the extent that it is the great talus slopes which have given rise to the idea of an extremely effective frost-weathering climate, one may for the present point to other possibilities as explanations for them; (a) easily weathered bedrock (Chapter 2.3), and (b) a very long post-glacial period? (Chapter 2.43).

2.43 Deglaciation and post-glacial climatic changes

It is still not possible to give a clear picture of to how great an extent the Isfjord area was ice-covered during the optimum period of the last ice age. Possible striae and glacial sculpture were to a great extent destroyed after the melting of the ice in the easily weathered kinds of rock (Högbom, 1911, p. 32). The findings of erratic boulders are few. They have, however, been met with at up to 600 m above sea-level west of Billefjorden about 30 km north-west of Templet (op. cit., p. 35) indicating that the inland ice may have covered even the highest mountains during at least some period of glaciation.

Högbom assumes that during the great ice-melting there existed mobile tongues of ice which filled up the fjords far ahead of the modern glacier fronts. Such a stage of fjord glaciation is indicated by "lateral moraines of compacted talus masses" (op. cit., p. 40) and also a recent system of crossing glacial striae on dolerite rocks near sea-level (op. cit., p. 41), for example, at Gåsøyane at the mouth of Billefjorden.

Well-preserved shore terraces and fine series of old strand lines occur in many places. The upper marine limit (= UML) could be relatively accurately determined at fully 90 m above sea-level. Feyling-Hanssen (1955, pp. 51, 57) reconstructs the post-glacial land upheaval and climatic development on the basis of a comprehensive inventory of mollusc shells on the shore terraces. The time scale is drawn up by correlation with other North Atlantic coasts:

Table 1 A (cf. Table 1 B, p. 26)

The post-glacial climatic development and land elevation in the Isfjord area (after Feyling-Hanssen, 1955).

Year	Period	Formation	Level
	Sub-recent	Lowest terraces	0 m
500 B.C.			
	C. Post-glacial warm period	Mytilus terraces	5 m
		Lower Astarte terraces	15 m
		Upper Astarte terraces	
4500 B.C.			40 m
	B. Post-glacial temperate period	Mya terraces	
7000 B.C.			60 m
	A. Late glacial cold period	Scattered Mya and Saxicava	
?			90 m

The parts of Spitsbergen at present free from ice would consequently, according to Feyling-Hanssen, to a large extent have been freed from land ice at the latest about 7000 B.C. The great deglaciation, according to this idea, would have occurred earlier on Spitsbergen than in the Scandinavian mountains.

Liljequist (1956, p. 70) puts forward another view. He outlines the probable atmospheric circulation during the ice age and considers it "possible that . . . (Spitsbergen) . . . reached the optimum in glaciation during a period when the great European inland ice was still melting away".

By C^{14} dating of mollusc shells or driftwood on the highest shore terraces, it will probably be possible within the near future to draw up a

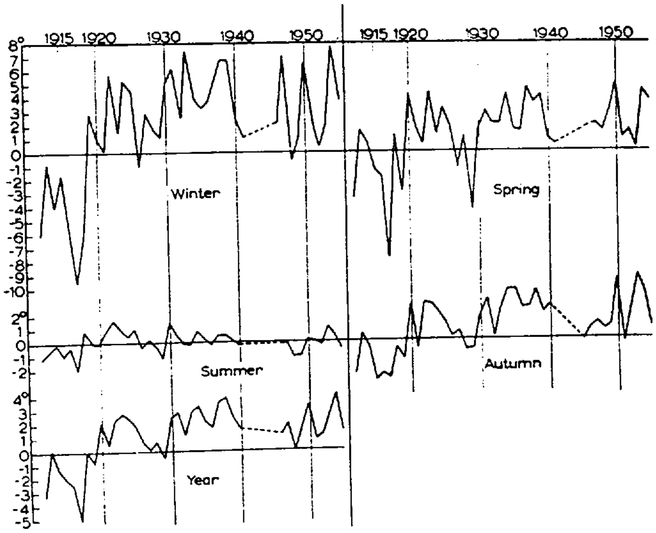

Fig. 9. Mean temperatures at Isfjord Radio between 1912 and 1955. Winter = Dec.—Feb., Spring = March—May, Summer = June—Aug., Autumn = Sept.—Nov. After Hesselberg & Johannessen, 1957, p. 23.

more certain chronology for the deglaciation and the post-glacial period on Spitsbergen.[1] Such determinations have already been carried out on material collected by W. Blake at Murchison Bay in Nordostland in 1958. Two determinations have given an age of about 35,000-38,000 years (oral statement[2] by Blake). These preliminary results must until further notice be treated with caution, but they indicate that *we must perhaps reckon with a considerably earlier deglaciation and longer post-glacial period* on Spitsbergen than has previously been assumed to be the case.

It is likewise still not possible to reconstruct with any greater certainty the climatic variations on Spitsbergen in the Late Quarternary period, but it is probable that they followed the same pattern as seems to hold good for Iceland and Scandinavia (Ahlmann, 1953, p. 38, after Eythorsson, Liestøl, Bergström). Cf. Table 2. The latest climatic improvement of all is recorded in the temperature charts from Spitsbergen, where measurements were begun in 1912 (Fig. 9).

Fig. 9 gives the differences of the mean temperatures from those of the reference period at Isfjord Radio. "The great change in the temperature conditions . . . happened in the years 1917—1922 . . . A smoothing by hand gives a rise of about 7° C for the winter and later on a slow increase of about 1° C." (Hesselberg & Johannessen, 1957, p. 23.)

As is apparent from Fig. 9 the winter temperatures have been raised appreciably, the spring and autumn temperatures noticeably and the

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[1] C^{14} datings are at present being carried out on the author's behalf on mollusc shells, which have very kindly been provided by Dr. Feyling-Hanssen. Cf. Table 1 B, p. 26.

[2] Cf. Olsson, 1959, p. 91.

summer temperatures only slightly.[1] The climatic improvement on Spitsbergen had, however, proceeded some time before 1912, as is shown by the fact that the glacier fronts have retreated ever since the latter part of the 19th century. "It seems probable that it began about the year 1870, together with the recent temperature rise in Northern Europe. A basis for this supposition is that the number of days with Arctic sea-ice at the coast of Iceland began to decrease at that time." (Op. cit.).

Table 1 B (cf. Table 1 A and page 92).

New C^{14} datings of mollusc shells from raised terraces at Billefjorden. Datings by Dr. I. Olsson of Uppsala. Collections by Dr. R. W. Feyling-Hanssen of Oslo.

Locality	Sample No.	Level	Age before now
Kap Ekholm	358 b	56 m	9840 ± 150 years
Phantomvika	349 b	50.7 m	9980 ± 140 »
Myadalen	326 b	42 m	9310 ± 200 »
Ekholmvika	350 b	17 m	7595 ± 110 »
Mytilusbekken	343 b	5.8 m	3810 ± 90 »

Table 2.

Schematic collation of the probable Late-Quarternary climatic periods on Spitsbergen. The scheme can be combined with Feyling-Hanssen's (see Table 1 A).

Year	Period	
	G. Temperate period	The majority of the larger glaciers are retreating rapidly.
About 1920		
	F. Transitional period	The majority of the larger glaciers are retreating.
About 1870		
	E. Cold period	Iceland, Norway, Sweden have a cold maximum in the 17th and 18th centuries.
About 1600 A.D.		
	D. Temperate period	
About 500 B.C.		

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[1] Cf. also Hesselberg & Birkeland, 1940, p. 25.

CHAPTER 3

Morphology and Development on Slopes alongside Valley Glaciers

An illustration of late-glacial denudation and slope formation

The main interest in this thesis is concentrated on the talus slope at Bjonahamna (Plate I and Map No. I), which is dealt with in more detail in Chapter 4. This talus slope probably began to be built up in a phase of the great deglaciation, was afterwards for a certain period exposed to abrasion and finally as a consequence of land uplift came to lie above the reach of the waves and to undergo a period of "undisturbed" development.

In order to elucidate its probable earlier development, two other localities which are in earlier stages of the imagined process of development are dealt with in Chapter 3. The localities described and discussed are as follows:

(1) Nunatak sides alongside Tunabreen (Chapter 3.1). The debris is removed by a very active glacier.
(2) Talus cones alongside Kommissaerbreen (Chapter 3.2). Talus cones have begun to be formed alongside a stagnant valley glacier.
(3) The talus slope at Bjonahamna (Chapters 4 and 5). Large talus cones, nowadays undisturbed by the action of glaciers or waves.

3.1 DENUDATION OF A NUNATAK AT THE TUNA GLACIER

3.11 Description

Tunabreen is the most westerly great side-branch of von Postbreen. It ends in a steep ice-cliff innermost in Tempelfjorden. On the east side of Tunabreen lies the longish nunatak Langtunafjell (Fig. 4). Plate III shows that debris from the sides of the nunatak is being removed by the moving glacier first as a lateral and then as a medial moraine.

Langtunafjell is not included in the geological map (Plate I) in GHM, but would seem to have approximately the same bedrock as Ultunafjell, situated west of Tunabreen and marked on the map mentioned. The southern part of Ultunafjell consists of "limestones and cherts with a few thin gypsum bands" below the level of about 200 m (Campbellryggen group ?, GHM, p. 341). Between about 200 and 400 m lies a series of "Wordiekammen limestones" and still higher up probably come the "upper gypsiferous limestones". Hence it is possible that the higher parts of Langtunafjell may contain gypsum strata. If such strata exist, they are, however, probably not thick, for to a large extent the gypsum strata decrease in thickness from lower Gipsdalen, where they are thickest, towards the north-east, where they give way to limestone. "Only a few feet of gypsum remain" on Gerardfjella west of Ultunafjell (GHM, p. 345).

Plate II (c) shows the western, regularly furrowed nunatak wall of Langtunafjell at closer range. The height of the summit ridge above the surface of the glacier is about 450 m on the right in the picture and about 600 m on the left. The mountain side is made up on the right of a steep wall at the bottom and a débris-covered slope above, up towards the ridge. The lower wall is bare and furrowed by small chutes, and the upper slope is covered with a thin layer of loose material and divided into larger, open V-shaped funnels, which do not break through the summit ridge. This, along with the regular funnel forms, indicates that the chutes were not formed by large, instantaneous slides but probably by small falls (later combined with creep and water erosion?)

Almost all the débris from the wall on the right of Plate II (c) is being removed by the ice as a lateral moraine. Only very small talus cones are to be seen on the original picture. To the left, on the other hand, a compound, relatively large talus slope could be formed along a part of the wall which does not project as much and is therefore more protected against removal by the ice. How débris from the walls is carried out onto the surface of the ice and is transformed into lateral moraines is discussed in more detail in Chapter 3.2.

Plates II (c) and III accordingly give an interesting insight into the removal of the débris in the nunatak stage; almost all the material is removed by the glacier except in sheltered situations where relatively large talus slopes have managed to be formed. It is conceivable that these will contain a core of snow or ice.

The pictures give an impression of a rapid breaking down on the mountain walls. This impression is also received on looking at the glacier directly in the field. It is also generally assumed that this environment — nunatak walls near to the firn limit — has particularly strong frost-weathering and disintegration. It may therefore be of interest to try and calculate approximately how rapidly the disintegration takes place in this environment with Langtunafjell as an example, even if the calculation has to be made with several uncertain factors.

The following section is accordingly rather to be regarded as an experimental calculation which may give a preliminary idea of the order of magnitude of the denudation.

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3.12 Discussion

Problem 1: — *How fast is Tunabreen moving and how large are the quantities of surface moraine which it removes annually from Langtunafjell?*

From Plate III it is clear that the lateral moraines from Langtunafjell are met and removed in the form of a medial moraine, which after a curve to the right reach the ice front. The length of the medial moraine is about 6 km. This and the other medial moraines on the Tuna and von Post glaciers are very constant phenomena. They run without interruption for kilometers over the glaciers, vary comparatively insignificantly in breadth and are also to be found on maps and photographs from 1908 (G. de Geer, 1910), 1910 (Philipp, 1914), 1936 (Plate III) and 1954.

The glacier ends in a perpendicular ice wall, which rises about 40 m above the surface of the water. In this section the author observed in 1954 that *the medial moraine did not continue down into the ice but only formed a relatively thin layer on top of the surface of the ice (Plate II (b)),* apart from the smaller quantities of material which had fallen down into the crevasses which towards the glacier front are more and more numerous. On De Geer's photographs from 1908 and earlier and also on aerial photographs from 1936 this and other medial moraines appear in the same way as *distinct surface-moraine bands.* Hoppe, Liestøl and Winsnes (oral communication) have made the same observation on other glaciers on Spitsbergen.[1]

By the very fact that the author was able to establish that the medial moraine from Langtunafjell is superficial, there is a possibility of calculating how large a quantity of moraine material is carried away each year with the medial moraine if it is possible to determine the yearly movement of the ice, and the breadth and thickness of the moraine.

We choose a point on the medial moraine about 1 km south-west of the mountain and assume that the following values hold good for the transport volume there:

(a) breadth of the medial moraine = 50 m (measured on the aerial photograph from 1936). The value is possibly about 10 m too low.

(b) average thickness of the medial moraine = 0.2 m. The value is based primarily on observations in the field by Winsnes and Liestøl, of the Norwegian Polar Institute (both oral communications). According to Winsnes, the medial moraines in the von Post Glacier were on an average estimated to be 0.1—0.2 m thick and with a maximum of 0.8 m. Liestøl measured the thickness of medial moraines about 100 m wide composed of easily weathered Tertiary

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[1] In the literature one often meets with the view that the medial moraines of the glaciers continue down inside the ice (Sharp, 1948, p. 183; Flint, 1957, p. 72).

rock at Nathorstbreen, Spitsbergen. On an average the thickness amounted to 5—10 cm.

(c) rate of movement of the medial moraine = 100 m per year. The value is, of course, very uncertain and may, inter alia, probably vary considerable from year to year. Thus Tunabreen made a rapid forward movement between 1924 and 1932 (Dege, 1941, p. 284; Liestøl, oral communication). The estimate of the moraine's rate of movement is based on Hoel's values for a probably more rapid flow situation on the Lilliehöök Glacier (ref. in Pillewizer, 1939, p. 38[1]) and Ahlmann's values for the probably slower July 14 Glacier, the breadth and inclination of which correspond well with those of Tunabreen (Ahlmann, 1948, pp. 9, 57).

The Lilliehöök Glacier's width is about 3 km and its movement was about 180-360 m per year in the middle of the tongue about 1 km from the front.

The width of the July 14 Glacier was about 2.5 km. Its maximum rate is reckoned to correspond to a movement of about 60 m per year. The inclination of the ice surface was about 35 m/1000 m. Tunabreen's width is about 3 km and its inclination about 25-30 m/1000 m at its confluence with von Postbreen.

The yearly removal of surface moraine from the Langtuna nunatak according to the assumed conditions is:

$$50\text{ m} \times 0.2\text{ m} \times 100\text{ m} = 1000\text{ m}^3.$$

Problem 2: — *How great is the annual breaking down of Langtunafjell's ice-free sides?*

The lateral moraines adjoining Langtunafjell *are probably composed in the main of material which has been carried down onto the glacier by falls or slides* from the ice-free mountain sides. This, *inter alia,* emerges from the fact that talus cones are lacking below the rock-fall chutes which debouch on the moving ice, whilst, on the other hand, relatively large talus formations are found alongside the walls which are not directly exposed to base erosion by the ice (Plate II (c)). The state of affairs is illustrated still more clearly by Plate IV (a) and Map No. III from the Kommissaerbreen.

The lateral moraines may moreover in principle be supplied with material through movement upwards from underneath, for example, along the shear planes in the ice. Such moraines have, however, not been observed alongside the nunataks nor in medial moraines either, after examination of the area in the field and of aerial photographs. The author considers therefore that *the supply of moraine through movement from underneath is insignificant* in the locality in question.

If, contrary to expectation, a considerable part of the medial moraine comes from former ground moraine circulating upwards, this implies that the wall retreat is still slower than the calculation below indicates.

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[1] Pillewizer (1939) has carried out careful measurements of movement on the Gås Glacier, but since this is considerably shorter and steeper than Tunabreen, they have not been compared here as regards movements.

Another conceivable source of error in the following calculation is *loss of material through falling down and washing down* of loose material into and under the ice. To judge from the aerial photographs, crevasses are not particularly numerous along the sides of the glacier or in the proximity of the point on the medial moraine chosen for the calculation. On the other hand, the crevasses increase considerably in numbers out towards the glacier front without the medial moraine being obliterated. So falling down would consequently not seem to play even there any greater role, which is also clear from the fact that the ice cliff below the medial moraine is fairly clean. See Plate II (b).

A certain washing down of material from the valley sides and the lateral moraine probably occurs. This is adjudged to be relatively limited on account of the small quantities of melt-water which are available in this climate with a small annual precipitation and small ablation as a consequence of low summer temperatures. For the same reason the loss through chemical weathering is regarded as very small (cf., however, Corbel, 1957, Photographs 24-26). The loss of material through washing down would, however, seem to be the most uncertain factor in the whole of this calculation and it is therefore necessary to enter a reservation that a large proportion of surface moraine "disappears" in this fashion. The *removal* of superficial material with the medial moraine calculated above amounted to 1000 m^3 per year. This is regarded as a minimum value for the supply of loose material from the nunatak walls. If the corresponding maximum value for loose-material supply is set as high as 5000 m^3 per year, the author has probably taken into consideration with a sufficient margin a possible, significant washing down and falling down of surface moraine into or below the glacier.

The yearly supply of loose material from the Langtuna nunatak should, according to the above, correspond to 1000-5000 m^3 of surface moraine. The total surface of the nunatak slope above the valley glaciers can be approximately calculated from a map. The vertical projection of these slopes (to be called in what follows "the vertical surface") amounts to about 9 km^2, calculated from a manuscript map on a scale of 1:200,000 at the Norwegian Polar Institute.[1]

From these values an approximate measure of the annual horizontal retreat of the nunatak slopes can be obtained. If one is to calculate how large a retreat of the solid bedrock a certain quantity of loose material corresponds to, one has, however, also to take into consideration that the pore volume is considerably greater in the moraine than in solid rock.

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[1] The calculation was made without regard to the detail relief on the slopes in the following way: the west side of the nunatak, length 10,000 m × mean height 550 m; east side, 7000 m × 275 m; south side, 1000 m × 400 m; north side, 1500 m × 350 m. To which must be added 3 glacier cirques on the west side. Total vertical surface about 9 km^2.

It is probably reasonable to assume that the pore volume is at least 33 % greater in the moraine than in the bedrock.[1]

The quantity of surface moraine supplied annually from Langtunafjell is 1000 m^3 to 5000 m^3 minus 33 % pore volume = 670 m^3 to 3350 m^3. The total vertical surface of the Langtuna nunatak is 9,000,000 m^2. The annual horizontal retreat of the slopes of Langtunafjell is 0.074-0.37 mm, to be rounded to 0.05-0.5 mm.

3.13 Summary

The breaking down of mountain sides adjacent to moving glaciers can probably in a suitable climatic environment[2] be calculated by *measurement of the thickness, width and rate of movement of superficial lateral or medial moraines* and also by taking into consideration possible *losses of loose material by falling down and washing down* into the ice, as also possible *addition of material by movement from underneath.*

Such a calculation has been carried out above with an example taken from the Langtuna nunatak on Spitsbergen. The calculation is based on values which are uncertain, above all with regard to the following factors: (a) loss of loose material through washing down, (b) the average movement of the glacier per year. On this account only an idea of the order of magnitude of the breaking down has been obtained. The calculation suggests the following.

During the last few decades the breaking down of steep nunataks of easily weathered sedimentary rocks from the Carboniferous close to the firn limit in the Tempelfjord area has probably been of the *moderate order of magnitude of 0.05-0.5 mm* horizontal retreat in solid rock per year.[3] A value of *about 0.1 mm per year (= 1 m in 10,000 years) seems most probable* with regard to the conditions assumed. (Cf. Chapter 5.31.)

The above calculation is as stated uncertain and only to be regarded as a preliminary attempt. It ought to be possible without great difficulty to correct the values to greater exactness, if future glacier expeditions wish to take up moraine measurements on their programmes in accordance with the viewpoints stated above.

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[1] A few rough measurements show that the pore volume of similar debris is very likely greater than 50 %, but from this must be subtracted a certain percentage, difficult to estimate, for the joints in the bedrock of the wall.

[2] A climate deficient in precipitation with small ablation.

[3] For a comparison with other areas, see Chapter 6.24.

3.2 SLOPES ALONGSIDE KOMMISSAERBREEN

3.21 Description of the valley

Kommissaerbreen is a glacier which occupies the bottom of Bjonadalen, a deeply incised little transverse valley about 3.5 km long and barely 1 km wide. It separates Sindballefjell from Templet and emerges at sea-level east of Bjonahamna (Fig. 4). The glacier is fed by the snowfield on the summit plateau of Templet (at its highest about 800 m above sea-level). From the plateau two tongues of ice, one from the north-east, the other from the west (here called "Kapellbreen"), go down and are united in Bjonadalen. The firn limit is thought to have lain at 575-600 m in 1924 (Plate IV (a)). If — as is not improbable — the firn limit lay about 200 m higher during the post-glacial warm period, the glacier would not have existed then. A short description of this glacier is given by Sweeting & Groom (1956).

Bjonadalen with its little glacier gives at first sight a strong impression of intensive denudation at the present day. Broad streaks of debris run from the rock-fall chutes in the valley sides furthest in out over the glacier surface, where they curve downwards (Plate IV (a) and Map No. III). In the middle part of the valley they change into great lateral moraines, which at first raise themselves in the form of ridges over the glacier surface, then broaden out and form a close covering of surface moraine over the distal part of the glacier. The covering of surface moraine is about 0.2 m thick. From the steep and dirty ice-front stones and gravel often fell down into the strongly silt-bearing glacier river.

In the middle part of the valley a number of talus cones have been formed along both sides of the glacier.

The river has built up a large, semicircular delta in Tempelfjorden. According to S. de Geer's map (G. de Geer, 1910, Pl. 8) the delta has a surface above the level of —5 m of about 1 million m^2 and a depth at the front slope of about 70 m. A rough calculation indicates that it contains a quantity of material of the order of size of at least 40 million m^3.[1] This is a significant volume, bearing in mind that the collection area is a small valley glacier with an area of only about 1.75 km^2. One may compare, for example, the corresponding conditions on a valley glacier in easily weathered bedrock (mica schists) in Lappland, namely, the Kårsa Glacier. The volume of its delta amounts to about 11 million m^3 and the area of the glacier bed to 2.65 km^2 (Ahlmann & Tryselius, 1929, p. 31).

The Bjona delta, according to these values, should proportionally have a volume 5-6 times greater than the Kårsa delta. The calculations

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[1] The delta was regarded as a double cone with the base area (= 1 km^2) at the level of —5 m. The height of the upper cone = 60 m, the depth of the lower cone = 65 m.

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of volume are, of course, most schematic, but the proportions are probably of a correct order of magnitude.

In spite of the many signs of strong breaking down (the streaks of debris, the talus cones adjacent to the glacier, the great lateral moraines and the great delta), a closer study gives information of a moderate breaking down in recent times here as in the case of Langtunafjell at Tunabreen.

The glacier front did not reach ahead of the valley in "post-glacial" times, for undisturbed shore terraces are found there at least up to 69 m above sea-level, possibly right up to 89 m above sea-level (De Geer, 1910, Pl. 8). The glacier front had to a large extent the same situation in 1882, 1908, and 1924 (photographs) as in 1954. A certain, insignificant, vertical shrinkage of the glacier would seem to have occurred in 1882-1954, according to picture comparisons.

Kommissaerbreen accordingly appears after examination of older photographs to be probably dead and stagnant at least at its distal part, but in spite of this and in spite of "the climatic improvement" after the 1870's, it has only grown thinner to an insignificant extent and the front has hardly retreated at all since 1882. A similar state of affairs prevails at a small valley glacier[1] at Gipsvika, which is shown on examination of photographs from 1896-1954. While *the fronts of the large glaciers have retreated considerably* on Spitsbergen, *several small valley glaciers seem to lie in an almost conserved condition* and offer tough opposition to melting.

3.22 The morphology of the valley sides

Bearing in mind the formation of the accumulations of debris on the valley sides, Bjonadalen can be divided into three sections (Plates IV (a) and V (a) and Map No. III):

(a) The inner part. Just below the firn limit fall and slide material forms curved streaks on the glacier surface. Talus cones were not formed, nor connecting lateral moraines either. Apparently a certain movement and removal of material by the glacier still occurs here.

(b) The middle part. Fall and slide material from zone (a) forms lateral moraine ridges with an ice core. Fine talus cones of about 10-50 m in height occur.

(c) The outer part. A compound talus slope both towards Templet and towards Sindballefjell.

It is of particular interest for the discussion in Chapter 4.3 that old, isolated remains of lateral moraines form small terraces on the valley side immediately in front of the glacier's right flank.

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[1] The glacier is situated close to the part of Templet called Skiltvakten. Therefore the name "Skiltvaktsbreen" is proposed here for the glacier mentioned.

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3.221 Description of the inner and middle parts of the valley

3.2211 East side

A closer description is here given first of the section of the valley which is shown in Map No. III and Plate IV (a) and which comprises the middle and a portion of the inner valley side towards Sindballefjell. (Map No. III will be found in a pocket in the back cover.) The mountain wall is about 250 m high. It is steeper than the side towards Templet, divided into many steps with sloping shelves between and dissected by rock-fall chutes, which at the top widen into semicircular funnels (E-G on Map No. III). The spirifer wall is about 30-40 m high and goes along the 400 m level with a slight descent towards the south. A bumpy, loose, easily weathered limestone comes immediately above the spirifer limestone.

The section south of rock-fall chute H (Map No. III) gives an interesting insight into the origin of the wall relief. The spirifer wall here projects in a wedge-shaped angle, for which reason the collection area for snow and water increases if one moves along the wall from the tip of the wedge towards the north. The section is clearly seen in Plate V (a). The more the collection area above the spirifer wall increases in height, the more strongly dissected the wall becomes. This testifies that *rock-fall chutes and funnels in it are to a certain extent formed by erosion from above downwards and not by undermining* weathering and falls. The same state of affairs appears, though not equally clearly, in the majority of pronounced corners of the mountain plateau of the Tempel massif.

Map No. III and Plate IV (a) illustrate how fall and slide material is carried out on the ice in front of the rock-fall chutes A-H, I and J. The material forms a lateral moraine, which rises in a sharp, asymmetrical ridge. Its height above the surface of the ice has increased to about 8 m in front of C-D and to about 16 m below H, depending on the fact that the 2-decimetre-thick moraine covering encloses an ice ridge, which is protected from melting, whilst the unprotected ice alongside the moraine melts and is lowered. Between the moraine and the valley is formed a V-shaped hollow.

A series of talus cones about 20-50 m high was formed at D-H. They end against the lateral moraine and have obviously lost a quantity of material to it by the movement of the glacier. The cones are beautifully arched and extended with tongues up into the rock-fall chutes. The type is described in more detail in the following section.

3.2212 West side

The valley side towards Templet in the middle section of the valley looks to a great extent the same as the side towards Sindballefjell just described. It is, however, less steep in the upper part and therefore somewhat more easily accessible, for which reason it could be investigated more in detail.

The lowest step in the wall is formed by the vertical spirifer wall at about 400 m above sea-level. Above it there comes immediately the bumpy, easily weathered limestone, in which deep rock-fall chutes with U-shaped bottoms have been cut between boldy formed pillars and towers (Plate IV (b)). Above it the mountain side is formed to a large extent of an unstable débris slope with a straight profile and a gradient of about 38° immediately below the summit plateau. In this quarter lay longish hanging snowdrifts. The summit plateau reaches 700 m above sea-level.

The material on the even, upper slope is made up of stones about 2—10 cm in size (cherts, limestone) above a black, smeary mass of fine sandy material, which easily slid downwards beneath the feet. The covering of loose material was probably thin, for the bedrock peeped out in several places.

Several well-shaped cones about 10—15 m high lay side by side adjacent to the glacier in this section (Plate IV (a)).

Table 3.

Height, gradient and profile in talus cones at the Kommissaerbreen.

Cone	Height	Mean inclination	Profile	Top	Base transition
B2[a]	About 30 m	34°	Slightly convex	Convex	Slide at the base.
B5	About 10 m	36°	Slightly convex	Convex	Angular break towards the snow.
B7	About 15 m	36.5°	Slightly convex	Convex	Angular break towards the snow.

[a] The cones are numbered in sequence with B1 immediately above the Kapellbreen.

The material in the cones is made up of angular stones of cherts and limestone, about 1—20 cm in size, together with isolated boulders of a maximum size of about 1 m. No evident sorting of débris was present. The material lay very unstably. Under the stones on the surface there was in several places a stony, smeary mass of finer black material. This originated very likely from the débris slope above the wall where similar material was recorded. Probably it was carried down by melt-water or slides and spread over the surface of the frozen ground across the cone. The frozen ground lay at about 40 cm depth in the talus material and came up to the surface in the vicinity of the snow patches. The finer, black material was exposed in the proximal part of small slide-scars.

The colour of the debris varies somewhat with age and gives certain possibilities of judging this. The fresh material is dark-coloured, grey-black or grey, the older grey-brown and the oldest yellowish brown. On several of the cones thinly scattered grey-black to grey material occurred. The predominant colour on the cones in the middle part of Bjonadalen and the one that prevails entirely in the outer talus slopes and on the surface moraine was yellowish brown.

Surface forms. Certain cone mantles were even, others uneven, principally on account of small slide-scars or small mudflow levées. From several of the cones curved tails of débris emerged at the base down to the glacier. They were sharply delimited at the side several metres wide, and about 1 dm thick (Plate IV (b)). They had certainly been formed by the movement of the glacier.

Water and snow. In the rock-fall chutes ran small streams of melt-water, partly from remaining wet snow. In the process rills were formed in the snow, which in many places contained smaller stones, testifying to transport of fresh material by the water down onto the cones.

A continuous covering of snow surrounded the cones, of which the majority (on 27/7/54) were for the most part bare (Plate IV (b)). A couple had a thin layer of fresh débris scattered over the snow patches. It is possible that the cones are mixed with ice in the interior.

Vegetation. At the sheer top of one cone grew some specimens of a type of grass (*Poa* sp.). Narrow bands of grass vegetation were found on the crest of the talus between the tops of the cones mostly north of the Kapellbreen.

3.222 Description of the moraine terraces in the outer part of the valley

Kommissaerbreen becomes more and more covered with surface moraine the nearer one gets to the front. The glacier front itself appears as a steep slope between about 100 and 190 m above sea-level on Map No. II immediately west of the north arrow on the map. Behind the front the surface of the glacier is completely covered by surface moraine about 2 dm thick and the ice front is so dirtied that only in a few places is it possible to make out the ice (see Plate VI (a)).

In this connection it will be of special interest to establish how on the retreat of the glacier front some isolated terraces have been formed from the lateral moraines. Two such small terraces lie respectively at and in front of the west flank of the glacier, and one lateral moraine ridge still not disconnected at the east flank of the glacier. (Fig. 10).

Of the two western terraces the rear (a) is seen faintly on Map No. II marked by a contour at 180 m, and the front one (b_1) is seen more clearly. Its crest is marked by point 161.5 m. Both these terraces are seen in Plate V (b). a has the shape of a pointed ridge (thus not really terrace-shaped), sharply delimited from the talus slope by a V-shaped depression. It probably contains a core of ice. b_1 also has the slight ridge shape, but a gentle transition towards the talus slope.

The still not isolated lateral moraine ridge on the east flank of the glacier is not visible on Map No. II, as it lay hidden on the stereoscopic pictures on which the map is based. On the other hand, it appears on Plate VI (a) (1908) and also on Plate I (1936). On Plate VI (a) an isolated terrace appears in the foreground to the right. It is the proximal

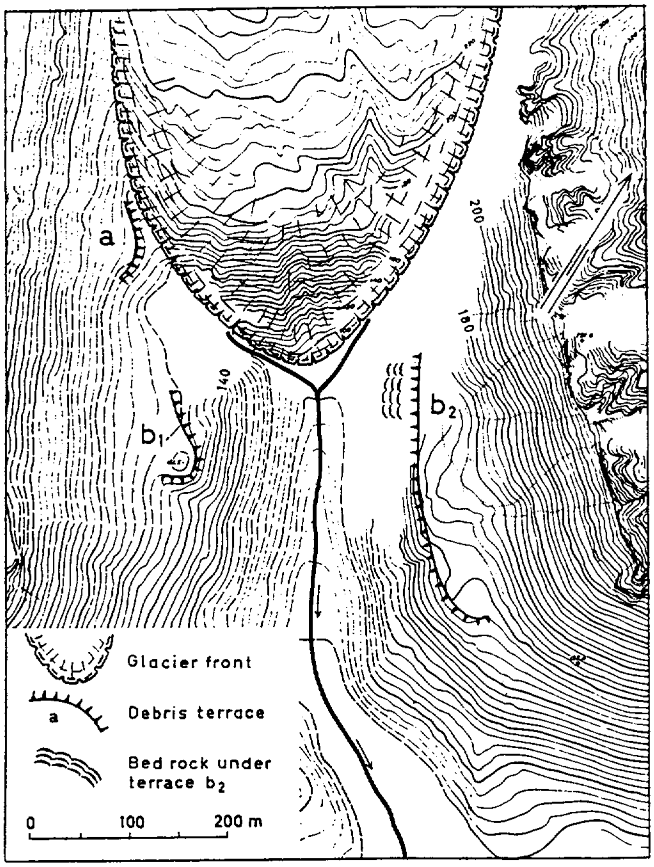

Fig. 10. Sketch-map of the terraces at the front of Kommissaerbreen (cf. Fig. 16 and Map No. II). Patches without contours are hidden on the photographs on which the map is based.

part of the so-called b_2 terrace. Note that it is made up of a covering of loose material, several metres thick, *which is resting on a projecting shelf of solid rock,* probably exposed by the undermining erosion of the glacier river. It is conceivable that several of the terraces situated further forward on the talus owe their occurrence in the same way as this to projecting, but concealed rock-shelves, which could be a contributory cause of the scattered occurrence of the terraces.

Accordingly, on the front of Kommissaerbreen, the following stages, amongst other things, in the formation of isolated terraces from lateral moraines may be observed:

(1) A part of a lateral moraine may be disconnected from the side of the ice front, for example, by a lateral, melt-water furrow (a) and remain lying as an embankment-shaped terrace on the talus slope. This lateral moraine terrace probably contains a large core of ice from the beginning.

(2) A former lateral moraine (+ glacifluvial material ?) could probably remain lying in scattered terraces in front of a retreating glacier, amongst other things, on account of the terraces resting on bedrock shelves (b_2).

3.23 Present-day turnover of material

The author has not been able to determine if the glacier is still moving. Had its movement been known an approximate calculation of the rate of disintegration on the sides of the valley could probably have been made in a similar fashion as for Langtunafjell at Tunabreen.

The following observations point, however, to a moderate supply of debris:

(1) A comparison between photographs from 1882, 1908, 1924 and 1954 shows the same number of talus cones in the parts of the valley reproduced. The cones have, moreover, about the same size from 1882 to 1954.

(2) Dirty avalanches had issued on the ice at A, B and D (Map No. III) in 1954 and carried with them both boulders and finer material. They had been released from the hanging drifts at the top of the rock-fall funnels towards Sindballefjell. The snow was dirtied in layers in the fracture surfaces of the hanging drifts. The remainder of a cone of avalanche snow is visible on Map No. III covering the lateral moraine below F. However, probably no significant supply of debris occurs through avalanches there, for in that case the surface of the ice in front of and distally of the F chute would be dirty, which is not the case.

(3) Between the Kapellbreen and the valley mouth the talus belt is composed of an even, compound talus slope with a straight profile and an inclination of about 36° right down to the angular base break, V-shaped in cross-section, towards the lateral moraine of the Kommissaerbreen. The bottom of this depression was filled with melting snow (see Plate V (b), foreground). Along the whole snow-band (about 1 km) there was only in one place about 10 cobbles that had rolled down and a few small boulders. This testifies that the talus slope, in spite of its steepness, is stable and at least this year did not receive or export any appreciable amount of debris.

(4) The talus slope of Sindballefjell on a level with the glacier front is covered with grass and herbs on its crest. The vegetational pattern has been exactly the same in its main features since 1908 (picture comparison).

There are also, however, signs which may point to a somewhat more copious turnover of material, at least in the inner part of the valley, than what the above-mentioned observations suggest. Thus it is clear from Map No. III that the moraine (the slide material) at A (and also I and J) does not form any ridge, nor any depression in the glacier either. The ridge develops first distally of B. It may be due to the fact that *the slide material at A (I, J) is so fresh* that the ablation has not managed to lower the ice surface round about. But as the ablation is probably insignificant so near the firn limit, the slide tongues mentioned may, in spite of their fresh appearance, be rather old.

The large delta at the valley mouth points to severe breaking down and transport of material, but this does not show the actual denudation in the valley. It is reasonable to suppose that most of the delta material was brought there during passed climate phases of more rapid deglaciation. Further if the post-glacial period is very long (see Chapter 2.43) this could contribute to explain why the delta is so large.

3.24 Summary

Talus cones, streaks of debris, lateral moraines and solitary moraine terraces in Bjonadalen represent features in the development of the slopes adjacent to a stagnant valley glacier.

The author cannot judge for certain the rate of disintegration alongside the Kommissaerbreen at the present time, but most indications point to a relatively slow turnover of material. At first sight, the disintegration strikes one as being very severe with, amongst other things, well-shaped talus cones alongside a glacier which apparently has recently been or still is slowly moving. The picture comparisons show, however, noticeably enough that the glacier with its talus formations has to a great extent been exactly the same since 1882. Nevertheless, a more active, recent turnover of material probably goes on in the inner parts of the valley than in its outer parts.

CHAPTER 4

The Morphology of the Mountain Walls and Talus Slopes at Bjonahamna

The forms of the mountain wall and the talus slopes appear clearly on Map No. I and also on Plate I and many others. The talus slopes investigated have been designated T1-T10 along the wall towards Tempelfjorden and SI and so on towards Sassenfjorden. The large alluvial cone at Bjonahamna has been designated A.

4.1 THE FORMS OF THE MOUNTAIN WALLS

(For the stratigraphy, see Chapter 2.3)

The summit plateau of Templet is even and flat. It reaches in the extreme south 513 m above sea-level. The lowest part of the severely dissected wall rises from the talus belt at the 164 m level adjoining Tl and at 220 m adjoining T9.

On account of the fact that harder strata alternate with looser the mountain walls have taken on a step formation. It is possible to distinguish *three larger such steps* between the talus slope and the summit plateau of Templet at Bjonahamna. Each of them consists of a steep wall, partly built up of resistant strata, and above the wall a gradually sloping shelf, composed of many small steps, often with a thin layer of debris on the solid rock. Reckoning from the bottom upwards the walls of the three larger steps are called *the c-cliff, the spirifer cliff* and *the productus cliff* (see Chapter 2.3, Fig. 5).

The wall is also divided up into *rock-fall funnels*, which lie in a row above each other in the following order reckoning upwards from below:

The spirifer funnels. Limited upwards by the spirifer wall, downwards by the break-through in the c-cliff.

The productus funnels. Limited upwards by the productus cliff, downwards by the break-through of the rock-fall chutes in the spirifer cliff.

The top funnels. Limited upwards by the edge of the top plateau, downwards by the break-through of the rock-fall chutes in the productus cliff. Se Map No. I.

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The c-cliff is severely dissected by rock-fall chutes and rock-fall funnels and remains in the form of a series of projections, which separate the spirifer funnels.

The spirifer cliff is vertical and usually relatively whole (Plate VIII (b)). It is about 40-50 m high and circularly curved in long arcs of about 100-150 m. They thereby form the rear wall in the spirifer funnels, which are regular both in form and size. The upper edge of the spirifer cliff has been broken through by erosion chutes from above, mostly in the funnels which have the greatest catchment area for snow and water (T4-T7). Between the chutes high ridges or pillars are formed (Plate IV (b)). The funnels which have a small collection area are not equally severely dissected (S1, T1, T2, T8, T9). In particular the spirifer cliff is whole and intact in the S1, T1 and T9 funnels, which all lie at a corner of Templet and therefore have small collection areas. They form a parallel case to the previously described "corner" in Bjonadalen (Chapter 3.2211, Plate V (a)).

The productus cliff appears in Map. No. I most plainly above T1. It too is curved inwards in semi-circular funnels, roughly conforming with the spirifer cliff. It is, however, more severely dissected.

At the edge of the plateau a large number of rock-fall chutes begin at intervals of 20-40 metres. They converge lower down in each funnel, are deepened and break through the harder bedrock strata at a few points. A closer look at the chutes shows that they usually have a flat U-shaped bottom, covered in stretches with a thin layer of stones and gravel (Plate VI (b)). Where the bottom of the chutes is exposed, the top strata of the bedrock appears as small steps with edges worn smooth. In several of the chutes bands of snow remained throughout July.

Most of the chutes were damp at the bottom but permanent streams or rills ran at the end of July only in some of the largest chutes (to T5 and T6). Two larger streams, moreover, ran down the alluvial cone A.

4.11 Discussion of the genesis of the rock-fall funnels

In some places on the walls were observed relatively insignificant traces of chemical weathering in the form of small solution pits and limestone crusts. Some of the aquiferous chutes which debouched in the spirifer cliff were narrow and cut down to a depth of about a metre at the bottom of larger chutes. This cutting down may perhaps be due to chemical weathering. For the rest, the rock-fall chutes as a whole are probably erosion forms, possibly established in interaction with undermining rock-falls (funnels and steep chutes) and later widened by nivation. The bottoms of the chutes probably got their rounded form through corrasion as well as by stone slides (and possibly snow slides ?). Cavetto-like enlargements along the sides of the chutes often occur and lend support to the interpretation mentioned (see Fig. 11 (c)).

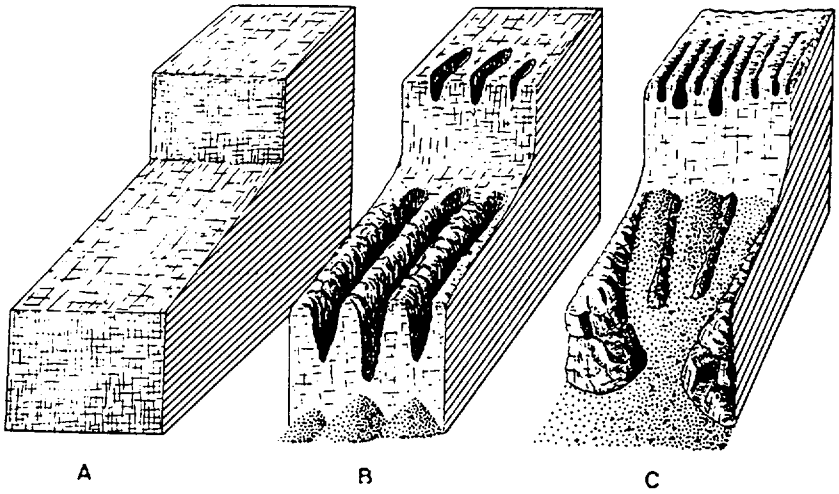

Fig. 11. Sketch showing the principles of development from a complete step (A) to rock-fall chutes (B) and further to a rock-fall funnel (C).

The role of nivation in the formation of chutes and funnels is also underlined by Högbom (1914, p. 281) and McCabe (1939, pp. 454, 463). Groom (1959, p. 369 f.) strongly emphasizes the importance of nivation and glacial erosion in the formation of (large ?) rock-fall funnels. "The glacier, by nivation, modifies the water-worn gully in which it originated to produce a characteristic, rounded, funnel-shaped hollow. The existence of such hollows on steep hillsides and escarpment faces is taken to be indicative of an earlier period of niche glacier activity . . ." (op. cit., p. 375).

To this the following points of view can be added.

1. The rounded funnel-like form of hollows in mountain-sides can also develop through weathering and rock-falls without the influence of glaciers. In mountain walls built up of easily weathered rocks, resting upon a hard layer, there will be a funnel-like ravine with all sides sloping roughly at 35-40° above every cleft of gorge through the hard layer. *This rounded funnel-form is a natural result of undermining, back-wearing rock-falls* (compare for instance, the forming of "dolines" in karst regions by the similar process of subsidence from below, yet without any free face as in a mountain scarp.) Similar forms can be seen in arid environments like Grand Canyon etc. See also Blackwelder, 1942, Fig. 1.

2. If the fall funnels at Bjonahamna described above have been carrying glaciers during "post-glacial" times, these glaciers must anyhow have been very small, as their talus cones have not been transformed into alluvial cones even at the melting of the hypothetical glaciers. Philipp (1914, p. 25) thinks that the relief of the walls would have been formed through erosion by glacier ice during the melting of the land ice in the following way: (a) a smooth trough valley covered with glacier ice,

(b) the ice mass in the valley bottom is thinned out, the ice along the smooth valley sides begins to flow *down*, not along, these sides, and (c) erodes a step in the valley side, and (d) when the ice mass has reached a certain degree of thinning out, it divides itself up into regular tongues which continue to flow down the valley sides and hollow out small cirques and "funnels".

A large number of objections can be raised against this hypothesis. It clashes with the principles of ice melting below the firn limit (see Mannerfelt, 1945, p. 10). The step formation suggested pre-supposes a strongly selective glacial erosion, which is extremely unlikely (cf., for example, Map No. II, the cartographic picture in a corner of Sindballefjell with three larger and several smaller steps, plainly developed right out on the corner of the mountain). The view that thin ice-tongues could form deeply concave funnel forms with gorges narrowing downwards in a valley side smooth from the beginning would seem to be unreasonable (see Philipp's own picture, Tafel IX:2).

A comparison of the forms in a number of funnels on Templet lends strong support to the correctness of the following interpretation of the development (Fig. 11). A complete step (A) owing its occurrence to alternating harder and looser kinds of rock was formed by undermining rock-falls. The entire step is broken through by several smaller, parallel or slightly convergent chutes with U-shaped cross-section (B in Fig. 11). These are widened out and when the dividing walls between them have been broken down, a larger funnel remains, in the bottom of which small remains of converging ridges stand up from the thin layer of loose material (Fig. 11, C). Stage A in Fig. 11 is shown by the spirifer cliff in Plate V (a), B by the spirifer funnel at S1 and C by the spirifer funnel at T8 and T11.

The regular size of the forms is a problem for which it is difficult to envisage a conceivable explanation. Probably it is dependent upon the structure and jointing of the bedrock.

Summary. Characteristic forms on the walls are the great steps which owe their occurrence to and are connected with certain resistant strata, and furthermore the regular, semi-circular funnels, the U-shaped chutes, the pronounced ridges and the pillars between the chutes.

In the author's view funnels and chutes are erosion forms, possibly established in interaction with undermining rock-falls, later widened by nivation. The age of the wall relief is discussed further in Chapter 6.

4.2 THE MORPHOLOGY OF THE TALUS SLOPES

4.21 Form, size, material and profile

The talus belt at Bjonahamna is reproduced, amongst other things, on Plate I and Maps Nos. I and II. It consists of a number of large cones, about 200-300 m high, which have grown together laterally. The

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Table 4.

Inclination values, etc. concerning talus cones and alluvial cone A at Bjonahamna. The cones have been grouped according to decreasing average inclination.

Group	Cone	Base m above sea-level	Relative height b-g[a]	(b-s[b])	Maximum thickness[c]	Average inclination b-g	Profile	Material	
								Top cm	Base cm
I	Sl	60	128	(-)	8	34.9° (P)[d]	Straight	0–2	2–20
	T9	132	92	(184)	18	34.8° (K)	Slightly concave	3–10	3–30
	Tl	52	152	(226)	-	34.2° (K)	Straight	3–10	3–30
II	T6	10	182	(278)	22	33.1° (P) 33° (K)	Straight to slightly concave distally	3-10	3-30
	T8	44	180	(268)	22	32.9° (K)	As T6	3-10	3-30
III	T4	22	178	(266)	20	32.5° (K)	As T6	3–10	3–30
	T5	15	185	(273)	24	29.5° (P) 29.3° (K)	Concave	3–10	3–30
	A (alluvial cone)		105	(-)	-	21°-22° (K)	Concave	1–10 ÷ boulders	

[a] b-g = the height from base to gorge or the height of the cone mantle (Sl, A).

[b] b-s = the height from base to spirifer cliff.

[c] "Maximum thickness" was measured on the cones in a horizontal line on Map No. I.

[d] P = according to clinometer measurement. K = according to the measurement on Map No. I.

majority are shaped like an hour-glass on account of the fact that the bottom of the spirifer funnels is occupied by streaks of débris which go directly over into the original accumulation cone (the talus mantle or cone mantle) via the narrowest part of the gorge (Plate VII (a)).

On the bottom of the spirifer funnels there usually lies two or more small top cones, one below each chute in the spirifer cliff. From each top cone emerges a longish, ribbon-shaped streak of unstable débris stretching down to the gorge. The cone mantles are finely and regularly arched, T1 particularly, owing to its free situation at the southern corner of Templet (Map No. I).

S1 is an example of a cone with a sheer top, separated from the spirifer funnel by the unbroken c-cliff. It represents a stage which has not gone so far in development as the rest (Fig. 11 B, Plate VII (a)).

The material in all the cones is of about the same kind and size;

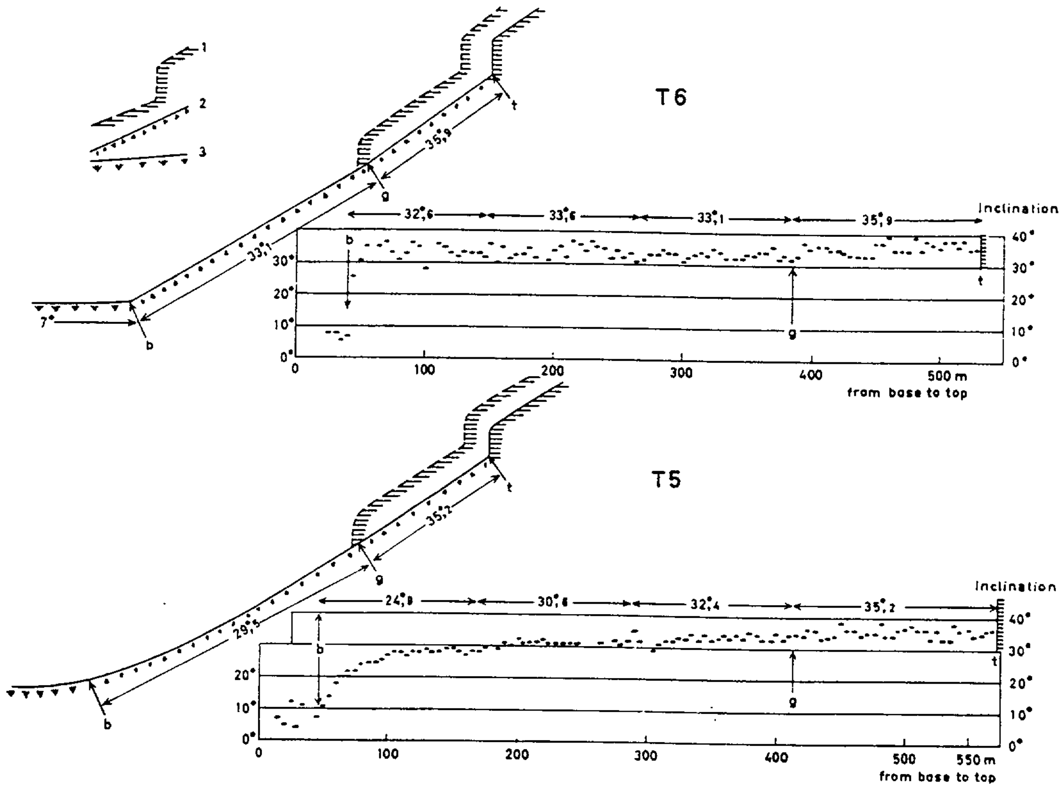

Fig. 12. Profiles and inclination diagrams of the talus cones T5 and T6 at Bjonahamna according to measurement with a special clinometer at every 5th metre along the slope (cf. Plate VII b). Material: angular stones and boulders of cherts and limestone, about 3—30 cm in size. T5 is slightly influenced by avalanches. The diagram of T5 shows clearly the gently concave basal transition (on both sides of b) and also the very even talus surface on the lower part of the cone ridge. T6 is slightly influenced by smaller slides and mudflows, which have not reached out to level ground. Note the break in the profile at the base (b). The cone has an almost straight profile and somewhat more uneven surface than T5. The talus surface in the funnel (g-t) is in both cases steeper than the cone mantle (b-g). The funnel on T6 is especially steep, most likely because the profile in its upper parts has been measured over talus covered with vegetation. 1. = bedrock. Broken contour = ridge between funnels. 2 = talus slope. 3 = flat ground with vegetation. Vertical scale same as horizontal.

angular stones and boulders of the predominating cherts and limestone, together with isolated boulders of sandstone and gypsum. This size predominates right down to the base, but more scattered boulders about 2-3 dm in size appear on the surface of the mantle from the middle and downwards and also to the sides (Plates VIII (b), IX (a) and IX (b)). The base fringe, about 50-100 m wide, on the raised shingle beach consists of boulders of a size of 1-2 m or larger (spirifer limestone, sandstone).

A number of pits of a depth of 0.8 m at most were dug in the cones for examination of the material beneath the surface. As a rule the same size of stone was encountered as on the talus surface, often with a somewhat increasing element of gravel and sand. See below Chapter 4.251-252. No distinct stratification was observed.

Thickness, inclination and profile. In spite of the fact that the material in the cones is very similar, they are different from each other in the matter of, amongst other things, profile and detail forms on the surface. In Table 4 some of the cones have been grouped according to decreasing average inclination and moreover some other data on them is given (see also Fig. 12 and Plate VII (b)).

4.22 Surface forms

The detail forms which appear on or near the talus surface are reckoned as surface forms. Most of these are described in more detail in other sections of this chapter, according to the references below.

Small slide tongues, see 4.251. *Mudflow gullies and levées,* see 4.252. *Avalanche tracks and avalanche débris tails,* see 4.253.

Solifluction terraces, small and covered with vegetation, appeared in the lower part of certain hollows between the talus cones, for example, between T4 and T5 about 75-150 m above sea-level. They probably owe their existence to melt-water from snow-drifts higher up in these hollows. To judge from the close and complete vegetation covering on the terraces they have had no recent movement to speak of.

Slide scars. A relatively fresh scar was found in the bottom of the spirifer funnel above T1. It was about 5 m wide, 10 m long and had been produced in the vegetation-covered, fine-grained material adjacent to the cliff. The underlying bedrock had been exposed in several places in the slide scar, by which it was possible to see that the loose material formed a layer some decimetres thick above the rock (see Plate VIII (b)).

Bump holes after rock-falls. On several cones there appeared series of small bump holes after rock-falls. The holes are usually oval, about 1 m long and ½ m deep. They form patterns like strings of pearls and often go in a slight curve obliquely down the cone mantles. The distance between the holes may vary considerably (2-30 m, etc.) and shows how far the bounding boulder has gone at each leap. It has been possible to date several of the fall traces by comparative picture examination (see Chapter 5.22).

The bump holes are of interest, inter alia, partly because they testify that boulder falls have occurred and partly because they offer the possibility of reconstructing how the fall happened, sometimes also how large it was. Furthermore they give an idea of the relative age of the fall through the vegetation in the holes etc.

In the lower western part of cone T5 two larger bump holes were

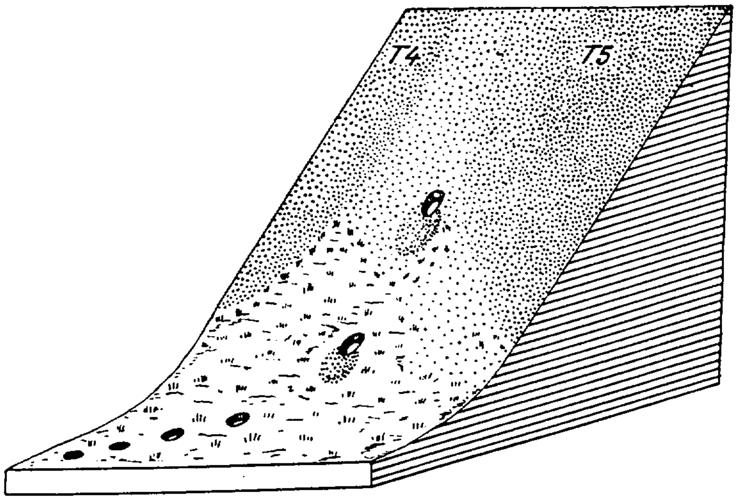

Fig. 13. Sketch of a series of bump holes from a boulder fall which fell over cone T5 before 1936. Plate XX.

found, estimated to be about 2-4 m wide, 4-6 m long, 1 m deep and oval in shape. They lay about 30 m from each other. The boulder which formed these bump holes had continued out over the level shore and there formed a 450-metre-long "string of pearls" of more and more closely lying bump holes (see Fig. 13 and Plate XVII (b)). It was possible to date the fall. The bump holes testify to great stability in the lower part of the cone. See further Chapter 5.225.

4.23 Vegetation

Between the talus tops along the spirifer cliff and in wedge-shaped surfaces between the talus tongues in the funnel bottom the vegetation is close and luxuriant (grass, moss, *Papaver radicatum, Oxyria digyna, Saxifraga groenlandica, Polemonium humile* and many others). Probable causes of the luxuriance are a favourable micro-climate, relatively fine-grained soil, fertilisation by birds, and moisture from the cliff. The gradient on these vegetation-clad parts of the funnel bottoms is often greater than in the debris streaks, probably on account of the binding effect of the vegetation on the debris. At several points the gradient reaches a maximum of 39-40°.

On the cone mantles appear scattered tufts of *Papaver, Oxyria, Saxifraga cernua* and *Sax. oppositifolia* and *Dryas octopetala.* Several cones are almost completely lacking in herb vegetation on the upper and middle parts of the cone mantles. Lichens occur principally on the lower part of the cones (*Caloplaca elegans* and others). The middle and lower part of T5's cone ridge is even and somewhat obliterated in cross-section, and also without vegetation (avalanches); even lichens are lacking and appear for the very first time nearer the base.

In the hollows between the cone mantles the vegetation is usually

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close. It consists of the same species as have been mentioned above plus a number of snow-bed species (mosses, *Salix polaris* and others).

The limit of the level ground, covered with close grass and moss vegetation, at the talus base is in most cases very sharply demarcated (Plate IX (b)), as also the limit of the close vegetation at the side of the cones.

Lichens, mosses and also higher vegetation seem readily to start their colonies at the edge of or between the slide tongues on the cones which have them (cause: older, more stable surfaces? better supply of moisture? more prolonged snow protection?)

In many places in the probably most stable debris there was observed a characteristic cross-striped patterning of lichen-coloured patches alternating with bare patches. The cross-striping runs parallel to the contours and indicates that in these places there has occurred a slow movement in the form of short slides, laying bare part of the previous lichen-covered talus. The clearest formation was the cross-striped lichen zone on cone T7 and also in the terrace slope below T9 (Plate XIX). These parts are probably the most stable débris-slope surfaces next after those which are covered with close moss and herb vegetation. That, however, these surfaces are not completely stabilized either, but may be subjected to momentary mass-movements is shown, for example, by the slide scar mentioned in Chapter 4.22.

4.24 Snow, water supply and frozen ground

On our arrival at Bjonahamna on July 10th, 1954, only a few snow patches remained on the talus slope and in the rock-fall chutes on the wall. Larger drifts also remained up on the summit plateau and along its edge.

The three largest expanses of snow on the talus slope at Bjonahamna were about 30-50 m long. Two of them lay in hollows between talus cones T8-T9 and T5-T6 and one adjacent to the eastern side-wall in the T6 funnel.

A comparison with older pictures (Plates XII, XVI (a), XVIII (a), XVIII (b) and XIX) shows, inter alia, the following features in the localization of the snow:

1. The snowdrifts have to a large extent the same localization from year to year.
2. The snow accumulates principally in (a) *the hollows between the talus cones,* (b) *the spirifer funnels* (particularly alongside the eastern side-walls and on the talus crest alongside the spirifer cliff), (c) the rock-fall chutes on the wall and at the top in the rock-fall funnels alongside (d) the edge of the summit plateau. The localization of the drifts shows that they are accumulated by easterly winds.

The positions mentioned in (a) and (b) probably have significance as regards the luxuriance of the vegetation in these places (snow protection in the winter, moisture in the summer). Nivation hollows or related features (McCabe, 1939, p. 456) had not been formed by these snow patches. Positions (c) and (d), together with the circumstance that the cone ridges seem to lie bare early in the spring (photograph in Berset, 1953, pp. 129, 225), probably have significance as regards the release of the avalanches and their corrading effect (see below Chapter 5.122).

Insignificant runnels or trickling water ran at some places down the spirifer cliff in each funnel. Larger runnels with an estimated 5-10 litres of water per second emerged in funnels T5 and T6. The water disappeared beneath the surface on the talus crest and came to light again at the base of the cones (Plate IX (b)). Two larger streams ran over the alluvial cone A.

To judge from the excavations undertaken, the frozen-ground surface at the end of July lay more than 8 dm deep in the cone ridges, about 3-5 dm deep towards the sides of the cones and still shallower in the vegetation-clad hollows between the cones. Alongside the remaining snow patches in these hollows the frozen ground came up to the actual ground surface. The upper surface of the frozen ground sank about 1 dm in one week at the end of July at the sides of cone T6.[1]

4.25 Morphological division and descriptive account of the talus cones at Bjonahamna

From Chapter 4.21 it has appeared that the cones at Bjonahamna are built up for the most part of the same material both as regards kinds of rock, form and size. On a rapid consideration the cones appear to be very like each other, but on a closer examination it is clear that they have distinct differences in the matter of *profile* and the *detail forms* of the surface. The reason for these differences in the form of cones built up of similar material is that they are to a certain extent *characterized by different transport processes*. This is evident both on an examination of the detail forms and on a closer study of the transport processes (Chapter 5).

The following division is chiefly based on the profile of the cone mantle and its surface forms. The division has already been put into practice in drawing up Table 4 (cf. the column "Average inclination").

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[1] In a newly opened mine shaft in north-facing talus at Longyearbyen the frozen ground lay about ½-1 m below the surface on 4/8/54. Under it lay a compact, frozen mass of stone and ice adjoining the bedrock.

Jahn (1958, p. 241) gives the following depths for the frozen ground at Hornsund at the end of September, 1957: in clays and boulder clays, up to 1.5 m: in sands and gravels, almost 2 m.

4.251 Talus cones characterized by small slides

This comprises S1, T1, T2, and T9. See Group I in Table 4. The cones are relatively steep. Average inclination 34-35°. The profile is straight right down to the angular base break. The mantle surface is covered over with downward-running, usually straight slide tongues about 1-10 m in width (see, for example, Map No. I, cone T5 120 m above sea-level). They form only very slight elevations on the even surface of the mantle, but nevertheless appear plainly (Plate XIV (b)). The material is assorted with the larger stones along the side and the smaller in the middle of the tongues (Plate IX (a)). The slide tongues owe their existence to the straight profile and the severe gradient. In Chapter 5 the movement on the formation of the slide tongues is described and it is pointed out that they constitute the essential form for the shifting of material, inter alia, on cones T1 and T2.

The mantle surface is almost completely free from large patches of vegetation. Lichens occur in the extreme lower part of the cones. The limit of the vegetation-clad ground between and below the cones is very sharply demarcated (Chapter 4.23).

The collection areas belonging to these cones are smaller than those of the majority of the other cones. The width of the rock-fall funnel at the summit plateau is thus above T1 only about 100 m, at S1, T2 and T9 considerably less. The small collection areas may be an explanation of why these cones have not been eroded by running water to a greater extent.

4.252 Talus cones characterized by mudflows

This comprises, inter alia, T6 and T8. See Group II in Table 4. Cones T6 and T8 have an average inclination of about 33°, that is to say, somewhat lower than Group I. The profile is slightly concave towards the base and the surface is covered over, particularly on T6, by slightly pronounced ridges, about 5-15 m wide, often with a slightly serpentine course downwards. The ridges are terminated distally by a tongue-shaped lobe, which, as distinct from the small slide tongues, in certain cases goes out somewhat on level ground at the talus base. These ridges are in all probability formed by watery mudflows (cf. Sharp, 1942). See below Chapter 5.226.

By such mudflows both finer and coarser debris is probably carried out over the cone, partly from the talus crest and partly from the chutes above the spirifer cliff. On several cones there were encountered streaks of black, gravelly and sandy soil, partly hardened on the surface. On excavating in such material at about 120 m above sea-level in the middle of cone T6, the finer material was found to be about 60 cm thick. No stratification could be observed. At depths greater than 60 cm there recurred talus material of stones about 2-10 cm in size, with no ap-

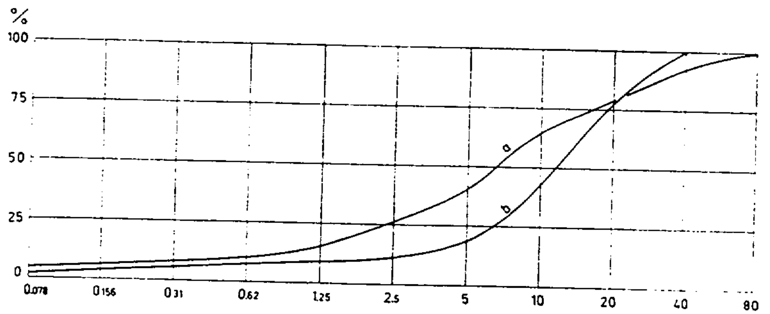

Fig. 14. Cumulative curves of particle-size distribution in relatively fine-grained material on talus cone T6, 100 m above sea-level. The material is probably from an old "mudflow levée". The surrounding talus material was about 2—20 cm in size. a = surface, b = 0.2 m below surface.

preciable element of finer material. The finer material met with was probably a residue following an old, obliterated mudflows levée. Fig. 14 shows the grain-size distribution in this material.

At many places in the region talus cones occur with open (fresher?) mudflow gullies, edged with a distinct levée on each side. They often reach out somewhat onto level ground and transform the talus cone in the direction of an alluvial cone (see Plate VIII (a)).

The width of the funnels is for T6 and T9 about 140-170 m at the summit plateau. In other words the collection area is greater than for Group I. There are, however, in the neighbourhood examples of isolated mudflows which have descended from very narrow rock-fall funnels.

4.253 Talus cones eroded by avalanches

See also Chapter 5.122. The group comprises T4 and T5. Both the cones are distinguished from the rest, partly by a more distinctly concave profile and lower average inclination (32.5° and 29.5°), partly by a more even, as it were obliterated mantle surface (Plate XV (b)). These cones would seem to have been eroded by snow avalanches. The signs of avalanche erosion are (1) the broad, even, rectilinearly delimited paths of light-coloured material, not overgrown with lichens, on the cone ridge, (2) the concave and diffuse transition to more level ground, where, inter alia, stones are spread out over the plant covering below the cone, and (3) a so-called avalanche debris tail in the middle of cone T4 (Plate XV (a)). The cones are also affected by erosion by mudflows, as is clear from the many divergent tongues along the sides.

4.26 Average inclinations in talus and similar slopes at Bjonahamna

From Table 5 and from the account in Chapter 4.25 it is clear that the differences in inclination and profile in the cones owe their existence to different transport (shifting) processes. It is therefore difficult to

Table 5.

Collation of average inclinations in accumulations of similar material (limestone, cherts, about 3-30 cm in size) in the Tempelfjord area.

Debris slope formed by undermining (abrasion)	40°
Talus slope, unstable top cones, formed by debris supply	36-37°
Talus slope, shifting by smaller slides	34-35°
Talus slope, slight erosion by mudflows	32-33°
Talus slope, slight erosion by snow avalanches	29-32°
Alluvial cone A, erosion by torrents	21-22°

make a correct comparison with the "maximum inclinations" which have been measured in similar material in other places.[2] The values seem, however, to be very similar. The circumstance that the talus cones on Spitsbergen are frozen inside seems accordingly to have no effect on the inclination.

Compact limestone	35½-37°	[2] The Alps (Piwovar, 1903)
Granular limestones	36°	
Lime sandstone	35-36°	
Limestone	35°	[2] Crete (Poser, 1957)

4.3 TERRACES ON THE TALUS SLOPES

A specially noteworthy feature on the talus slopes at Isfjorden are the high-lying terraces of loose material which are found in many places. An example of such a terrace is the one which lies over cone T9 at Bjonahamna (see Plate I and Map No. I). Fig. 15 shows a transvere profile through this terrace.

It is characteristic of this type of terrace level that it is situated above the upper marine limit[1] and that it is not horizontal but slopes slightly in longitudinal section. These terraces are thus not marine terraces. Probably it is this type of formation which Högbom (1911, p. 40) interprets as "lateral moraines of compacted talus masses". Feyling-Hanssen (1955, pp. 35, 76) mentions a terrace at 96 m above sea-level and supposes that it is an old lateral moraine.

At Bjonahamna terraces on the talus slopes occur partly at several places in the outer part of Bjonadalen (see Chapter 3.222) and partly at the talus cones T9, S2 and S6. If these formations are isolated remains of lateral moraines in accordance with the suggested interpretation mentioned above, they offer *an extraordinarily good opportunity of judging the total post-glacial supply of dèbris to the talus cones situated above the terraces.* It is therefore justified to enter upon a somewhat more detailed discussion of their form and probable manner of formation.

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[1] The upper marine limit is situated around 90 m a.s.l. in this region (Feyling-Hanssen, 1955, p. 35 f.).

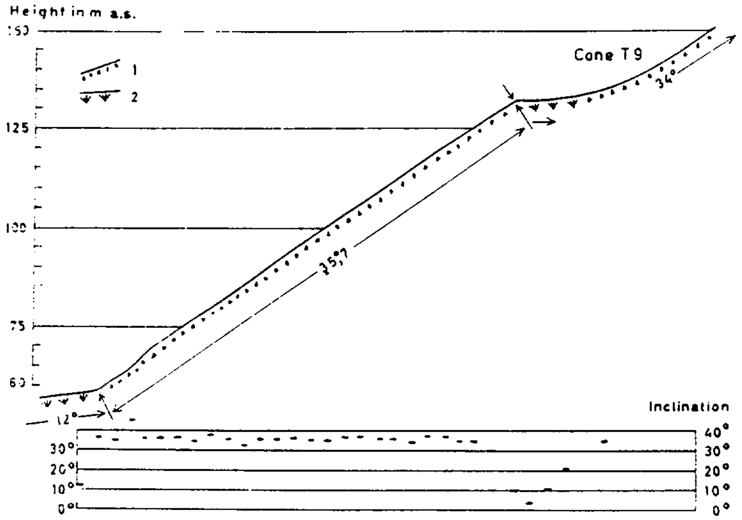

Fig. 15. Slope profile and inclination diagram from terrace at cone T9, Bjonahamna .(cf. Plate I). Horizontal scale same as vertical. 1, naked debris slope; 2, vegetation cover.

4.31 The terrace at talus cone T 9

The transverse profile of the terrace appears in Fig. 15. The profile is measured from the lower part of T9, near the east edge and in the direction of the line of fall downwards.

The terrace level is at most about 15 m wide and about 200 m long. It has the shape of a platform sloping slightly out towards the fjord, beginning in the middle of cone T10 about 140 m above sea-level, extending transversely over T9 and ceasing at T8 at about 130 m above sea-level. In the middle of T9 the terrace is only about 2-3 m wide.

The inclination diagram in Fig. 15 shows how the slope profile from an inclination of about 34° in the lower part of cone T9 passes over without a sharp break to the terrace which has an inclination of about 3-10°. The gentle base transition probably depends on an accumulation of fall boulders at the base of the cone in combination with slight shifting processes. The terrace level has a close vegetation of moss, *Dryas* and others. On top of the plant covering lay scattered fall boulders about 2-5 dm in size. The terrace level is very sharply demarcated from the terrace slope in front. In its upper part there was to be seen a layer of relatively fine-grained soil under the plant covering.

The terrace slope has an average inclination of 35.7° along the measured profile line. The surface is very even. The largest individual inclination values are found immediately above the angular base break (45°) probably because the material is moved by slow slides in which the steeper front of the slide tongues is halted at the base break[1]. The material on the surface was of relatively uniform size, angular to smooth-edged cobbles and boulders, about 1-3 dm in size.

The slope is clad here and there with lichens, which appear in short horizontal bands separated by areas of bare, yellowish brown stone. This "cross-striped lichen zoning" is obviously caused by short slide movements occurring infrequently. Shifting by recent larger slides also occurs (see Chapter 5.229).

The transition to level ground takes place through a very sharply pronounced break in the profile (from 37° to 12°) and is furthermore accentuated by the fact that the ground in front of the slope is covered with close vegetation (*Cassiope, Dryas,* moss). In this vegetation lie scattered small boulders.

The angular base break in the profile at the foot of the terrace slope shows that no appreciable accumulation or removal of stones or boulders from the terrace slope has occurred since the abrasion ceased to work at this level (55 m above sea-level). The old and dense vegetation in front of the terrace slope is a proof of the same thing but with a shorter range backwards in time.

4.32 Other terraces of a similar kind in the neighbourhood of Bjonahamna

A number of other terraces in the vicinity of Bjonahamna present a similar appearance. Some data about them has been collected in Table 6.

The situation of the terraces appears in Table 6. The formations a, b_1 and b_2 have been described in Chapter 3.222. The terraces at S2 and S6 have the same close vegetation up on the level as T9 and are thinly dotted over with boulders.

The S6 terrace has a couple of interesting details of form up on the level. One is a relatively recent subsidence hole about 1-1.5 m deep and 3 m long. Several boulders ½-1 m in size have slid down into the hole or hung in an unstable position with "recently" exposed, light-coloured sides, from which the moss had slid off in lumps.

The hole may be interpreted as a subsidence in consequence of chemical solution of loose material or (more probably) of solid rock within the terrace. It may also have been formed by a melting ice core.

The other interesting detail of form was an evident and indubitable *erosion gully,* which cut through the crest of the terrace and its outer edge. It was about 2-3 m wide, V-shaped but with a broad, flat bottom, that

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[1] Poser (1957, p. 118) reports a similar convexity at the base of talus slopes in Crete. The cause is probably slow movement by creep or small slides stopping at the base.

Table 6.

Collation of data on terraces in talus in the Bjonahamna region. The numerical values are in round figures. V = terrace level inward-sloping — = terrace level horizontal or outward-sloping. O = negligible vegetation. + = close vegetation.

Designation	Place	Height above sea-level (metres)	Terrace level Length (metres)	Greatest width (metres)	Shape	Vegetation
a	Bjonadalen. Adjoining glacier front. Towards Templet.	About 180	About 20 ?	About 10 ?	V	0
b_1	Bjonadalen. In front of glacier front. Towards Templet.	160	About 60	About 20	—	0
b_2	Bjonadalen. In front of glacier front. Towards Sindballefjell.	145–135	250	About 30	—	+
T9	Bjonahamna, cone T9 (Plate I).	140–130	About 200	About 15	—	+
S2	S.W. wall of Templet, cone S2 (Plate VII (a))	130–120	175	30–40 ?	V	+
S6	S.W. wall of Templet, cones S6, S7 (Plate X)	140–135	250	30–40 ?	-V	+

is to say, of a water-eroded form typical of the area, not to be confused with a suddenly formed mudflow gully, for these have a U-shaped cross-section and are surrounded by levees. This gully was completely covered by the same vegetation as the terrace level. Recent feeder streams from the talus mantle behind were completely absent.

The gully is indubitably of great age. It was probably formed by melt-water torrents on the melting of the land ice at the formation of the terrace.

In order to elucidate further the position and height of the terraces, they have been dotted in on a distance diagram (Fig. 16). It is clear from the diagram that there is no difficulty, as regards position and height, in interpreting at least the a, b_1 and T9 terraces as a sort of ice-contact features, laid down at the edge of a glacier which reached further forward than Kommissaerbreen does at the present day. S6 slopes in the same direction as the rest, but lies higher than S2. Both these terraces may be interpreted as ice-contact features laid down at different times alongside a sinking glacier surface. See below 4.33.

4.33 Discussion

The following are some conceivable alternative interpretations of the formation of the terraces. They may be ice-contact features of some kind, either (1) terraces following lateral moraines formed in a fjord-glacier

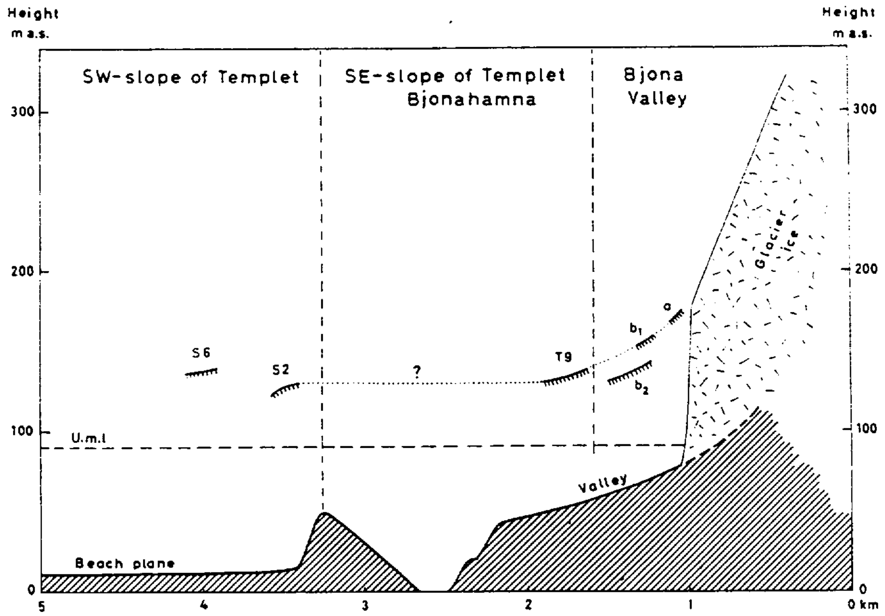

Fig. 16. Distance diagram of high terraces in the talus slopes near Bjonahamna. The diagram starts to the right with a vertical section through the Kommissaerbreen Glacier. The situation of the terraces at a, b_1, and T9 suggest that they are old ice-contact features. U.m.l. = the upper marine limit. Vertical scale = 10 × horizontal scale.

phase during the great ice retreat (this, approximately, is the view of Högbom and Feyling-Hanssen cited above) or (2) terraces following flat alluvial fans or other glacifluvial accumulations formed at the same time as the foregoing (somewhat similar to "kame terraces" according to Flint (1957, p. 149). (3) Bedrock shelves covered with loose material (moraine or glacifluvium, according to Alternatives (1) and (2)). (4) Large slides of talus masses with flat and sharp upper limit.

Alternative 1 is chiefly supported by a comparison with the recent glaciers in the area. They have large lateral moraines which in certain places form isolated moraine terraces on the valley sides, for example, on the front of Kommissaerbreen (Chapter 3.222). Terraces of "solitary" lateral moraines have also been described from many other glaciation areas.

A difficulty with the explanation according to Alternative 1 lies in explaining the large quantities of material which, judging by all appearances, are contained in the terraces. The recent lateral moraines contain as a rule insignificant quantities of moraine, since they were laid down from the beginning as ice ridges with a relatively thin coating of moraine.

How can the terraces at Bjonahamna be so large? Do they contain a rock core or an ice core? This question is touched upon slightly in the discussion of Alternatives 2 and 3 below.

Alternative 2 does not encounter the above-mentioned difficulty in explaining the large quantities of material. The material in the terraces is partly rounded and may very well be partly glacifluvium transported a short distance. The erosion gully on the S6 terrace is a fact in support of this alternative.

Alternative 3. A core of solid rock in the form of a shelf several metres below the terrace level has been exposed by the undermining of the terrace slope by the glacier stream in the inner part of b_2 (Plate VI (a)). For the rest, no traces of solid rock were observed on the terraces. It is not out of the question that there may be found a core of old glacier ice still within certain terrace accumulations (cf. Rapp, 1957, p. 197). The subsidence hole in the S6 terrace may indicate an ice core but may also have been formed in another way, for example, through chemical weathering in rock or loose material.

Alternative 4. In the literature there is, so far as the author knows, no case described in which a slide or any form of landslide has given rise to terraces in talus similar to the ones discussed here. On the other hand, there are many large talus slides described which have formed slide tongues with a lengthy concave lateral profile, without a vestige of terrace formations. The usual small talus slides do not form terrace formations either. The author therefore considers it out of the question that the above-mentioned terraces at Bjonahamna could be explained as recent landslips or slides. Against such a hypothesis, besides the general objections quoted above, the following may also be adduced. The slide hypothesis would not seem to be able to explain (1) the appearance of the terraces at certain relative limited levels, (2) their crests sometimes sloping inwards to the valley side, (3) their level decreasing in the direction of the fjord mouth, and (4) terrace b_2, which lies on a shelf of solid rock.

Conclusion. The above-described terraces on the talus slopes at Bjonahamna are very old terrace levels. In all probability the terraces are ice-contact features from late glacial times in the form of remains after lateral moraines (Alternative 1 above) with or without glacifluvially accumulated material (Alternative 1 + Alternative 2). They may in certain cases conceivably contain a core of solid rock or possibly old glacier ice (Alternative 1 + Alternative 2 + Alternative 3).

CHAPTER 5

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Material Turnover in Talus Cones at Bjonahamna, 1882-1954

This chapter is intended to give as detailed and clear a picture as possible of the material turnover within the area studied at Bjonahamna. Two of the main problems of this thesis are treated here in more detail, namely, (1) *what type of transport processes are at work on the walls and talus slopes of the area,* and (2) *how rapidly is the development taking place on these slopes at the present time (1882-1954)?*

The exposition aims at giving to the greatest possible extent quantitative measurements of the material turnover. The numerical values for the rate of disintegration etc. which the author puts forward at the end of the chapter should be regarded as a first step on the way from generally held, relative opinions of the type of "rapid" and "slow" disintegration respectively to a more exact, quantitatively formulated idea.

The chapter is divided up into three large sections. The two first are descriptions of what was observed in the field in 1954 (Chapter 5.1) and what has been observed on analysis of the picture material between 1882 and 1954 (Chapter 5.2). In the third section (Chapter 5.3) is given a summary and discussion of the whole observational material.

5.1 FIELD OBSERVATIONS, 1954

5.11 Supply of debris

The supply falls given in Table 7 are all that were directly observed by the four participants in the expedition during the period 10/7 to 2/8. If one considers that on all these days we lived close up to or on the talus slopes themselves, the quantity of the supply observed in this way must be characterized as small.

One gets this impression also on an inventory of the fresh debris found on melting snowfields. Three such snow patches, about 30-50 m in length, remained on the slope at Bjonahamna when we got there (see Chapter 4.24). On them on 11/7 lay altogether about 5 cobbles one decimeter in size and about ten smaller pebbles. Along a stretch, a good

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Table 7.

Collation of directly observed supply falls in the area of investigation during the period July 7 to August 2, 1954. All except Nos. 2 and 5 are from the talus slopes at Bjonahamna.

Type	Date	Time	Place	Notes
1. Boulder fall	14/7	18.30	A	32 boulders 2-5 dm in size fell in a swarm down the spirifer cliff from a rock-fall chute with a runnel down onto the alluvial cone. The foremost reached out on the cone to about 80 m above sea-level. Material: sandstone. The runnel down the cliff afterwards had a high content of mud.
2. Boulder fall	14/7	21.00	Western wall of Templet (S12)	4-5 boulders 2-5 dm in size fell down the spirifer cliff onto overgrown talus.
3. Mudflow	27/7	10.00	T5	About 1 ? m³ of pebbles, gravel and sand was carried down the spirifer cliff by the western runnel in funnel 5 and deposited on the talus crest. The runnel afterwards very dirty for some minutes.
4. Cobble fall	12/7		T5	Fall of isolated cobbles down the spirifer cliff on 4 occasions.
5. Cobble fall	13/7		Bjonadalen	Some cobbles fell down a water-carrying chute in the spirifer cliff.
6. Cobble fall	14/7	16.00	T6	Some cobbles fell down the spirifer cliff, and were dispersed down to the funnel gorge.
7. Cobble fall	28/7		S1	Several falls of isolated small stones.
8. Cobble fall	2/8		T5, T6	Several falls of isolated small stones.

kilometre in length, of snow remaining at the foot of the talus slope in the western, outer part of Bjonadalen, newly fallen cobbles (about 10 1-2 dm in size) were found only in one place. (See Chapter 3.23.)

A mat of sacking about 1 m² in size was laid out on top of a projecting boulder on the talus surface about 10 m below and straight in front of the largest supply chute in the T6 funnel. No debris was collected on this sacking during the time it lay out (15/7-1/8).

Two of the cobble falls observed were primary falls[1] from the c-cliff. In all the other falls it was not possible to decide whether they were primary or secondary falls.

It is noteworthy that both the boulder falls occurred on the same evening. On this occasion the weather was overcast and the temperature about + 4° C. A light, drizzling rain had fallen for some hours before the falls, but probably had no significance for their release. Several of the cobble falls occurred in calm, sunny weather.

As regards the course of the falls, the movements of the debris, its dispersal and deposition, see Table 7 above and also Chapter 5.312.

Summary: The supply of debris which was observed on the slopes

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[1] Primary fall = rock-fall of newly detached stones or rocks. Secondary fall = rock-fall of loose debris from shelves etc. in the slope (Matznetter, 1956).

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at Bjonahamna during the summer of 1954 (direct observations, inventory of debris on snow and on mats of sacking) was largely insignificant and amounted to an estimated 2-3 m³ altogether for the quite 1.5-kilometre-long wall.

5.12 Shifting and removal

According to a division previously published by the author (Rapp, 1957, p. 179) the following transport processes may be involved in shifting and removal of talus material: (1) individual particle movements (for an example here, see Chapter 5.121), (2) small talus slides (see Chapter 5.121, (3) large talus slides (not observed in the area), (4) talus creep (probably occurs but was not measured in the area), (5) avalanche transport (see Chapter 5.122), (6) Alpine mudflows (German "Muren") (see Table 6 and Chapter 4. 252 — traces of the process are common and the process itself has been described by Högbom, 1914, p. 288), (7) water transport (see Chapter 5.123), (8) solifluction (not measured in the area), (9) wind transport (see Chapter 5.124), (10) removal of material by glaciers (see Chapter 3), and (11) removal of material through abrasion (see Chapter 5.126).

5.121 Small talus slides

In unstable talus material, for example, in the talus streaks immediately below the spirifer cliff or on the upper part of cone S1, T1 etc., there were released on several occasions slides of ½-1 m in width and about 1-2 dm in depth. The slide tongues slid down several metres in slow motion, in which larger stones "floated" on top of the smaller, which revolved like marbles in the slide mass. The larger stones, which slid on top, were often directed with the long axis in the direction of movement ("longitudinal orientation". See Plate IX (a)). When the slide stopped, the longitudinal orientation of the stones lying on top was often abolished. Some few of them began to roll, freed themselves from the mass and rolled down to the base of the cone (S1), where one or two got to the vegetation-covered, more level slope below the cone. The last-mentioned form an example of shifting by *individual particle movement.*

At the slide were formed tongues of the same appearance as those which cover the greater part of, for example, the mantle surface of S1 and T1 right down to the base (see Chapter 4.251). These slides are in principle of the same type as the small tongue-like slides often occurring in gravel pits and in mounds of tipped ore, etc. As soon as a smaller slide has stopped, it is possible to distinguish a slightly bowl-shaped, oval erosion area in the proximal part of the slide path and a distal, tongue-shaped accumulation part, slightly convex both in cross-section and in lateral section. The slide mass itself is accumulated in the lower part of the slide course.

5.122 *Transport by avalanches*

Snow avalanches were not observed at Bjonahamna, where snowmelting was almost complete. On 16/7 Å. Holm and T. Roos on a visit to Gipsdalen witnessed many smaller avalanches, which were released from snowdrifts near the edge of the plateau on the north-facing wall of Templet. On account of the shady position the snow-melting here was considerably later than at Bjonahamna. The avalanches went down through the funnel gorges and out onto the talus cones below. On a visit to the spot on 31/7 the author observed a thin layer of avalanche-transported stones scattered about on the snow in the distal part of the cones.

In this place the funnels are particularly wide and semicircular-formed and the accompanying talus cones are concave in profile and eroded by avalanches in broad, even bands. The avalanches have probably contributed to the formation of the wide, open funnels in the mountain wall, just as they have formed the cones below. The situation is favourable to the accumulation of large quantities of snow sheltered from the driving wind over the summit plateau of Templet.

At the far end of Bjonadalen two relatively large dirty avalanches had been released from snowdrifts in the funnels under the plateau edge of Sindballefjell. They had gone out onto Kommissaerbreen and taken with them, inter alia, several boulders. The observations show that snow avalanches with a morphological effect occur at certain localities even in these plateau rock-slopes, which are poor in precipitation, steep and heavily dissected and otherwise to a large extent cannot be expected to be favourable to the occurrence of avalanches. (The detail relief in the walls themselves is so uneven that it must to some extent bind the snow.)

Many cones in Gipsdalen and in the transverse valleys north of Tempelfjorden are slightly marked by avalanche erosion; many are markedly transformed into avalanche boulder tongues (see, for instance, McCabe, 1939, Fig. 1, bright tongue to the left on the photograph). On the whole, however, the shifting on account of avalanches on the talus slopes in the area is judged to be of less significance than slides and mudflows.

5.123 *Transport by water*

Removal of material from the talus cones by running water (surface wash, streams) may occur through bed load, suspension or solution. Small streams came from the snowdrifts on the wall, ran underground through the talus cones and came to the surface again in several offshoots just in the base break (Plate IX (b)). Only the cones T5 and T6 had such permanent drainage during the month of July.

Bed load was not observed in these streams and did not occur earlier either to any appreciable extent, since no accumulations whatever from such transport were found at the talus base. On the other hand, a "pulsating" bed load transport was observed in the larger stream which ran over the alluvial cone A.

Suspension transport occurred on a couple of occasions in clear weather and strong insolation (on 19/7 and 2/8). The water from T5 and T6 was then very slightly muddied. The water from cone T5 was on one occasion (on 27/7) muddied for several minutes after a mudflow on the crest of the cone.

Both bed load and suspension transport is adjudged to be practically insignificant. Neither of them was able to form accumulations in front of the talus base. Transport of material in solution would seem, on the other hand, to be of a certain quantitative significance for material turnover on the talus cones and is therefore discussed somewhat in more detail here.

5.1231 The salt content of the stream water

Water samples were taken in a runnel at the base of cone T5 on 2/8/54. The total quantity of salt dissolved in the water was determined by evaporation. It amounted in round figures to 0.30 g/litre. In this some material in suspension was also included.

In addition the electrical conductivity and some of the kinds of ions included in it were analyzed.[3] The electrical conductivity was 318-348 $\chi_{20} \times 10^{-6}$. The proportion of sodium was 2.6-2.9 mg/litre, of calcium 51-59 mg/litre and of SO_4 109-118 mg/litre.

The proportion of salts in the water was accordingly large, mainly of $CaSO_4$. Gypsum is included in the bedrock, partly in several thin layers in the c-cliff and also probably in thick layers in the bedrock substrata of the talus cones (see Chapter 2.3). It is probably chiefly from this and from loose boulders in the interior of the cone that the calcium and SO_4 in the stream water come. The solution of limestone from the free mountain walls and rock-fall chutes would seem to be of small importance. This may depend partly on the rapid passage of the water and the low reaction rate in the cold water[1] (temperature from about 0.2° C to 0.5° C), and partly on the fact that the limestone to a large extent is silicious (cherts) and therefore relatively resistant to chemical weathering[2]. The traces of chemical weathering in the free walls are relatively insignificant (see Chapter 4.11).

5.1232 Probable total yearly removal of material in solution

A rough calculation of the order of magnitude of the quantity of material which is carried away every year from a cone by stream water in chemical solution will be made.

The average quantity of salts in the stream water is assumed to be

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[1] Cf. Lehmann (1956, p. 5) and Blanck (1928, p. 698).

[2] Cf. Bøgli (1956, p. 14).

[3] By Centrala Analyslaboratoriet, Uppsala.

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0.20 g/litre or 0.2 kg/m^3. This assumed value is probably *too high as an average value*, for it is based on measurements in August at a time of small outflow and high air temperature.

The proportion of salts is probably considerably lower during the spring flood than in August, partly on account of the larger quantities of water, partly on account of the lower temperature then.[1] The greater part of the precipitation — the winter's collected store of snow — is discharged at the spring flood, from which it appears that the probably lower proportion of salt in the spring-flood water plays a large part in the calculation. The value of *0.20 g/litre is therefore regarded as a quantitatively high maximum value* for the average salt content of the water. The total annual outflow on cone T5 is estimated at 30,000 m^3.

The estimate is based upon the following values:

Annual precipitation 300 mm (the value applies to Green Harbour, which probably has a greater annual precipitation than Templet). The area of cone T5 and its collection area (horizontal surface): 100,000 m^2. The total quantity of salt removed per year,

$$100{,}000 \times 0.3 \times 0.2 = 6000 \text{ kg.}$$

After reduction for evaporation and atmospheric salt this quantity corresponds to about 2 m^3 of solid rock.

The above calculation, which is based on values which are probably too high, both in the matter of proportion of salts and quantity of water, accordingly gives a maximum value for the order of magnitude of the yearly removal of material in chemical solution.

The statement of a yearly removal of 2 m^3 in chemical solution should be supplemented by the following points of view, in order to underline further that the calculated value is probably a quantitatively very high maximum value.

(a) The salt is made up for the most part of gypsum, probably from loose boulders in the interior of the cone and from its bedrock strata. The chemical solution has not produced any subsidience holes or such collapse forms on the surface of the cone and has not caused any sinking of the cone ridge either. Several of the cones display on the contrary definite signs of stronger arching in late times.[2]

It is, for example, extremely improbable that in 72 years 150 m^3 of material could be liberated and removed from the 1-2-metre-thick layer of talus material which lies on top of the frozen-ground surface on cone T7, without some subsidence forms or a considerable shifting being visible on the surface of the cone.

Neither on the talus material nor on the free walls and rock-fall chutes are the traces of chemical weathering manifest.

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[1] Cf. Eriksson, 1929, p. 79.

[2] For example, on cone T4, where slide tongues in later times have curved off from the cone ridge out over the sides of the cone.

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(b) The runnels run down the cones for a distance of at least 150 m out across the level shore area, overgrown with grass and moss, without leaving noticeable salt crusts.

5.124 Transport by wind

Wind transport of talus material could possibly be expected to have a certain importance. The author considers that such is not the case at Bjonahamna for the following reasons: (1) the snowfields which remained on and alongside the talus slopes were not dirtied by wind-borne material particles, and (2) the wind erosion has not been able to obliterate the several-thousand-year-old strand lines on the shore area in front of the talus slopes, nor has it effaced the old bump holes following a fall, which are found there. The material on the shore area is rather of a smaller size than on the talus surface, for which reason the possibility of wind erosion on talus is still less than on the shore.

5.125 Removal of material by glaciers

The slope at Bjonahamna has earlier certainly been subject to removal of material by a valley glacier, which carried away practically all debris except that which was lying in pockets in the mountain wall (see Chapter 3.1).

5.126 Removal of material by abrasion

This does not occur at the present day at Bjonahamna other than possibly on alluvial cone A. The removal by the waves of material from the cones during "the abrasion phase" was probably not significant, partly because the majority of the cones had a shallow and sheltered situation (with the exception of T1), partly because the higher lying cones came to be raised up relatively soon above the reach of the waves.[1] Furthermore the accumulation of the coarsest material at the talus base probably counteracted the removal by abrasion, as is the case at the talus slope of Tejstfjellet at the present day.

Tejstfjellet lies on the south side of Tempelfjorden. The simple talus slope there is at its foot severely exposed to the waves, which have formed an abrasion slope. This is sharply distinguished from the undisturbed talus slope above, partly by being steeper, partly by being almost free from vegetation. The abrasion scar is not conspicuously large. Its height varies between 10 and 15 m, its inclination is about 39° and the limit against the talus slope higher up (inclination about 35°) is sharply demarcated.

At the lower edge of the abrasion scar larger stones and boulders (inter alia, boulders of spirifer limestone of a maximum size of 6 m) had formed a mantle which constituted a protection against the attack of the waves.

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[1] Cf. p. 26, Table 1 B.

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5.2 COMPARATIVE EXAMINATION OF PHOTOGRAPHS TAKEN BETWEEN 1882 AND 1954

5.21 Picture material used and methods

A clear picture of the recent development was obtained by detailed examination of a series of older and newer photographs of the talus slopes at Bjonahamna.

The method, which may be called comparative photo examination, has often been used previously for other purposes (for example, study of the retreat of glaciers etc.). Bryan and La Rue (1927, p. 251) have also made use of a picture comparison in a short study of slopes. They compared three photographs from 1875, 1909 and 1925 for the estimation of the weathering on a mountain wall in Utah. Bryan's views on the method are worth quoting since they are to a high degree applicable not only to Utah but also to Spitsbergen. "Intricate but boldly carved canyons, cliff and precipice ornamented with pillars and pinnacles delicately poised . . . all these testify to erosive processes obviously now in action and apparently of almost catastrophic violence . . . It is easy to lose perspective and to conceive of the rate of erosion as much more rapid than it is in fact . . . The best estimates of erosion are indirect: . . . measuring the material carried by streams . . . Any opportunity of making a *direct* estimate of comparative rates of erosion, quantitative or qualitative, is therefore most welcome." (Op. cit., p. 251.)

The comparative photo examination is a method which to a great extent has a future before it. It would seem to give the best results on slopes wholly or partly free from vegetation. For the rest, it goes without saying that one ought to aim at (a) primary pictures as old and as clear as possible, (b) re-photographing from the same point and at the same time of year and day (if possible with the same camera as was used at the primary photographing), and (c) taking of stereoscopic pictures for stereoscopic examination and possible measurement of changes on the slope.

Of the older photographs the author during the work on Spitsbergen in 1954 had access to only some of Halldin's[1]. The rest were traced later[2]. Most of the pictures from 1954 have therefore not been photographed from the same points as the corresponding older photographs.

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[1] Preserved at Geografiska institutionen, Uppsala.

[2] Certain of De Geer's and Halldin's photographs, which are preserved by Mrs. De Geer, of Stockholm, and Geografiska institutet, Stockholm, respectively, and also Koller's and Luncke's photographs, which are preserved at the Norwegian Polar Institute, Oslo. The author wishes to thank Mrs. De Geer and the institutions mentioned above for kind permission to borrow and use the picture material.

Table 8.

List of the photographs which have been used for comparative picture examination of the slopes at Bjonahamna. The photographs reproduced in the photographic appendix are given in parentheses.

Year	Photographer	Size of negative (cm)	No. of pictures	Subject
1882	G. de Geer	13 × 21	2	Cones T1-T7, T8-T11. Outer part of Bjonadalen (Plates XI, XIV(*a*), XV(*a*) and XVIII(*a*), the last three enlargements of parts).
1896	G. de Geer	13 × 18	3	Cones T1-T10 from Bjona Point. (Plates XII and XVI(*a*))
1908	O. Halldin	12½ × 18 ?[a]	3	Cones T1-T10 from Bjona Point.
			1	Cones T8-T9 from the Bjona Delta (Plate XVIII(*b*)).
1924	A. Koller	12½ × 18	6	Cones T1-T11, Bjonadalen, Sindballefjell (Plates XIII and XVI(*b*)).
1936	B. Luncke	15 × 18	1	Aerial photograph (Plate I).
1954	A. Rapp	6 × 6 (Camera: Rolleiflex)	A large number of photographs	(Plates XIV(*b*), XV(*b*), XVII(*a*) and XIX)

[a] Halldin's negative was not found by the author; on the other hand, copies were available.

Short accounts of the photography of 1882 are given in Nathorst (1884, pp. 37, 39) and Nathorst (1883, p. 130 f.). The photographs of Templet at Bjonahamna in 1882 are probably the first which were taken at the spot, since no scientist had visited it previously (op. cit., p. 130). A short account of the photography of 1896, which comprised about 700 photographs, is given by De Geer (1896, p. 259 f.).

The comparisons were carried out by detailed examination of enlargements of the photographs under a magnifying glass. In the process the pictures were enlarged up to about 10 times. The sharpness of detail was very often particularly good, even in the older pictures. The pictures which were photographed from the same point in the terrain were also examined under a mirror stereoscope.

In the series of photographs the talus cones especially and also parts of the c-cliff and the spirifer cliff appear clearly. The parts of the wall which lie higher up could not, on the other hand, be examined as thoroughly. There are good opportunities in the examination of the enlargements to discover *changes* on the talus slopes, primarily (a) *newly fallen boulders* (about 2 m size or larger — smaller boulders and stones are not usually seen) which have stopped above the base fringe[1], and (b) *new slides and mudflows,* in particular such as have covered vegetation or other details on the slope.

Clear proofs of stability on the talus slopes are furnished by (a) *boulders which remain in the same place* (which can to a certain extent be decided by comparison with or measurement from adjacent details on the pictures. Detailed measurement is awkward on account of different photographing points and different lenses in the cameras), (b) *patches of vegetation* which have not changed either shape nor position, (c) *slide tongues* or *mudflow courses* which have neither changed their shape nor been effaced, and (d) *bump holes* which have not been filled up again.

5.22 Picture comparisons

Time intervals between the photographs are denoted in the following way: 1882-1896, Period I; 1896-1908, Period II, 1908-1924, Period III; 1924-1936, Period IV; and 1936-1954, Period V:

5.221 Talus cone T1

Photographs: 1882 (Plates XI and XIV (a)), 1896 (Plate XII), 1908 (not reproduced), 1924 (Plate XIII), 1936 (enlargement of Plate I) and 1954 (Plate XIV (b)). The cone mantle is hidden as to about half its surface. Information as to position according to the system of coordinates in Plate XIV (b).

The cone is characterized by a large number of slide tongues (Chapter 4.21), which cover the mantle. It is steep (34°) and has a straight profile. Vegetation cushions are entirely lacking on the mantle surface. The boundary of the vegetation at the base is sharply demarcated.

Picture examination. — Three boulders have been added at *e6-7* during Period I. All these have turned up on the cone mantle and may consequently have been brought there by a shifting fall from having lain previously in the part of the funnel bottom hidden in the picture. Two larger boulders which have turned up in the funnel at *d9* (Period III) are, on the other hand, certainly supply falls, probably from the spirifer cliff. A slide tongue has forced its way out into the vegetation at the base during Period I and been further widened during Period II *(d3-4)*.

A slide about 5 m wide and some 10 m long and consisting of talus material with a covering of turf was released from the funnel close by the spirifer cliff *(fg9)*. The slide mass covers the little cone at *e7* like a dark

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[1] The base fringe in several pictures is entirely or partly obscured, but the large boulders which have fallen right down there in late times were distinguished in the field, since they have formed bump holes on the shore area. The field investigation thus compensated this deficiency in the picture examination.

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cap. The slide occurred in Period V. The slide scar at *fg9* is concealed on Plate XIV (b), but was observed in the field (Plate VIII (b)). The slide has covered over the surface in patches right down towards *e5*. Three slide tongues at *c4* have forced their way lower down (Periods I-V?).

For the rest the slide tongues which cover the talus mantle have not changed during the period 1882-1954, which testifies that *the surface of the cone mantle cannot have been covered by* scattered stone falls, *nor undergone noticeable shifting* over and above the 4-5 slides mentioned previously.

The stability of the cone is also illustrated by the fact that about ten larger boulders (about 2-5 m in size) in the funnel have not changed position between 1882 and 1954 *(d,e9-10)*. Two boulders at *b5* have also lain still during this period.

5.222 Talus cone T2

The examination comprises the same pictures as for T1. Information as to position according to Plate XIV (b). The mantle appears on the pictures more clearly than T1's, but the funnel is partly obscured on several pictures by shadows. The talus base is hidden on the pictures from 1882 and 1896. This cone, like T1, is characterized by a large number of slide tongues, which cover the mantle and together with the lack of vegetation patches give the observer a first impression that the cone is unstable and in a relatively rapid shifting state.

Picture examination. — No newly produced boulders appear on the pictures between 1882 and 1954. Of about ten slide tongues which cover the lower part of the mantle only two have come into existence after 1882. One of these reaches with its tip to *h,i1* (Period V), the other to *f1-2* (Period IV-V?). The former has covered over three patches of vegetation certainly visible in 1924 and 1936. For the rest, the slide tongues which cover the lower part of the talus mantle have not changed between 1882 and 1954. In the funnel at least four large boulders have certainly lain still since 1882.

5.223 Talus cone T3

The same pictures as for T1. Information as to position according to Plate XIV (b). The mantle appears clearly on the pictures, but the funnel is partly obscured by shadows. The base is hidden on the pictures from 1882 and 1896. The cone is not as densely overlaid by slide tongues as the two previous ones.

Picture examination. — A new boulder at *k6* (Period II) and one at *k5* (Period III ?), both on the boundary between cones T2 and T3.

A slightly bow-shaped trace of a fall in the shape of a series of bump holes comes from T2 and goes obliquely into T3 at *k6*. From there it can be followed down towards *lm1* (Period V ?). It was probably caused by a solitary large boulder.

A slide tongue at *np4-6,* trilobate in its distal part, seems to be fresh in 1954, but its period cannot be determined. A broad dark slide tongue over the middle of the cone ridge with its tip at *m4* appears in 1882 and 1896, but was effaced in 1908. The patches of vegetation at *n9-10* have possibly grown somewhat after 1924.

On the lower part of the mantle no changes are seen. About 25 irregular patches of vegetation form a thin border at the base *(j3-q3)* of the same appearance from 1924 to 1954, which gives a record of the stability of the cone.

5.224 Talus cone T4

Photographs: 1882 (Plates XI and XV (a)), 1896 (Plate XII), 1908 (not reproduced), 1924 (Plate XIII). 1936 (Plate I enlarged) and 1954 (Plate XV (b)). Information as to position according to co-ordinate system in Plate XV (b).

The talus base is hidden on the pictures from 1882 and 1896. The cone is somewhat eroded by avalanches, to judge from the obliterated ridge, overlaid by a broad streak (avalanche path), sharply and rectilinearly demarcated from the coarser material at the sides (seen best in Plate XV (a)). Moreover an avalanche debris tail appears immediately under the designation "T4" in Plate XV (a). (See also Chapter 4.253).

Picture examination. — A new boulder (the lower one at *e9*) seems to have turned up in Period IV or V.

Bump holes following a larger boulder are seen in 1954. They go in a slight curve from T5 into and over T4 to *j3*. They may possibly be connected with the large bump holes at *n1* on cone T5 (see below).

A slide about 5-10 m in width went over the vegetation border on the side of the cone at *i6-j5* (Period II). A second slide, at least 10 m wide, covered over the patches of vegetation at *d4-5* in Period III. These slides, which went down in the middle of the cone ridge and curved away obliquely out over the sides of the cone, indicate that the cone mantle is in slow growth and that the supply of material is accordingly greater than its removal, for example, through chemical solution. The latter is the only form of current removal which cannot certainly be said to be completely insignificant.

A mudflow left the left-hand part of the funnel *(e8-g6)* probably in Period IV.

Among the prominent unchanged details is noted a boulder at *j4* (same position 1882-1954) and also a large number of patches of vegetation at the sides and base of the cone (for example, *e3* and *g2*).

5.225 Talus cone T5

Photographs: 1882 (Plates XI and XV (a)), 1896 (Plate XII), 1908 (not reproduced), 1924 (Plate XVI (b)), 1936 (Plate I enlarged) and 1954 (Plates XVII (a), XV (b) and XVII (b)). Information as to position according to co-ordinate system in Plate XV (b). The cone is eroded by avalanches.

Picture examination. — A large boulder fall descended cone T5 in Period IV. Two large bump holes are still visible in 1954 somewhat above *n1* and *p0*. The bump holes continue in three crooked paths out over the shore area (Plates XVII (b) and XX). The fall is made up of disc-shaped boulders of spirifer limestone about 2.5 m in size and is probably a primary fall from the spirifer cliff above T5 (see further Chapter 4.22).

Two series of bump holes are seen in the lower right-hand portion of T5 in Plate XV (a). They form curved tracks from cone T6.

The depression between T4 and T5 has large surfaces covered with vegetation. The pattern is in detail the same between 1882 and 1954. It may be observed, inter alia, that not even the gaps in the carpet of vegetation have decreased.

5.226 Talus cone T6

Photographs: 1882 (Plate XI), 1896 (Plate XVI (a)), 1908 (partly visible in picture not reproduced), 1924 (Plate XVI (b)), 1936 (Plate I), and 1954 (Plate XVII (a)). For description of morphology, see Chapter 4.252 and Table 4.

Picture examination. — Two large mudflows have gone from the left-hand part of the funnel down the entire cone probably a short time before 1882 (Plate XI). They are terminated distally each by its tongue-like accumulation, the left-hand one on Plate XI reaching down to the talus base whilst the right-hand has stopped somewhat above. They both appear in 1954 (Plate XVII (a)), but their accompanying erosion gullies higher up on the cone have been effaced. Cone T6 is distally covered by similar large mudflow (?) tongues of older date, some of which go out onto level ground at the base (see also Map No. I). The central part of the cone ridge has been stable and unaffected by larger slides since long before 1882, as appears from the "old" cross-striped pattern of lichens. This pattern also testifies to the fact that no covering layer of scattered debris has been added for a very long time.

5.227 Talus cone T7

Photographs: 1896 (Plate XVI (a), 1924 (Plate XVI (b)) and 1954 (Plate XVII (a)).

This cone has a small collection area, inconsiderable spirifer funnel and inconsiderable arching. No changes can be discovered on the mantle surface between 1896 and 1954. The lower part of the mantle has a cross-striped lichen pattern, which indicates stability and practically no covering or shifting in late times.

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5.228 Talus cone T8

Photographs: 1882 (Plate XVIII (a), the cone partly visible), 1908 (Plate XVIII (b)), 1936 (Plate I) and 1954 (Plate XIX). Information as to position according to the co-ordinates in Plate XIX.

Picture examination. — The highest of the rock pillars above the T8 funnel at *f 13½* has lost the top boulder during the period 1908-1954. This is the only change which has been traced on the walls at Bjonahamna on all the pictures examined.

Two small slide-tongues, one on each side of the cone top *(ed10-9, ef10-9),* came into existence between 1936 and 1954. For the rest, no changes are visible. About 40 patches of vegetation on the sides of the cone and its lower part are unchanged in position, shape and size between 1908 and 1954. The higher of these are also visible on the 1882 photograph and have the same shape even then. Note particularly, for example, the patch of vegetation which has the shape of a man's profile facing left *(e5-6)* and compare its shape between 1882 and 1954.

A boulder in the middle of the upper part of the cone ridge *(e9)* has the same position between 1908 and 1954.

5.229 Talus cone T9

Photographs: same as for T8. Note that the base of this cone lies at the terrace *h-m8*. The examination also comprises the terrace slope *h-m8-5.*

Picture examination. — A broad slide descended the terrace slope at *m7-6* (partly outside Plate XIX) between 1908 and 1924. It did not force its way down to the foot of the terrace slope and would seem therefore to have moved slowly.

No changes are visible in the wall and funnel and on the cone between 1882 and 1954 (a small slide tongue has possible gone down at *j10-i9* between 1908 and 1954).

5.230 The talus slopes on both sides of the mouth of Bjonadalen

Photographs: 1924, 1936 and 1954 (not reproduced).

Picture examination. — This has shown the following changes here. A relatively large mudflow went from the outermost rock-fall funnel of Templet towards Bjonadalen between 1936 and 1954. It was checked at the talus base. The erosion gully and the surrounding mudflow levées were very well marked in 1954. A smaller mudflow with two accumulation tongues at the front went from the first rock-fall funnel on Sindballefjell (T11) during the same period. It followed the left-hand edge of the talus cone and reached down to the talus base. Both these mudflows show that even the smaller funnels with small collection areas emit from time to time mudflows which shift material right down to the talus base.

Table 9.

Boulder falls (b), talus slides (s) and mudflows (m) traced on the talus slopes at Bjonahamna on comparison of pictures taken between 1882 and 1954. The changes which were discovered in the picture examination are summarized in the table below (see also Plate XX).

Cone	Plate No.	1882 to 1896	1896 to 1908	1908 to 1924	1924 to 1936	1936 to 1954	Indeterminate time
T1	XIV(*b*)	s(d3-4) b(e6-7)		b(d9)		s(e7) b(b3) b(c3)	s(c4)
T2	XIV(*b*)					s(hi1) s(f1-2)?	
T3	XIV(*b*)		b(k6)	b(k5)?			s(np4-6) b(m1)
T4	XV(*b*)		s(i6-j5)	s(d4-5)	m(e8-g6)? b(e9) ------ b(j3)?	 -----?	
T5	XV(*b*)				b(n1-p0)		
T6	XI						b(before 1882) m(before 1882)
T7							
T8	XIX					s(ed10-9) s(ef10-9)	
T9 Terrace slope	XIX			s(j10-i9) s(m7-6)	----------	-----?	
Beyond T10						m	
T11						m	
Total		1s 1b	1s 1b	2s 1s? 1b 1b?	1m? 2b 1b?	4s 1s? 2b 1b?	2s 1b (1b) (1m)

5.3 SUMMARY AND DISCUSSION OF THE MATERIAL TURNOVER BETWEEN 1882 AND 1954

In Table 9 no distinction has been made in the notation between larger and smaller slides and mudflows and boulder falls respectively. Moreover in some cases two mass-movements observed on the same cone within the same period have been denoted as one movement. The table is

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consequently equivalent to a rough summary of the observations made in the picture examination.

In all, according to the table, 12 talus slides, 3 mudflows and 10 boulder falls occurred and have been traced on the pictures between 1882 and 1954. Even if the picture analysis has not revealed all the movements of the types mentioned, which occurred during the period in question, from the quantitative point of view, however, the most important have probably been included.

5.31 Wall retreat and supply falls

The only change which has been traced on the walls in the picture examination is that a rock pillar above the T8 funnel has lost its top (Chapter 5.228).

The talus slopes appear more clearly on the pictures than the walls. Supply falls and also to a certain extent shifting through dry slides gives in an indirect way an idea of the wall retreat. To express it more simply, *the wall retreat is reflected* most clearly *on the talus slopes* in the first place through *supply falls* and in the second through dry *shifting slides*. It ought, however, to be pointed out that many supply falls consist of loose material which has lain for a considerable time in chutes and on shelves above the spirifer cliff (so-called secondary falls). Such falls may be said to be delayed evidence of an earlier wall retreat.

5.311 Larger boulder falls (comprises boulders larger than 2 m)

The larger boulders which have fallen down the talus slope are found chiefly in two positions, namely, partly up under the spirifer cliff on the talus crest and partly down on the base fringe. This would seem to depend on the following facts. Many of the large boulders have discharged from the spirifer cliff and have thereby had so short a distance to fall that they have remained lying on the talus crest on impact. The boulders which, on impact, begin rolling (longer distance to fall, rotation in the air, boulders not oblong, etc.) soon get on account of their size such a great kinetic energy that they are not stopped before they are down on the base fringe.

A number of the large boulder falls probably come from rock pillars crashing down higher up on the wall (for example, the fall from the pillar above T8, Chapter 5.228).

The bump holes on the cones give a good picture of how the boulders move and how they are scattered. The large boulders, which fall down the cones towards the base fringe, rotate rapidly and move by bouncing in long leaps. They roll upright like wheels and often go obliquely down the slope in a bow-shaped path from one cone to another (see Plate XVII (b)).

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Larger boulder falls occur relatively seldom, probably one or two cases every decade. At least 8 boulders about 2 m in size or larger have come into existence on the talus crest between 1882 and 1954 according to the picture comparisons. The last great boulder fall which reached the base fringe occurred between 1924 and 1936.

The great majority of conspicuous *boulders on the talus crest* (at least 25) *have lain still between 1882 and 1954 without being moved further or broken in pieces.* This indicates stability and gives moreover a further evidence that the frequency of boulder falls from the spirifer cliff is extremely low. Otherwise the number of boulders on the talus crest would be considerably greater, since it has appeared that the boulders which stop on the talus crest remain lying there for long periods.

On a rough estimate the supply through larger boulder falls during the period 1882-1954 has probably amounted to about 100-200 m^3 or about 2-3 m^3 per year on the mountain wall, which is about 1.5 km long.

5.312 Smaller boulder falls and pebble falls

Smaller boulder falls probably occur annually (one was observed by the author in 1954) and *pebble falls* are probably numerous (ten observed in 1954). These two types of fall do not appear on the photographs, but their frequency has not been so high that they have caused noticeable retreat of the wall in any place during the 72 years between 1882 and 1954.

The pebble falls which were observed in 1954 were made up partly of isolated stones from the spirifer cliff and partly of swarms or streams of stone slides from the rock-fall chutes. These falls usually reached only a short distance down in the spirifer funnel. In two cases the leading stones got down through the funnel gorge onto the cone mantle (see Table 7, Chapter 5.11).

An observed fall of 32 boulders descended alluvial cone A. The leading boulders penetrated down to a point with an inclination of about 20°.

The predominant supply of material to the cones probably takes place through cobble and pebble falls, as appears, inter alia, from the fact that both cone mantles and débris in the spirifer funnels mainly consist of cobbles and pebbles and only to a very inconsiderable extent of boulders over 3 dm in size.

The magnitude of the volume of material which is supplied yearly through smaller boulder falls and cobble falls is discussed in more detail in the following section.

5.32 Shifting

The forms of shifting which are seen best on the pictures are slides and mudflows, in particular those which have covered over vegetation or other details on the slope. *The mudflows* are recognized by the fact that they form long, narrow, often winding courses, consisting of an erosion furrow in the middle surrounded by a levée on each side. The transverse profile of the furrow is U-shaped. The front usually forms a tongue-shaped accumulation. The mudflow tongues are often divided up into several ramifications.

The slide tongues are often proportionately broader and straighter than the mudflow courses and also slightly convex in cross-section. All transition stages between the two forms may conceivably occur.

Shifting in the form of the rolling or sliding of individual stones on the talus surface does not, of course, appear on the pictures, nor does movement through creep of different kinds. However, the pictures give in an indirect way evidence of the small importance of these more diffuse and "imperceptible" shifting processes, for example, boulders which remain in the same place for a long time, patches of vegetation which have not changed shape or position, slide courses etc. which have not changed shape or been effaced.

Avalanches have a clear shifting effect on cones with wide collection funnels (e. g. the wall of Templet towards Gipsdalen) and wide funnel gorges (T4, T5). Avalanche shifting displays itself by the shape of the cone (see Chapter 5.122), but the picture analysis cannot give information of how many dirty avalanches have possibly occurred during the period 1882-1954.

The pictorial comparisons confirm the idea already given by a study of the surface forms of the cones, namely, that *smaller talus slides* are responsible for the essential shifting and formation in this type of cone (relatively uniform debris of stones and small boulders, short distance to fall). The debris from walls and rock-fall chutes is largely accumulated first on the top cones at the bottom of the spirifer funnels. From there the debris is carried further by momentary dry slides (e. g. on cones T1 and T2) etc. or sometimes by a mudflow (e. g. T6 and T11) or by avalanches (T5 and T6). The slides are very often checked above the talus base, whilst the mudflows often reach insignificantly out over more level ground.

Twelve dry slides of up to 10 m in width and three mudflows have been traced on the pictures as newly emerged between 1882 and 1954. Moreover a couple of mudflows on cone T6 would seem to have occurred shortly before 1882.

For the rest, the detailed and, on the majority of the cones, clearly manifest pattern of slide tongues, herb cushions, lichen patches, etc. has not changed since 1882. This circumstance constitutes a certain proof that there has occurred no covering deposit of debris nor any considerable "invisible" shiftings over and above the cases just mentioned as observed on the pictures (the avalanche paths on T4 and T5 form an exception to this; "diffuse" supply and shifting on them is not visible on the pictures).

The slides observed indicate that the cones have been in process of slow growth during the period 1882-1954. Supply and shifting have been greater than removal of material.

The slides give an opportunity to estimate the quantity of material which has been supplied to the cones by pebble falls and small boulder falls, for, as has been pointed out above, the slides form in many cones the most important way in which the material is shifted from the top cones in the spirifer funnels down onto the cone mantle. It is clear from Table 9 that on cones T1-T4 eight slides were observed between 1882 and 1954. These cones are the ones which could be best checked by the pictures. If one assumes that on an average at most 5 slides per cone have occurred during the 72-year period, a *high average value* has probably then been obtained. If it is further assumed that each slide tongue has contained on an average at most 75 m^3 of material (width 5 m, length 30 m, depth 0.5 m), one obtains a shifting by slides of about 375 m^3 per cone in 72 years or about 5 m^3 per year on the most active cones. To judge by the slides, *the yearly supply of debris through pebble falls and small boulder falls consequently amounts to at most 5 m^3 per year as an average figure for the most active cones during the period 1882-1954.*

In round figures and with a subtraction for pore volume (33 %; see Chapter 3.13 and 6.22), one may probably set the yearly supply of compact material at about 1-5 m^3 per cone. Cf. chapter 6.24.

5.33 Removal

Removal of material in solid form (by water, solifluction, talus creep, wind) has practically not occurred at all since abrasion of the foot of the cones ceased.

The only form of removal which may be of appreciable extent at the present day is that by chemical solution. This removal of material can as to its order of magnitude be indicated only in rough outline. With the guidance of an analysis of the salt content in a few water samples taken at the beginning of August, 1954, and also by estimating the total annual outflow, the removal has been estimated at *at most* about 2 m^3 per year on the cones most affected by streams (Chapter 5.1232). For the other dry cones chemical solution probably falls considerable below this value.

To judge by many signs, the removal of material from the cones between 1882 and 1954 has clearly been less than the supply, which has been calculated as at most about 5 m^3 per year on the largest cones (Chapter 5.32).

5.34 The question of a continuous or non-continuous growth of the talus cones

The post-glacial growth of the talus cones can be thought of in different ways, so the following three alternatives may be discussed:

(a) *Momentary* growth. Sudden formation of a catastrophic kind through one or a few large falls, with no or slow material supply in between. Causes: ice melting, delayed liberation of "ordinary" falls (Ahlmann, 1919, p. 125), earthquake, climatic change? Morawetz (1933, p. 28) considers, for example, that many talus cones are formed at a late period, as a consequence of the latest climatic changes or even through isolated "weather catastrophes"! To this it is objected that large rock-slides do not form talus but slide-tongues (Heim, 1933, p. 106).

(b) *Fluctuating* growth. Variations of longer duration than in the previous case, for example, caused by climatic variations. Cold climate, heavy supply of debris; milder climate, slight supply of debris (Fromme, 1955, pp. 101, 127).

(c) *Continuous* growth. Relatively even supply of material, possibly with smaller, but not severe, fluctuations, owing their occurrence to climatic changes, etc.

All these alternatives could probably occur in combination. But for the talus cones at Bjonahamna probably only alternatives (b) and (c) could be possible as the quantitatively most significant. The very regular and rounded forms of the rock-fall funnels and cones testify that they were not in the main formed by large catastrophic falls.

A strongly fluctuating growth, owing its existence to climatic variations, seems to the author to be doubtful, inter alia, by comparison between the localities of Bjonahamna and Langtunafjell, which are very different as regards local climate. In spite of the fact that the Langtuna nunatak is in a "late glacial" stage of development, the breaking down there seems not to be much more rapid than at Bjonahamna. Another argument against a *strongly* fluctuating, climate-dependent material turnover is given by the examination of the Bjonahamna slope on pictures from 1882 to 1954. The series of pictures shows no conspicuously more rapid supply of material during the "cold period" (1882-1920), compared with the milder period (1920-1954); possibly it shows a *slight* tendency to the opposite state of affairs.

The author accordingly has most belief in a development according to alternative (c) on the talus slope at Bjonahamna. This is not to say that the frost-changing climate in itself has little effect on the breaking down. The cause of the small fluctuations in the supply of debris etc. at Bjonahamna would seem rather to be that the post-glacial climatic variations on Spitsbergen, as elsewhere, have, in spite of everything, been too small for them to have been able to cause great reversals in the talus regime.

CHAPTER 6

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The Age and Development of the Rock-fall Funnels in the Light of Volume measurements

The attempts at reconstruction of the development of the talus formations which have been made up till now in this thesis have been based on a study of the morphology and partly of their recent material turnover at Bjonahamna. Moreover a certain idea as to the conditions of deglaciation could be obtained by comparative study of talus slopes alongside recent glaciers.

The studies of the recent material turnover by direct observations and also by picture examinations has clearly shown that since at least as far back as 1882 the development has been relatively slow on cones and walls. What then were the conditions earlier still?

The question will be treated in this chapter with the help of the following method. On Map No. I is measured the volume of a talus cone and that of the accompanying rock-fall funnel (the collection area). After that a calculation is made of how great a wall retreat the volume of the talus cone represents (see Chapter 6.21). In this fashion it is possible to get an idea of *the total post-glacial wall retreat* on the assumption that the talus formation has not been subjected to appreciable removal of material in post-glacial times[1].

6.1 PREVIOUSLY PRESENTED VIEWS ON THE AGE OF THE ROCK-FALL FUNNELS

The problem of the age and development of the wall relief has earlier been discussed by many authors. Some of the viewpoints one meets with in the literature are cited below.

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[1] Many of the authors who have described talus in an Arctic or Alpine environment have considered that the removal of material from the talus formations has been so considerable that a calculation of the post-glacial wall retreat in the way mentioned above would not be possible (for example, Malaurie, 1950, p. 14). The author shows in Chapter 6.22 an example to the contrary. Other such examples have been pointed out by Poser (1954, Abb. 7 and p. 140) in the Eastern Alps.

G. de Geer (1910, p. 21): "... it would perhaps be possible to prove that certain topographic features have been *preserved from the pre-glacial epoch*". As an example, De Geer refers to a map (Plate 9, op. cit.) of a ravine and its alluvial cone "showing a great discrepancy between the amount of postglacial accumulation and the total amount of erosion".

Högbom (1914, p. 283) criticizes De Geer's idea. The ravine[1] in question is not, according to Högbom, partly pre-glacial but *post-glacial*. The alluvial cone at its mouth is relatively small, principally on account of the removal of material through solifluction.

Wråk (1916, p. 297) considers (without arguing the matter) that the last glaciation on Spitsbergen was only a more extensive valley glaciation than that which we have there now. The mountain sides would have stuck up like nunataks above the ice and not been submerged by it. Therefore rock-fall chutes and funnels could have been *established interglacially and been widened both in glacial and post-glacial time.*

Büdel (1948, Abb. 5, pp. 36-37, and 1953, p. 262) adopts to a great extent Högbom's view of a rapid, post-glacial establishment and formation of the relief in the walls.

The authors mentioned above consider that the rock-fall funnels were formed by frost-bursting and nivation. An entirely different interpretation of the genesis of these formations is given by Philipp (1914, p. 25), who considers that the funnels may have been formed by glacial erosion. This hypothesis is criticized by the author in Chapter 4.11.

6.2 CALCULATION OF THE VOLUME OF ROCK-FALL FUNNELS AND TALUS CONES

6.21 Methods

The author has made some attempts to calculate the proportions between the volume of a talus cone[2] and that of its rock-fall funnel[3]. Both these volumes were measured on Map No. I on its scale of 1:2000.

The volume of the rock-fall funnels was calculated in the following way. The surface of the excavation which the contours form in the mountain side was measured with a planimeter. Each even 20-meter curve was measured (e. g. T9 at 240, 260 and 280 m above sea-level and so on, up to the summit plateau of Templet). After that the volume of the whole funnel was calculated according to the formula[4]

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[1] The terms "ravine" and "ras-skar" used in the discussion quoted are in this case the same as the author's term "rock-fall funnel".

[2] Here the volume of the cone mantle is meant (from talus base to funnel gorge).

[3] Rock-fall funnel = the volume of the entire collection area from funnel gorge to the summit plateau of Templet.

[4] The author wishes to thank Dr. A. Sundborg, who suggested the formula.

$$V = 20\Sigma(y_l + \dots + y_i + \dots + y_k) \text{ (Formula A)}$$

where V = the volume, y_l = the surface of the lowest 20-metre curve in the funnel, y_k = the surface of the highest 20-metre curve in the funnel and y_i = the surface of an intermediate 20-metre curve in the funnel.

The above formula implies a certain approximation and gives somewhat too large a value. The error would seem to be without practical significance and in each case probably does not distort the proportion of cone to funnel. The calculation becomes somewhat more exact, the shorter the interval taken between the curves measured. An interval of 20 m was considered to give a sufficient accuracy in this case.

The volume of the talus cones was calculated in a similar way. (If the cone or funnel has a very regular conical shape, its volume can be calculated according to the formula for the volume of the cone. See, for example, Chapter 6.22.) The surface of the segment of a circle which the contour forms on a cone was measured for each even 20-metre curve. The volumes of the 20-metre layers was calculated and added according to the above. By this means it is easily possible to obtain from the map the volume of the arched, prominent part of the cone. However, it is not known how much talus material is concealed behind the arched part of the cone. In other words, the substratum of the talus cones cannot be reconstructed with certainty, in particular not below the cones which have grown together laterally. Where the cones lie apart, however, it seems very likely that their substrata is made up of the straight prolongation of the intervening slope in under the cones. The calculations of volume were made on this assumption. It is further assumed that the projecting wall spurs between the rock-fall funnels have had a constant position during the formation of the funnel.

6.22 Calculation of the volume of funnel and cone T9

Cone T9 is accumulated above a prominent terrace, the level of which is 140-130 m above the sea (for description, see Chapter 4.31 and Fig. 15). The terrace, which lies above the upper marine limit, is, according to the argument in Chapter 4.33, a kind of ice-contact formation of moraine or glacifluvium, piled up all along the side of the ice during the late-glacial ice retreat. This implies that the cone has not been subjected to abrasion, as have the other cones at Bjonahamna. Ever since the edge of the supposed fjord ice retreated in late-glacial time past the cone, it has not been the subject of appreciable removal of material, as is illustrated in more detail below. *Consequently in cone T9 there remains practically all the debris which in post-glacial time has come down from its rock-fall funnel.* This has the effect of making the cone specially suitable as a starting point for an attempt to get at the order of magnitude of the total post-glacial denudation.

The following features in the shape of the slope testify that no appreciable removal of material in solid form has taken place from the cone since the terrace was formed (see Chapter 4.31): (1) the distinctive shape of the terrace area, and (2) the sharp base break in the profile at the foot of the terrace slope. The old and close vegetation above the terrace area and in front of the foot of the terrace slope testifies that no removal of material has occurred during at least the last century.

Removal from the cone through small falls, slides, mudflows, creep, and solifluction has to go over the terrace and thereby cover over the vegetation and transform or completely conceal the terrace. This has not taken place[1]. Isolated boulders may conceivably fall over the terrace without affecting it, if, for example, it is snow-covered. After having passed the terrace, such boulders must, on account of the steep gradient of the terrace slope, continue down to its foot, where in the course of time they would form an accumulation which levelled out the base break and covered over the vegetation. This has not taken place and consequently this form of removal does not enter into the question either.

Removal by running water in suspension or solution is probably extremely insignificant from the T9 cone with its inconsiderable catchment area for snow and water. No traces of suspension transport are visible at the base of the cone or of the terrace slope.

The cone has not merged laterally with T8 on the left-hand side; on the other hand, it has merged to a slight extent with T10 on the right-hand side. The substratum of T9 is assumed to lie in the extension of the even section which lies between T8 and T9. This intervening triangular section could only be supplied with inconsiderable amounts of débris since the T8 and T9 funnels were formed, as its rock-wall area then came to be restricted to a relatively small, triangular surface of the c-cliff. In this intermediate space the debris layer is therefore probably thin on top of the rock core. This view is confirmed by the fact that the rock core comes to light to the left of T8 at the intersection close to the alluvial cone A. The bedrock is covered by a layer of loose material about ½-1 m thick. The substratum of T9 has accordingly been extrapolated from the cartographic picture as the extension of the straight slope between T8 and T9 and also the extension downwards of the intermediate space between T9 and T10. In order that the volume of the cone shall be obtained with a wide margin, it has been assumed that its substratum furthermore lies somewhat lower than the even surfaces on both sides of the cone (2 m lower in the lower part, 1 m lower in the upper part of the cone).

The calculation of volume has been carried out in two different ways (I and II):

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[1] This matter has also been observed by Philipp (1914, p. 18).

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I. The base of T9 is considered as marked by contour 132. The shape of the cone has been simplified to a part of a cone with the tip at 232 m above sea-level, in the middle of the funnel gorge. The volume is therefore 2000 (232-132)/3 or 67,000 m³.

In order to be able to compare the volume of the accumulated debris with its equivalent in denuded solid rock, the pore volume must, however, be subtracted from the volume of the cone. This pore volume is purposely set as low as 33 %. Then *a compact volume of about 45,000 m³* is obtained.

II. A calculation according to Formula A gives *the corresponding value of 55,000 m³* for the compact volume. In spite of the above-mentioned lower value probably being more correct, this higher value is used for the calculations which follow.

In the talus volume is not included the loose material which lies in the bottom of the spirifer funnel. It amounts, however, to an extremely small quantity, both if one compares it with the cone below the funnel gorge and if one compares it with the volume of the spirifer funnel itself. This material is therefore left wholly out of consideration, both in calculating the volume of the cone and that of the rock-fall funnel.

The volume of the rock-fall funnel at T9 has also been calculated in two ways (I and II):

Calculation I

Level (m above sea-level)	Surface (square metres)	Volume (cubic metres)
440	?	
420	?	
400	480	
380	1620	
360	2040	About 55,000
340	2480	
320	2560	
300	2680	
280	2120	About 200,000
260	1200	
240	280	
232	0	About 34,000
		Total: About 290,000

Calculation II according to Formula A gives the volume as 309,200

In the computation of the volume of the funnel according to Method I the part between 232 and 280 m above sea-level has been

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simplified into a part of an inverted cone, that between 280 and 360 m to a part of an oblique cylinder with a varying cross-section and that between 360 and 440 m again to a part of a cone with the tip at the 440 m contour. The top of this cone does not appear on the map, but the approximation was made after examination of stereoscopic photographs, from which it is clear that the funnel reaches at least up to 440 m. According to these approximate calculations, the relation of the T9 talus cone to the T9 funnel accordingly becomes 45,000/290,000 or somewhat less than 1:6 (1:6.4). According to Formula A, the same relation becomes 55,000/309,000 or somewhat more than 1:6 (1:5.6).

In the calculation the volume of the cone has been increased liberally and that of the funnel narrowly. Cone T9 below the funnel consequently contains at most one-sixth of the volume of material which the rock-fall funnel in its present form represents. Since cone T9 has probably not been subject to appreciable removal of material in post-glacial times, the greater part of the rock-fall funnel is probably older than post-glacial.

6.23 Volume measurements on other cones

Cone T9 is not unique in the matter of the disproportion between cone and rock-fall funnel. An example, which shows perhaps still more clearly than the case of T9 a "shortage" of material, is that of the cones S6 and S7 at the south-west wall of Templet (Plate X). These cones stand on the top of terrace S6. The accompanying rock-fall funnels in the wall correspond to a many times greater volume than what is contained in their small cones. The ravine and alluvial cone discussed by De Geer (1910, Pl. 9) and Högbom (1914, p. 283) (see Chapter 6.1) are, on the other hand, not equally unambiguous. Since alluvial cones are in principle more affected by water erosion than talus cones, a relatively large part of the alluvial cone mentioned may have been carried away by stream-water in combination with abrasion, as the formation lies at a low level (cf. alluvial cone A at Bjonahamna).

For the sake of comparison similar measurements were made on the map of the cones T2-T5, together with the accompanying rock-fall funnels. In that connection it is to be noted that these cones have merged with each other laterally more than was the case with T9, for which reason the substratum of the cones has to be reconstructed by a more uncertain extrapolation than in the case of T9. This applies particularly to T2 and T3. In all cases, however, the volume of the rock-fall funnel, in spite of the amply calculated volume of the cones, is so much greater than the latter, that it cannot be doubted that the wall relief is in the main older than post-glacial. *The calculated volumes of the rock-fall funnels represent moreover minimum values for the quantities of material which have*

Table 10.

The volume ratio and calculated wall retreat at Bjonahamna.

	T3	T4	T5	T9
Volume[a] of the talus cone (=*C*) in cubic metres	108,000	145,000	165,000	55,000
Volume of the rock-fall funnel (=*T*) in cubic metres	570,000	738,000	1,260,000	309,000
Ratio of cone to funnel (=*C*/*T*)	1/5	1/5	1/8	1/6
Horizontal surface[b] of the funnel (=*H*) in square metres	32,000	44,000	56,000	14,000
Vertical surface[c] of the funnel (=*S*) in square metres	28,800	36,600	45,200	16,000
Horizontal retreat[d] of the wall in metres				
Total (=*T*/*S*)	19.8	19.9	27.9	19.3
Post-glacial (=*C*/*S*)	App. 3.7	App. 4	App. 3.7	3.4

[a] The volume of the talus cone = volume of the cone mantle from base to funnel gorge minus 33 % pore volume.

[b] Horizontal surface of the funnel = the surface of the funnel in vertical proured on the map in horizontal projection.

[c] Vertical surface of the funnel = the surface of the funnel in vertical projection, calculated according to the formula $S = 20 \Sigma (b_1 + \ldots + b_i + \ldots + b_k)$, where b_1 is the width of the funnel at the lowest 20-metre countour, b_k the width at the highest 20-metre contour and b_i one of the intermediate 20-metre contours.

[d] The figures for the wall retreat refer to an average value for the whole vertical surface.

been conveyed from the funnels, inter alia, for the reason that *the projecting partition walls between them also may have retreated by which the volume of the excavation is diminished considerably.*

A similar calculation of volume was also made for talus cone T1, the most well-formed of all. In the matter of this cone, however, a complication arises in the calculation. The cone is situated in the south corner of Templet. Its substratum is therefore probably not even, but probably projects into a corner under the cone. If it is assumed that such is the case, the calculation shows that the cone takes up one-seventh of the volume of the funnel. If one assumes that the substratum of the cone forms a straight plane from one side of the cone to the other, the proportion of cone to funnel becomes 1 :3.

6.24 Discussion

The talus cones at Bjonahamna, according to the calculations given above, contain *at most* one-fifth to one-eight of the volume of bedrock which would be required in order to "fill out" their respective rock-fall funnels. The ratios are relatively equal for the abraded cones T3 and T4, on the one hand, and the non-abraded cone T9, on the other. This may indicate that the abrasion has not removed any considerable quantities of material from T3 and T4, but may also be connected with a heavier supply of material to the latter. The smallest cone, relatively speaking, is T5, in spite of the fact that its funnel is the largest. Is the cause more powerful chemical solution and removal? Or removal by avalanches in the abrasion phase?

In Table 10 the total and the post-glacial wall retreat have been given. The post-glacial retreat was calculated in such a way that the compact volume of a cone was distributed evenly over the vertical surface of the corresponding funnel (C/S). The value which is then obtained for the wall retreat is here called a "smoothed" value. It is *greater* than if the volume of the cone had been distributed on the actual surface of the funnel with the whole of its detail relief included. According to approximate calculations on Map No. I, *the vertical surface of the funnel* is about $^3/_4$ to $^3/_5$ (average value about $^2/_3$) of *the actual surface of the funnel.* If one reduces the smoothed values for the wall retreat at Bjonahamna to about $^2/_3$, one consequently obtains figures which are comparable with the retreat calculated on simple walls. The same thing applies to the "total retreat", which has been calculated in such a way that the volume of the whole funnel has been distributed evenly over its vertical surface.

In Chapter 5.3 the author examined the recent material turnover on the cones and arrived at the conclusion that the supply has clearly been greater than the removal during the period 1882-1954, and also that the supply has probably amounted to about 1-5 m^3 per year and cone during the period mentioned. This would imply a yearly horizontal retreat (smoothed) of at most 0.11-0.17 mm in the cases of T5 and T3.

It is of interest to see how these values, which are based on a study of the current material turnover, agree with the values for the wall retreat which have been obtained by the analysis of forms (the volume measurements) on the map.

Table 11 (below) contains values of different reliability. The estimation of the recent disintegration at Bjonahamna is probably more certain than at Langtunafjell. In the former case the probable order of magnitude of the *largest* average disintegration was calculated; in the latter the calculation had reference to the corresponding *smallest* disintegration. The extreme values are in both cases calculated with a wide margin.

The wall retreat alongside the glacier on Langtunafjell is probably somewhat — but not many times — more rapid than that on Templet at Bjonahamna. In the latter place the recent retreat is very probably of the order of magnitude of 0.02-0.2 mm per year; at Langtunafjell it is probably of the order of 0.05-0.5 mm per year. Both the maximum values quoted are surprisingly small (for example, they correspond to at most

Table 11.

Calculated rate of wall retreat at Bjonahamna and Langtunafjell.

	Average reatret per year mm				Probable extreme values (rounded figures) mm
Bjonahamna	T9	T3	T4	T5	
1882–1954 (probable maximum values)	?	0.17	0.14	0.11	0.02–*0.2*
Whole post-glacial period					
If 10,000 years min.	0.34	0.37	0.40	0.37	0.34– ?
If 30,000 years min.	0.11	0.12	0.13	0.12	0.11– ?
Langtunafjell (Chapter 3.1)					
Recent wall retreat	–	–	–	–	*0.05*–0.5

2 and 5 m respectively of wall retreat in 10,000 years), considering that they apply to a climate-morphological environment which is considered to have the most severe recent denudation in the world.

Some values can be given for comparison. In the Eastern Alps Poser (1954, p. 140), by assessing the volume of talus cones, estimated the wall retreat at 7-10 m every 10,000 years (0.7-1.0 mm per year) in gneiss, schist and serpentine in three localities. These values are characterized by Poser as surprisingly small (op. cit., p. 140). From the tropical rain-forest region of Brazil Freise (1933, pp. 2, 3) reports a wall retreat of 2-20 mm per year in granite. It is not clear from the descriptions whether the walls in question are simple or dissected and in that case whether the values are calculated with regard to the detail relief. The comparison is therefore approximate. If Freise's values are correct, they may serve as an example of an extremely rapid denudation.

Mortensen (1956, p. 98) gives several examples of walls in arid and semi-arid environments which have practically not retreated at all in 5-6000 years (rock-carvings), whilst King (1956, p. 105) reports so high a figure as 1.5 mm per year as an average value for granite walls etc. in the savannah and steppe regions of South Africa.

The author's values for wall retreat on Spitsbergen are consequently less than all the values quoted here except Mortensen's.

It ought perhaps to be pointed out once more that the values quoted above were calculated in different ways and that it is difficult to judge the accuracy of the calculations.

The above values accordingly represent a number of ideas as to the horizontal retreat in walls of solid rock. It is more usual to report the

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denudation within an area in vertical measurements, calculated with the guidance of silt removal by rivers or the size of a delta formation. The measurement of the denudation which is then obtained refers to breaking down and removal of both loose deposits and solid rock. *It is very likely that the high values for denudation given as a rule by such calculations within previously glaciated areas depends on a heavy soaking and evacuation of the relatively fresh moraine material,* which the land ice left behind. Consequently it hardly applies to denudation on solid rock but to a relatively rapidly transient post-glacial stage of strong moraine evacuation, which has not yet reached equilibrium. For example, the Western Alps, where the larger rivers have values of 0.4-0.5 mm per year and the smaller rivers values as high as 1.5-2 mm per year (Winkler—Hermaden, 1957, p. 694) as an average vertical denudation for their total drainage area.

6.25 Summary of volume measurements on the map

The talus cones at Bjonahamna contain, according to the calculations given above,[1] at the most 1/5 to 1/8 of the bedrock volume which must have been carried down from the funnels on their formation. The removal of material from the talus cones in post-glacial times certainly did not have anywhere near such large proportions that it could have caused such a great shortage of debris on the cones. This appears most clearly in the case of T9, for this cone has not, like the others, been subject to abrasion. It has, as a matter of fact, not undergone any noteworthy removal of material in post-glacial time.

The other cones were, it is true, abraded for a time, but to judge by comparisons with cones abraded at the present day at Tempelfjorden, this form of removal has probably not been of extensive proportions in the shallow and sheltered situation at Bjonahamna.

The relief on the walls (rock-fall funnels, large rock-fall chutes) is consequently older than post-glacial in its main formation. Neither was it probably formed in its entirety during the melting of the ice (late-glacially), for the denudation forms are so large that they probably demand a longer period than an ice-melting phase for their formation. This is indicated partly by a comparison with the present-day conditions at Tunabreen, where mountain walls in the nunatak stage are not being broken down particularly rapidly (*at most* 0.5 mm retreat per year), and partly by a comparison between the post-glacial wall retreat in the rock-fall funnels at Bjonahamna (about 4 m) and the considerably greater total retreat in the same funnels (20-28 m). For conclusions, see Chapter 7.1.

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[1] The volume of the cones was calculated liberally, that of the funnels narrowly. The difference in pore volume is probably greater than the 33 % assumed. The dividing walls between the funnels may have retreated somewhat, simultaneously with the wall in other respects. The three factors mentioned operate in the same direction, i. e. they tend to increase the disproportion of cone to funnel.

CHAPTER 7

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Conclusions

7.1 CONCLUSIONS AS TO THE DEVELOPMENT OF THE WALL RELIEF

The author's studies of mountain walls and talus slopes in the Tempelfjorden area have led to the following conclusions:

(1) The rock-fall funnels in the walls were essentially formed before post-glacial times. They were probably formed chiefly by nivation and small rock-falls.

(2) They were possibly established inter-glacially (pre-glacially?) and in the main widened in glacial (late glacial?) times. Their widening continued during post-glacial times.

Consequently their genesis is possibly as follows: (A) inter-glacial establishment; (B) glacial widening, alternatively (1) "covering ice" for a longer or shorter glaciation optimum but not total destruction of the funnels, and afterwards widening of them during a late-glacial nunatak stage, or (2) not "covering" ice, only valley glaciation and widening of the funnels during a nunatak stage of long duration; (C) post-glacial widening probably corresponding to an average wall retreat of about 3-5 m (Bjonahamna).

These conclusions are in keeping with the suppositions of De Geer and Wråk, but imply a considerably slower development than that which Högbom and other authors pre-suppose (cf. Chapter 6.1).

7.2 CONCLUSIONS AS TO THE DEVELOPMENT OF THE TALUS CONES

The main interest of the thesis was directed towards the talus slope formed by about 10 large cones at Bjonahamna. The development of these cones has probably run its course according to the following scheme:

A. *The deglaciation phase.* The upper part of the mountain wall free from ice, the lower part covered with moving glacier ice (corresponding to the conditions at the present day at the Langtuna nunatak). Almost all debris was carried away by the glacier, on which was formed a large lateral moraine on the surface of the ice.

B. *The abrasion phase.* When the ice had disappeared from the valley side, talus cones began to be accumulated on the top of bedrock and moraine material. At certain places these cones were formed on top of remaining lateral terraces of moraine (and glacifluvium?). The sea reached up to around the present 90-metre level and consequently abraded the lower part of the cones, yet not T9, which stood on a terrace. The removal of material from the cones by abrasion was probably not of significant proportions, partly because most of the cones have a shallow and sheltered situation (except T1), partly because the higher lying cones came relatively soon to be elevated above the reach of the waves. The assortment on the talus (accumulation of the coarsest material at the base) also counteracted the removing effect of the abrasion.

C. *The "dry phase".* The cones are dry in so far as they are beyond reach of the effect of the waves. The new C^{14} datings (cf. p. 26) indicate that the dry phase has lasted about 10.000 years for the cone T1 etc.

Recent development

The supply of debris in modern times (1882-1954) to the cones probably corresponds to a horizontal, "smoothed" wall retreat of about 0.02-0.2 mm per year. Pebble falls and small boulder falls are quantitatively most important for the supply, large boulder falls less important.

The shifting corresponds to the supply and takes place essentially in the form of momentary, dry slides. Next in the matter of quantitative importance come mudflows and then avalanches. As regards the importance of talus creep, it appears from picture examination etc. that this form of transport has played no appreciable role on the lower part of the cones. How its effect operates on their upper parts could not be ascertained.

Removal seems at present to occur chiefly by solution and is considerably less than supply and shifting, for which reason the cone mantles are slowly growing in area at the present day, to a large extent with inclination preserved and a straight profile. The exceptions are certain cones affected by mudflows and avalanches, which are becoming slightly concave at the base.

A comparison with the rate of breaking down on nunatak walls alongside a present-day glacier (Tunabreen) indicates that one ought not to reckon with a more rapid breaking down than at most 0.5 mm of wall retreat per year at Bjonahamna during the close of the deglaciation phase and possibly the beginning of the abrasion phase.

The moderate order of magnitude of the present-day disintegration at Bjonahamna and at Tunabreen is probably representative of the Permo-Carboniferous mountains on a large scale on Spitsbergen.

The disintegration at the present day is consequently relatively slow, but the talus cones are large in spite of this, if one makes a comparison

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with many other climatic environments. This lack of agreement between present-day supply and the size of the cones cannot be explained by the talus slopes themselves having choked the supply of debris by growing up and covering their former collection areas, because the free wall surfaces are still large. It is possibly conceivable that the explanation of the disproportion may lie in the fact that the supply of debris has been much heavier during certain past time-phases (colder climate? climatic reversal? earthquakes?) of a 10,000-year post-glacial period. But the explanation may also lie in a more continuous development during a post-glacial time which has lasted considerably longer than 10,000 year.[1]

As regards the *methods* used by the author the comparative photograph examination especially has proved to be very useful for the study of the rate and type of slope development, even if this development was more slow than the author at first had expected. No doubt this method offers one of the best ways of getting more exact knowledge of the development of steep slopes in various rocks and climates.

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[1] *A short comment on the new C^{14} datings* (p. 26) may be added (April, 1960). The datings refer to raised terraces at Billefjorden but are probably valid also for Templet at Tempelfjorden, as the distance is only 20-30 km between these localities and as the upper marine limit runs at about 90 m in both fjords (cf. Feyling-Hanssen, 1955, p. 47).

The datings give the main trend of the land-rise curve from the altitude of 56 m down to the present sea-level. They indicate a rapid uplift at first and a slow one later on. The curve from Billefjorden fits very well with a land-rise curve from Nordaustlandet, based on numerous C^{14} datings on samples collected by W. Blake. (Personal communication by I. Olsson.)

The new datings from Billefjorden in the author's opinion indicate the following as regards the post-glacial development at Templet.

(1) The outer parts of Billefjorden and Tempelfjorden were already deglaciated 10,000 years ago. A rapid land uplift was occurring at that time.

(2) We do not yet know if the land-rise curve can be extrapolated from 56 m to 90 m with the same gradient or if there exists one or several steps in the higher part of the curve.

(3) The unknown land-rise interval from about 90 m to about 56 m corresponds at Bjonahamna to theoretical shorelines running over the middle and lower parts of the terrace slopes (T9, S2, S6) discussed on p. 56 f. above. If the "unknown" period (90-56 m) was very long, the terraces ought to have been completely obliterated by wave abrasion. As this is not the case at all the author's belief is that a *rapid land uplift also occurred in the 90-56 m interval.* If this supposition is correct, the post-glacial period at Bjonahamna started about 10,000 years ago or a little earlier.

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[1] See also p. 96.

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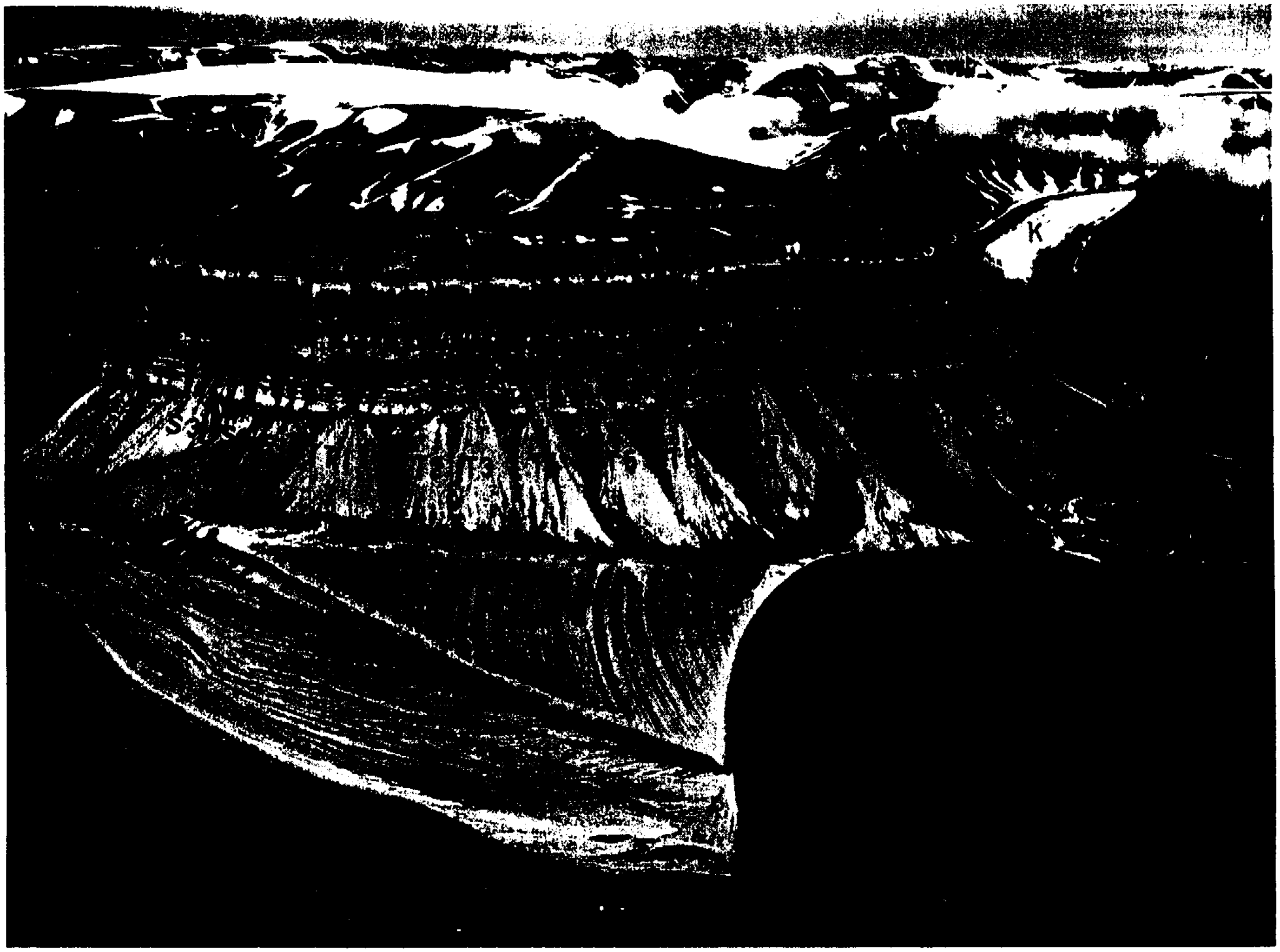

Plate I. Mount Templet at Bjonahamna, Spitsbergen. Dissected mountain walls with limestones, cherts and sandstones of Carboniferous and Permian age. A series of talus cones (S3—T9) and one alluvial cone (A). In the foreground the Bjona Point with its beautiful series of raised shore-lines. To the right Bjonadalen with Kommissaerbreen Glacier (K). Scale: The cones are 200—300 m high. Air photograph, B. Luncke, 1936.

Pl. I.

Pl. II.

Plate II (a). View from the talus slope at Bjonahamna. Weathered c-cliff to the left, the great delta of Bjonadalen in the centre, the ice-cliff of Tuna and Von Postbreen in the background. Scale: the line on the cliff is roughly 1 m. A. R., 14/7/54.

Plate II (b). The front of Tunabreen with ice-cliff roughly 40 m high. The medial moraine from Langtunafjell is the dark, broad band to the left. This and the other medial moraines are superficial, as is shown in the picture. T. Roos, 2/8/54.

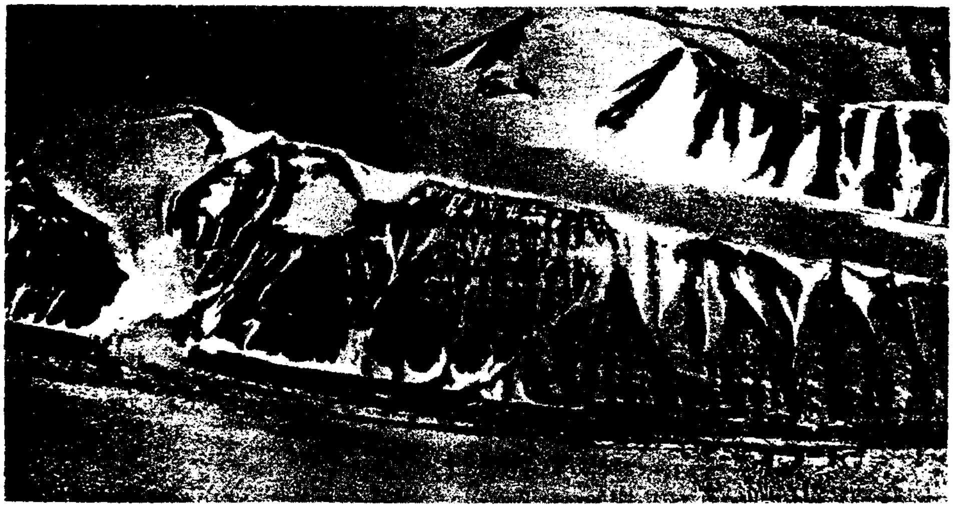

Plate II (c). Western face of Langtunafjell dissected by chutes and rock-fall funnels. To the left is a cirque glacier. Lateral moraine on Tunabreen in the foreground. The crest reaches about 600 m above Tunabreen on the left. Air photograph. B. Luncke, 1936.

Plate III. The front of Tuna- and Von Postbreen in Tempelfjorden. Langtunafjell is the long, ridge-shaped nunatak on the right. Air photograph, B. Luncke, 1936.

Pl. III.

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Pl. IV.

Plate IV (a). Kommissaerbreen from Templet. Note the curved bands of lateral moraines coming from the scree chutes and funnels of the valley sides. Map No. III covers the right-hand part of this photograph. A. Koller, 1924.

Plate IV (b). Talus cones, 20—30 m high, passing over to ridges of lateral moraine. Kommissaerbreen, central part, Templet. The deeply dissected cliff with pinnacles rising over talus cones is the upper part of the spirifer cliff. A. R., 22/7/54.

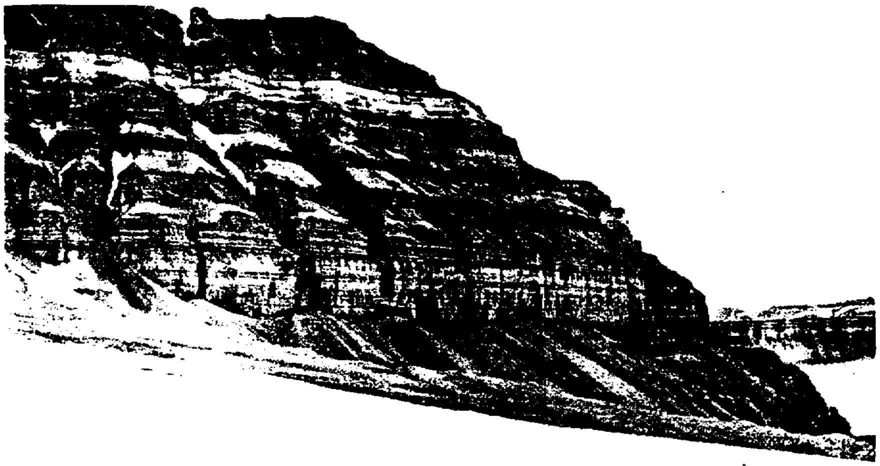

Plate V (a). Sindballefjell at Kommissaerbreen. The spirifer cliff stands immediately above the talus slope. The white band near the top plateau is the productus cliff. Dissection is more advanced to the left, where the collection area for snow and water is greater than to the right. Glacier in the foreground. Chutes and cone marked H on Map No. III to the left. A. R., 22/7/54.

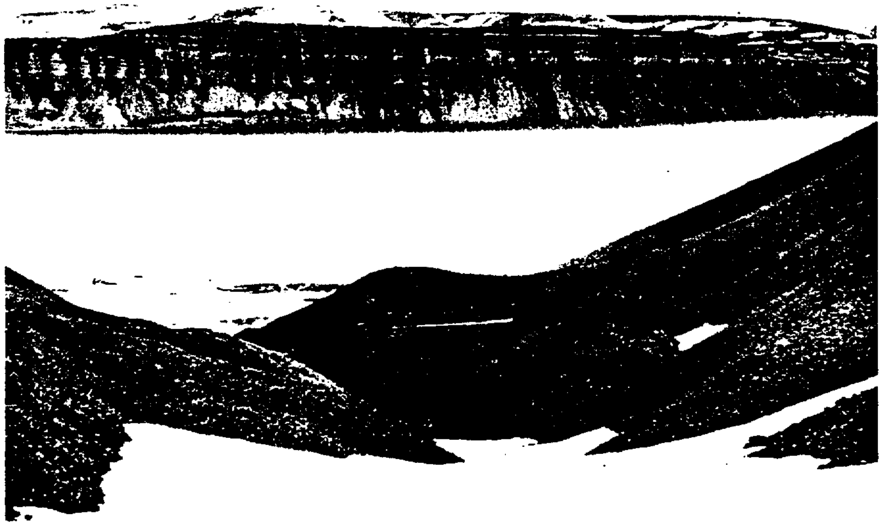

Plate V (b). Two terraces in front of the right-hand side of Kommissaerbreen. The nearest (a in Fig. 16) is ridge-shaped and must be a remnant of the lateral moraine (foreground, left). The second terrace (b_1) is slightly concave upwards. It is thus more modified than the first but very likely has the same origin. A. R., 27/7/54.

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Pl. VI.

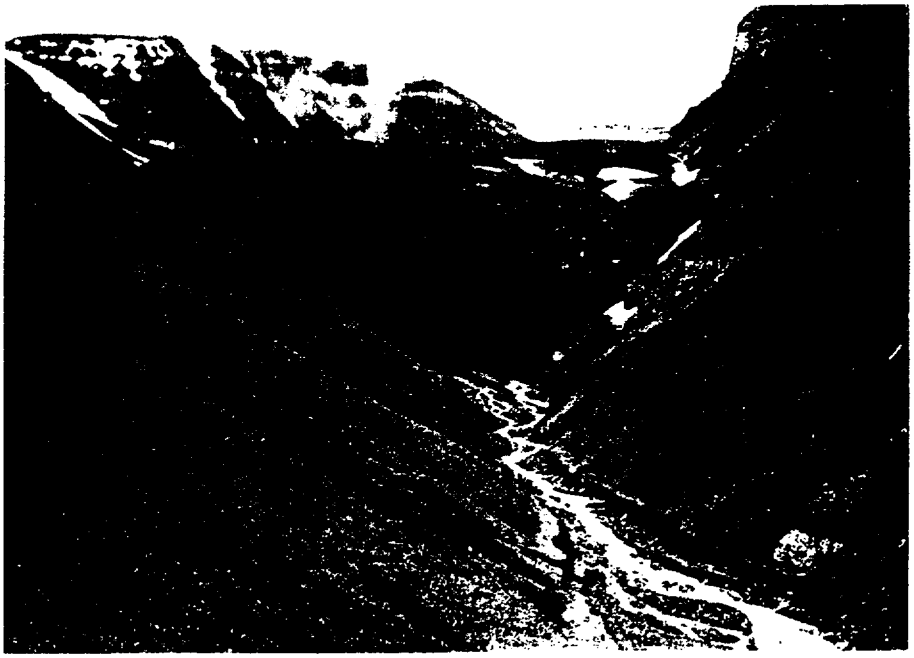


Plate VI (a). The steep front of Kommissaerbreen, all covered with surface moraine. Note the terrace of débris lying upon the bedrock shelf (light-grey rock above the lowest snow-patch to the right). O. Halldin, 1908.

Plate VI (b). Typical U-shaped chute breaking through the c-cliff above cone S1. Two thin layers of white gypsum are visible, one in the centre (about 0.5 m thick) and one to the left. The photograph was taken downwards across the upper part of the chute. The dark line to the left is the shore of Sassenfjorden. A. R., 28/7/54.

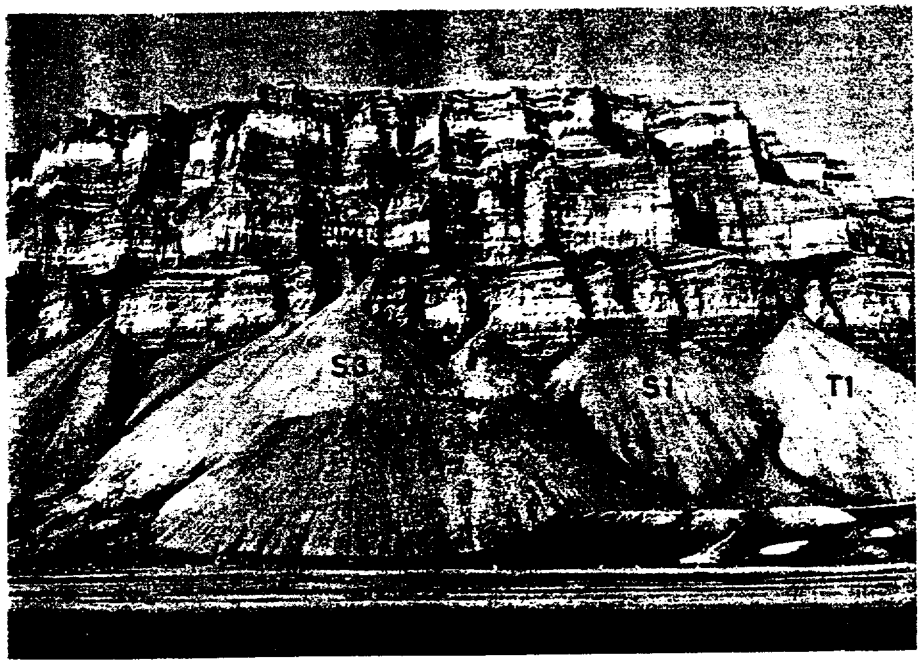


Plate VII (a). South-facing slope of Templet. The three main steps of the scarp are clearly visible. The c-cliff shows growing dissection above cones S1, S2 and S3. Note the high terrace in front of S2 and S3. A. R., 29/7/54.

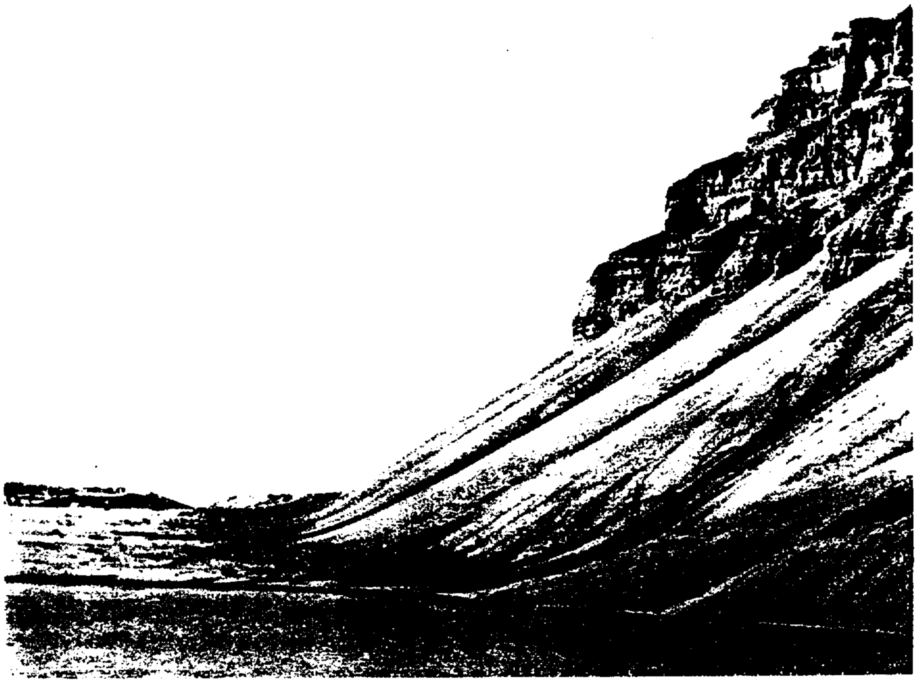


Plate VII (b). Scarp and talus cones at Bjonahamna. Most of the cones have an almost straight profile and a sharp break at the base. One cone (T5) in the centre has a smooth concave profile most probably formed by the work of snow avalanches. Scattered boulders form a base fringe in front of the cones. A. R., 21/7/54.

Pl. VIII.

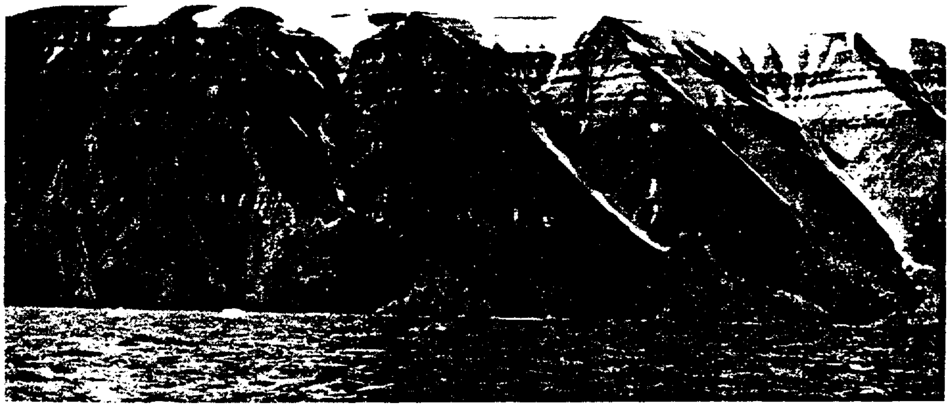


Plate VIII (a). Rock-fall chutes and funnels with their debris accumulations. Sindballefjell at Tempelfjorden. Top plateau roughly 600 m above sea-level. Small chutes to the left, greater and greater funnels to the right. Their cones also form a developmental series from talus cones to gullied talus to alluvial cones from left to right. A. R., 25/7/54.

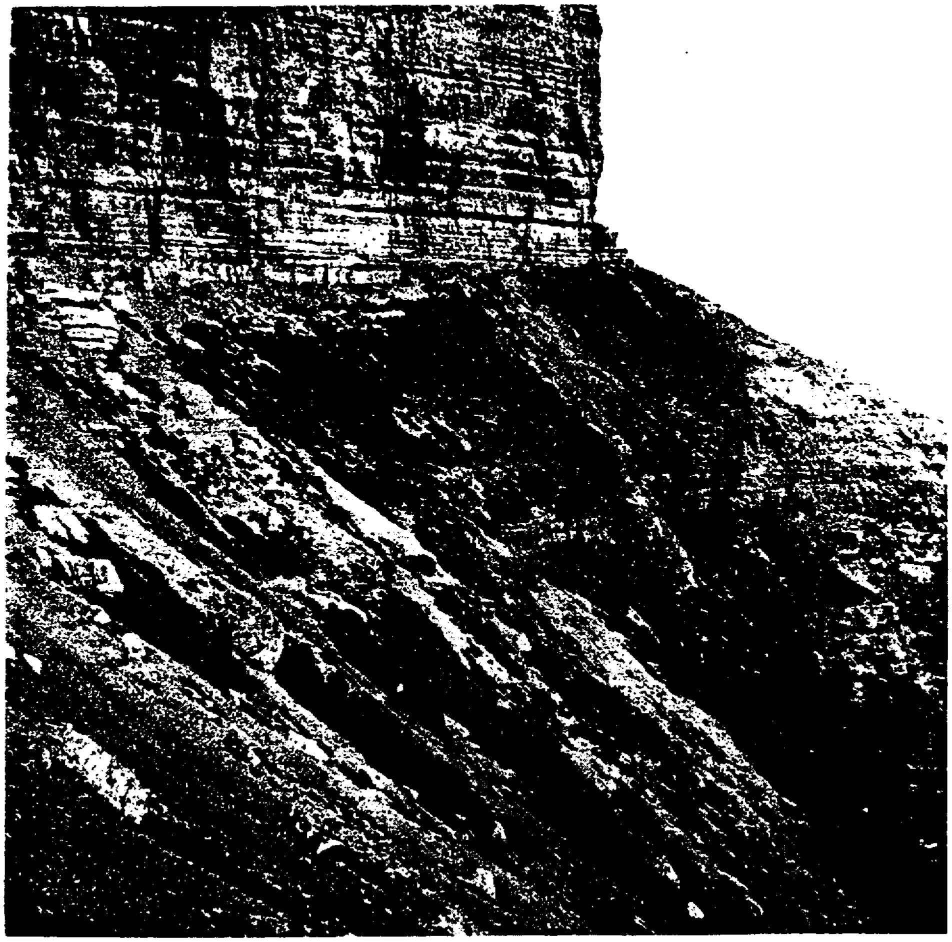
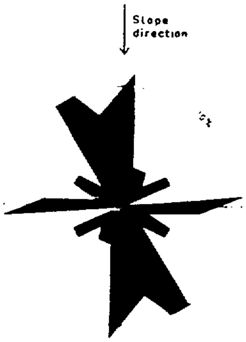


Plate VIII (b). Bottom of spirifer funnel above cone T1, Bjonahamna. Vertical spirifer cliff, thin cover of debris over bedrock, earth-slide scar on vegetation-covered slope to the right. A. R., 28/7/54.



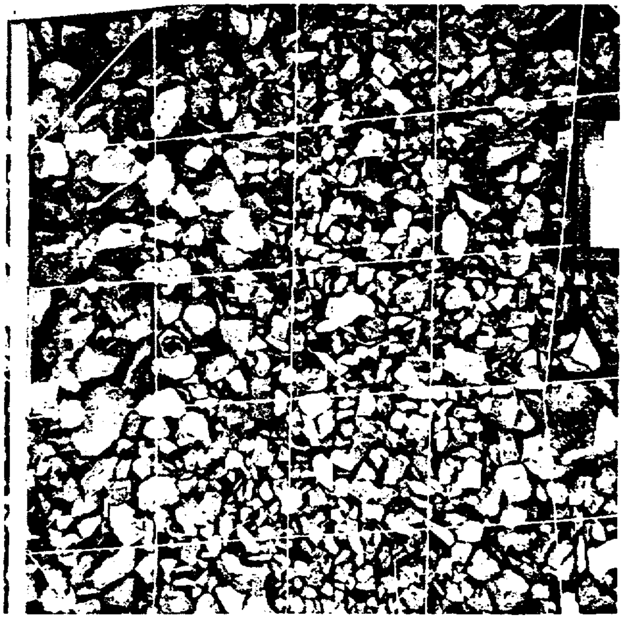


Plate IX (a). Surface of talus cone, Bjonahamna. Detail from a narrow slide-tongue with coarser pebbles at the sides and finer in the middle. Net has 20-centimetre squares. Up and down in the picture are the same as on the slope. Compare with the diagram of stone orientation from the same surface. Two maxima are seen. Possibly explained thus: transverse orientation — rolling stones, length orientation — gliding stones. A. R. 1954.

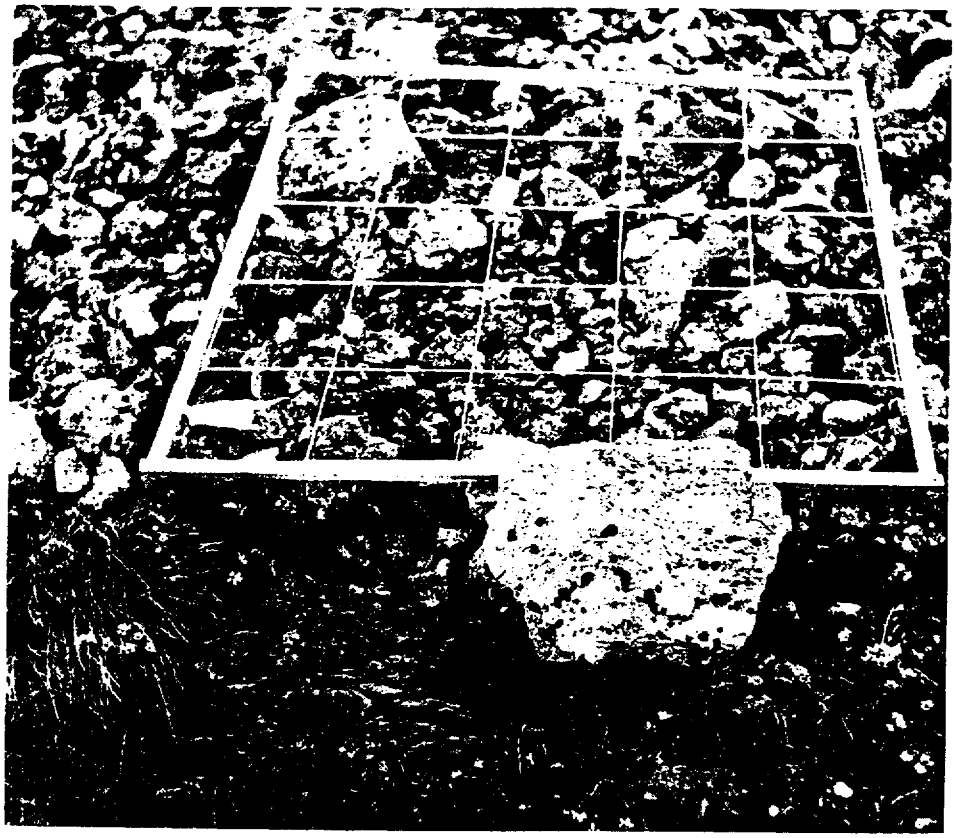


Plate IX (b). The base break of talus cone T6, Bjonahamna. Note the sharp boundary between lichen-covered talus and flat surface in the foreground, covered with grass and herbs. A rivulet runs under the left-hand part of the ribbon. Net has 20-centimetre squares. A. R., 1954.

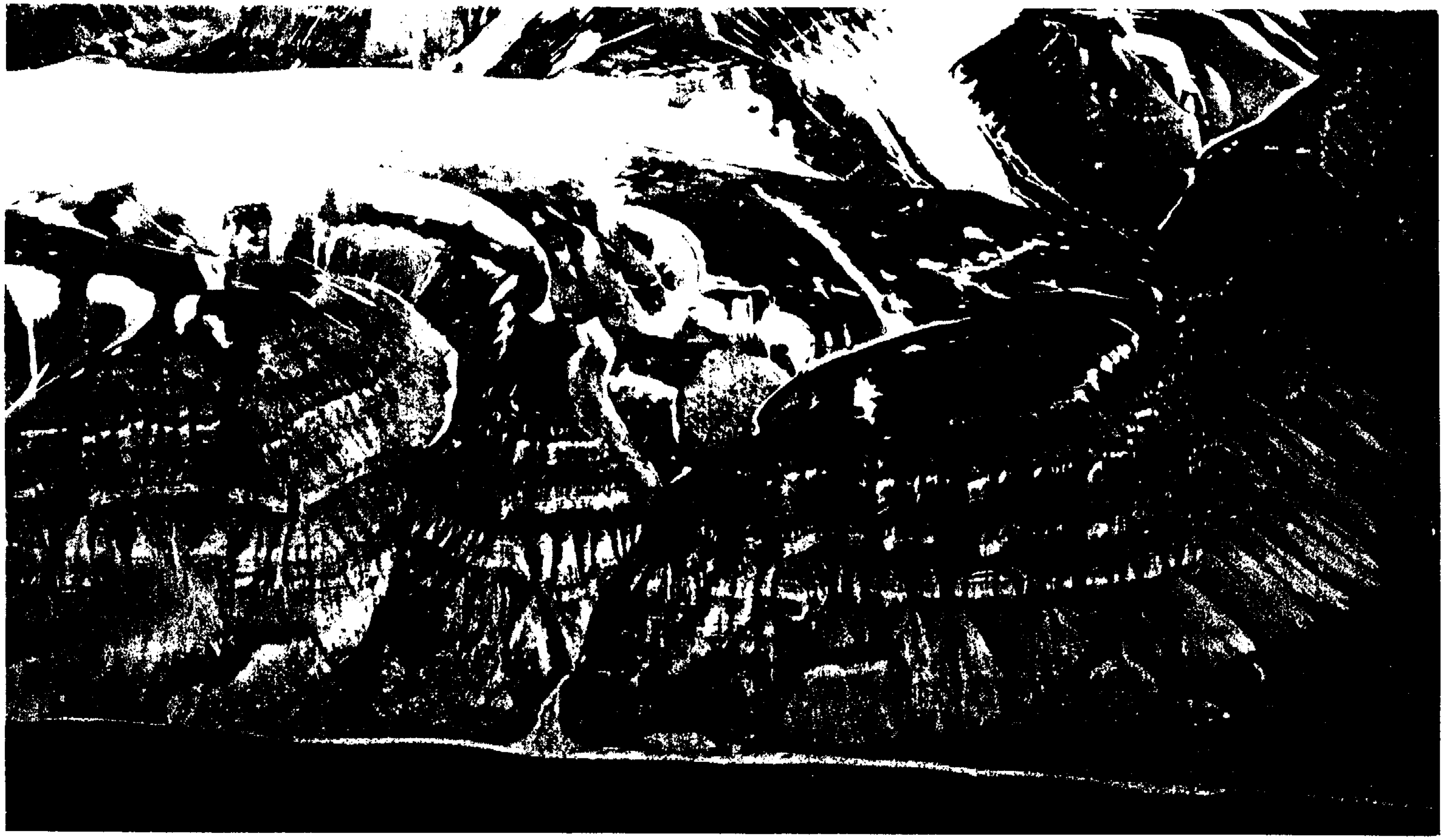


Plate X. The Sassenfjord side of Templet from the air. Terraces S2 and S6. Deeply incised small valleys dissect the top plateau. Air photograph, B. Luncke, 1936.

Plate XI. Templet at Bjonahamna from Bjona Point. Talus cones T1–T6. G. de Geer, 19/7 1882.

Pl. XI.

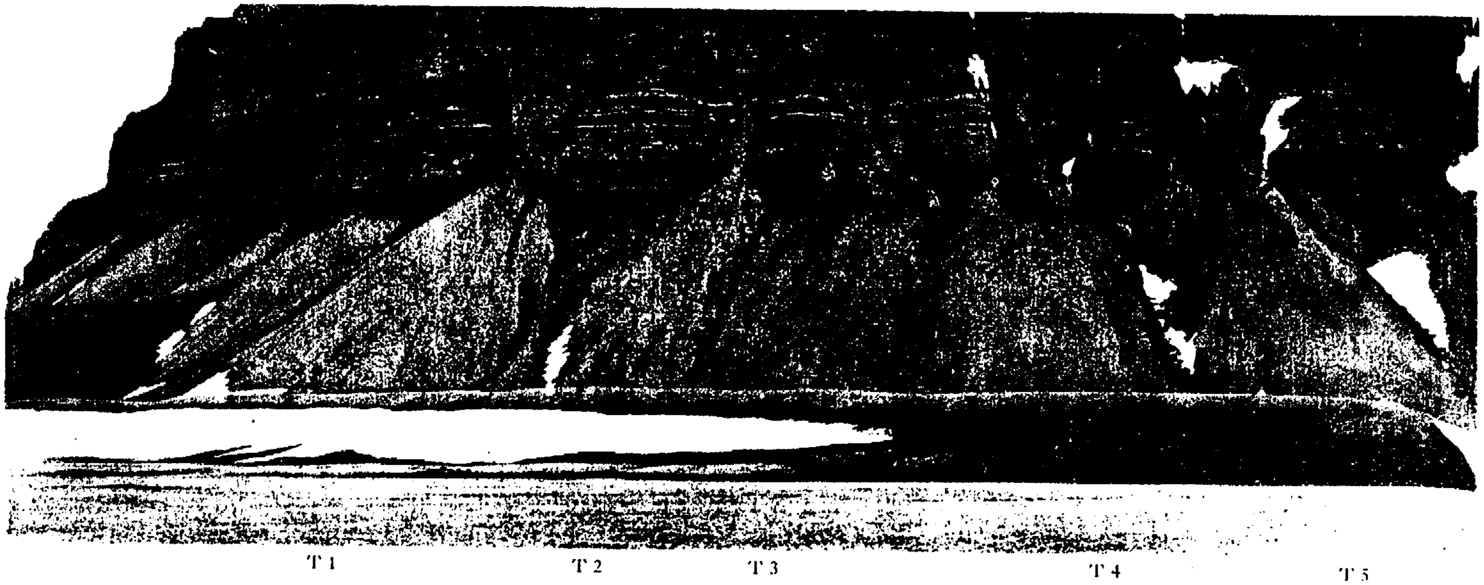


Plate XII. Templet at Bjonahamna from Bjona Point. Talus cones T1 - T5. G. de Geer, 1896.

Pl. XIII.

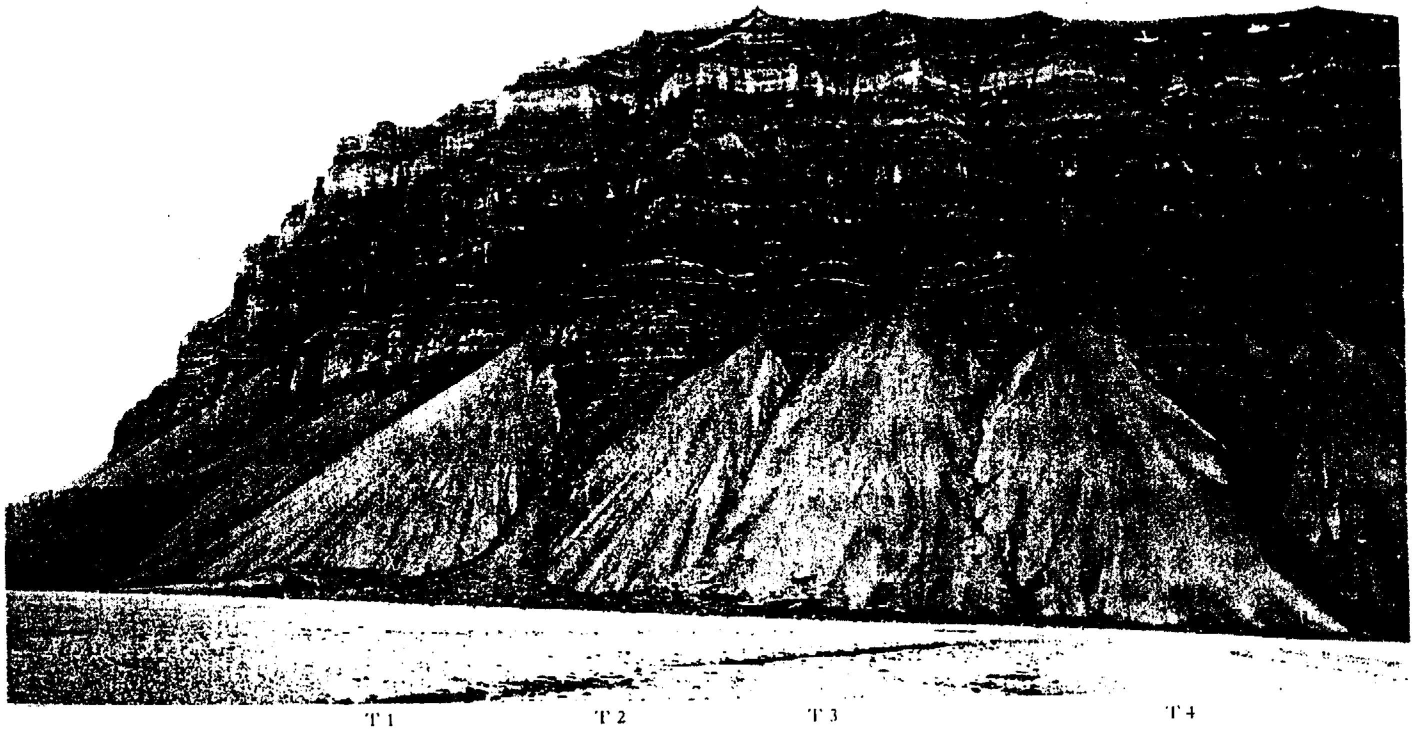


Plate XIII. Templet at Bjonahamna, cones T1 T5. A. Koller, 1924.

Pl. XVI (Plates XIV and XV will be found in the pocket on the back cover)

Plate XVI (a). Talus cones T6—T8, Bjonahamna. G. de Geer, 1896.

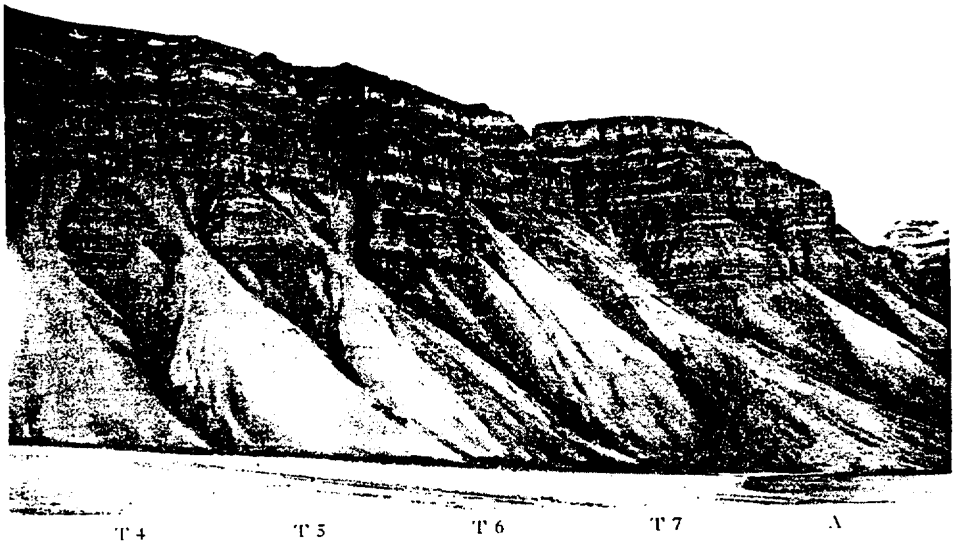


Plate XVI (b). Talus cones T4—T8, Bjonahamna. A. Koller, 1924.

Pl. XIV.

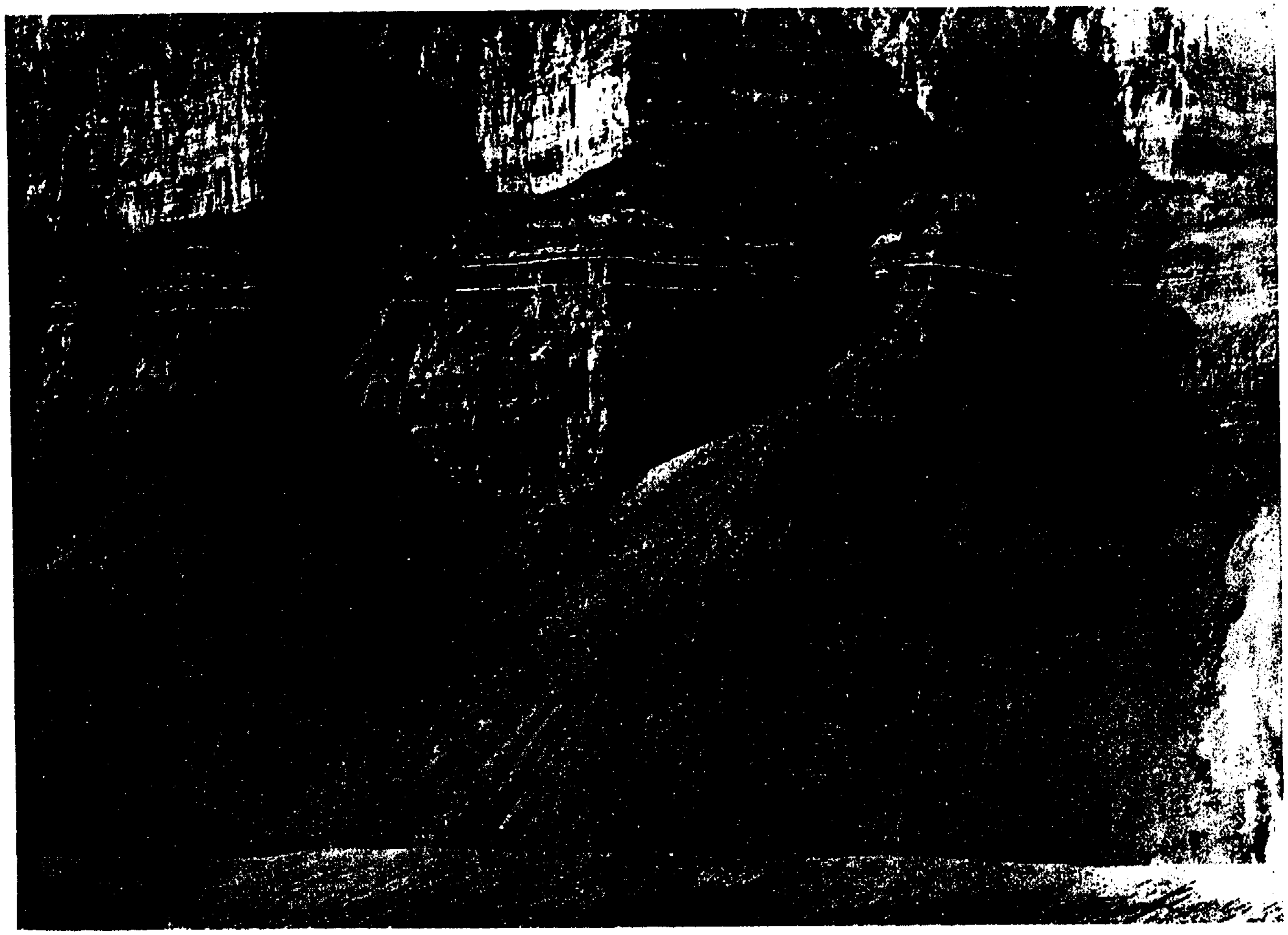


Plate XIV (a). Talus cones T1 T3, Bjonahamna. Enlargement from Plate XI. G. de Geer, 19/7 1882.

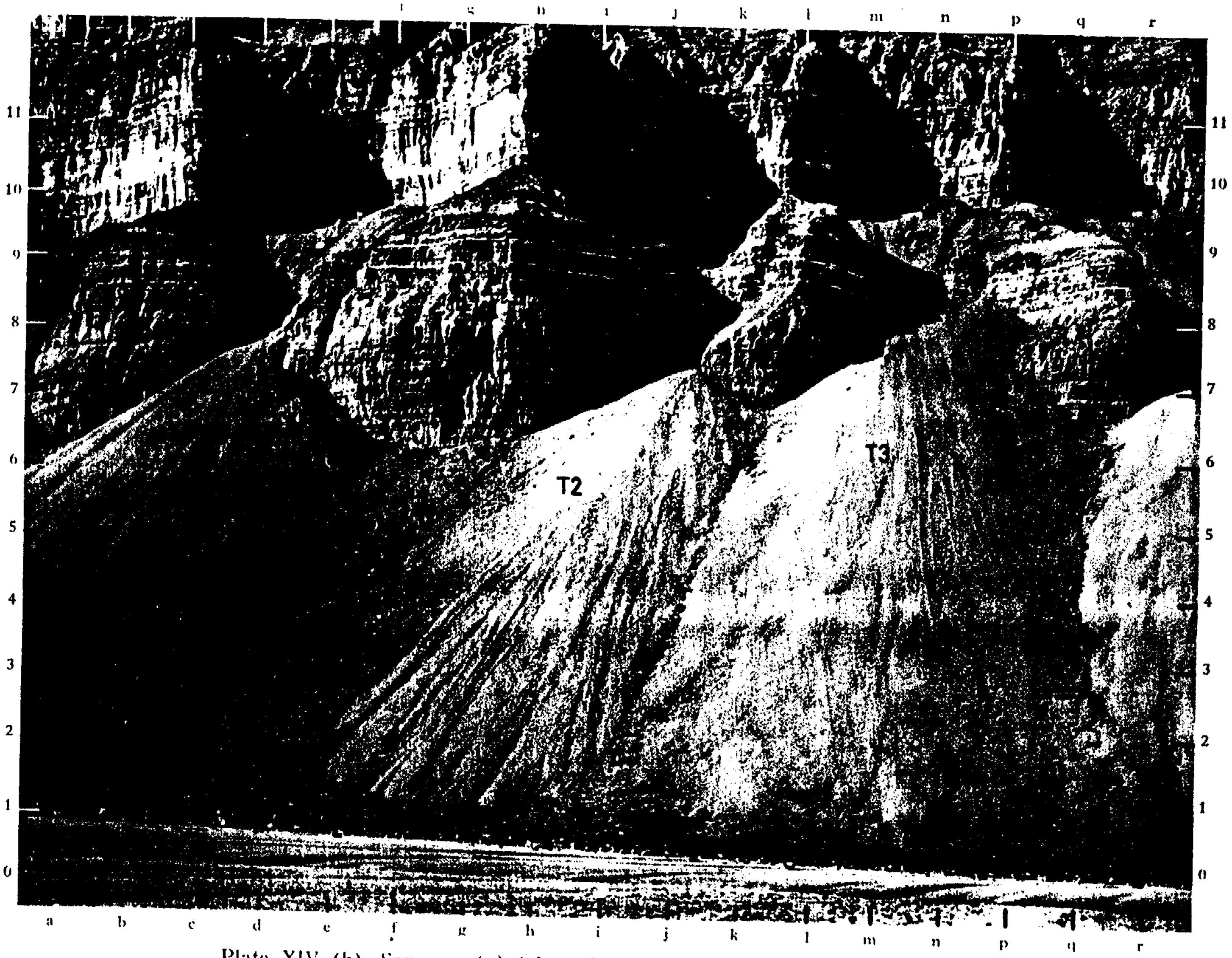


Plate XIV (b). Same as (a) taken closer to the talus base. A. R. 21-7/1954.

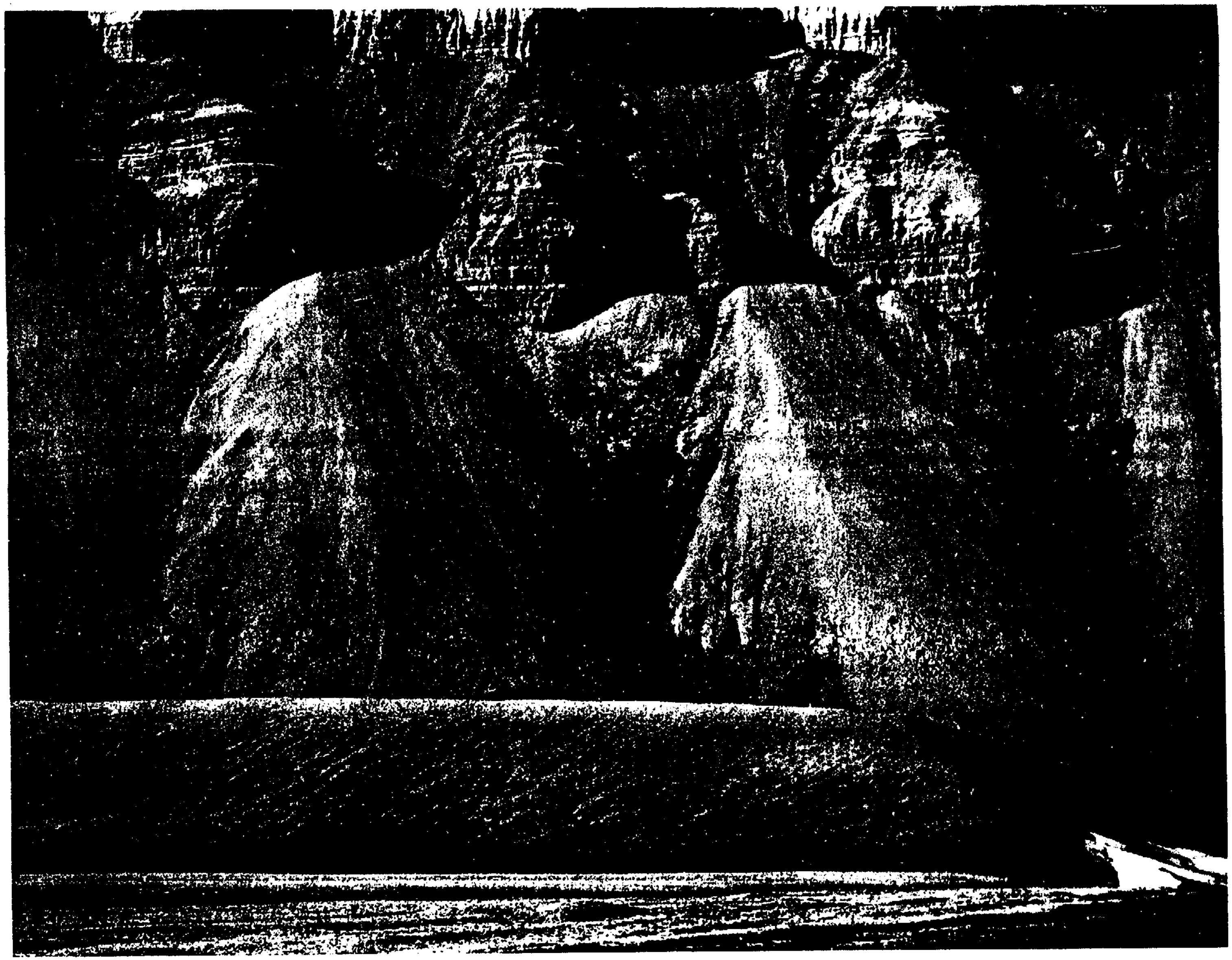


Plate XV (a). Talus cones T3—T5, Bjonahamna. Enlargement from Plate XI. G. de Geer, 19/7/1882.

Plate XV (b). Same as (a). A. R., 21/7/1954.

Plate XVII (a). Talus cones T5—T7, Bjonahamna. A. R., 1954.

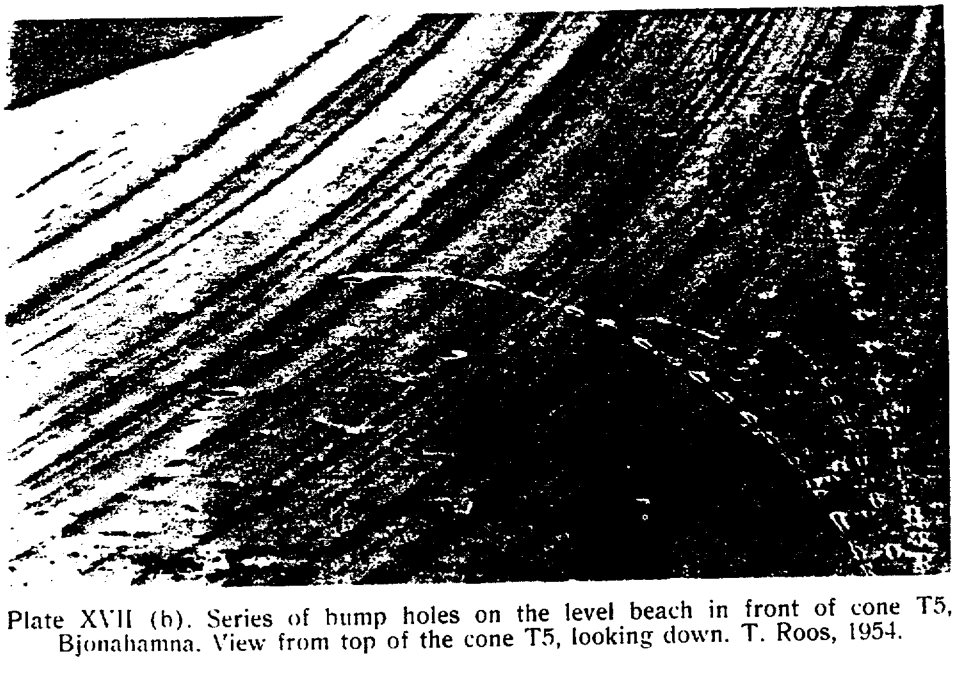


Plate XVII (b). Series of bump holes on the level beach in front of cone T5, Bjonahamna. View from top of the cone T5, looking down. T. Roos, 1954.

Pl. XVIII.

Plate XVIII (a).
G. de Geer
19/7/1882.

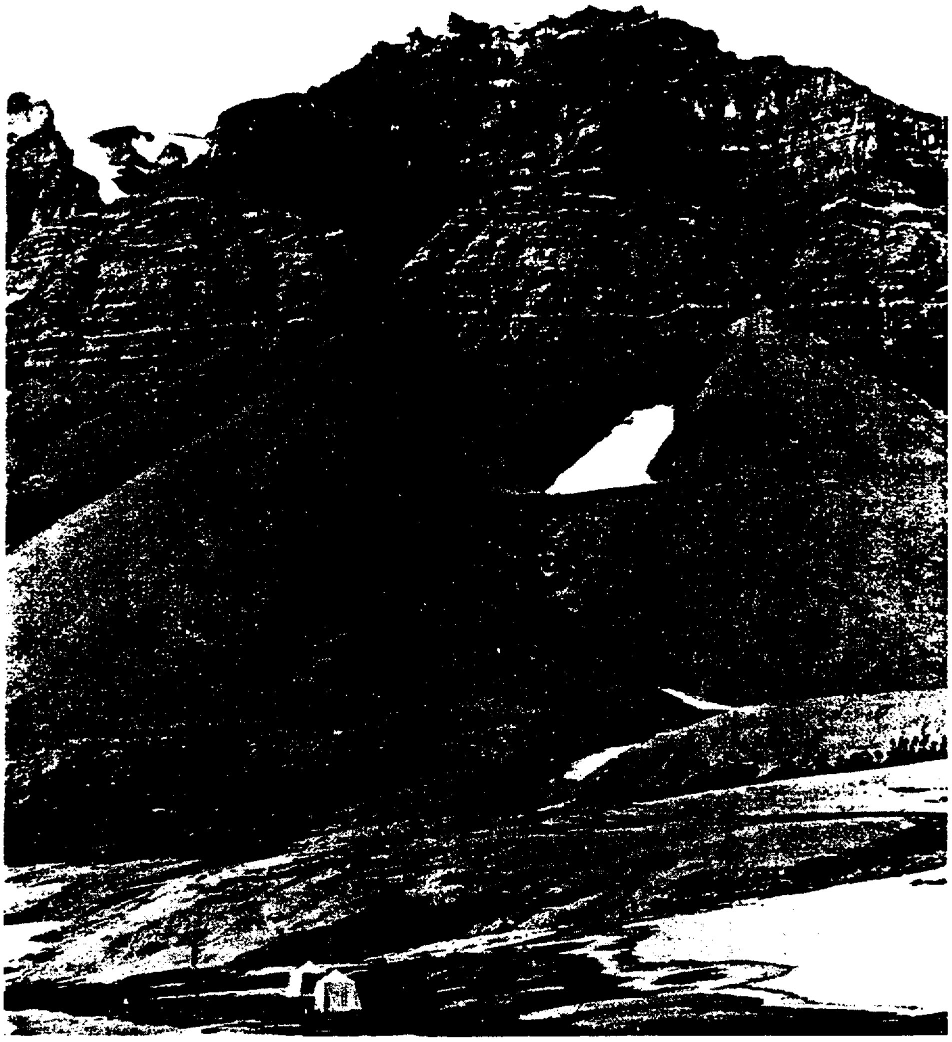


Plate XVIII (b).

O. Halldin 1908.

Pl. XIX.

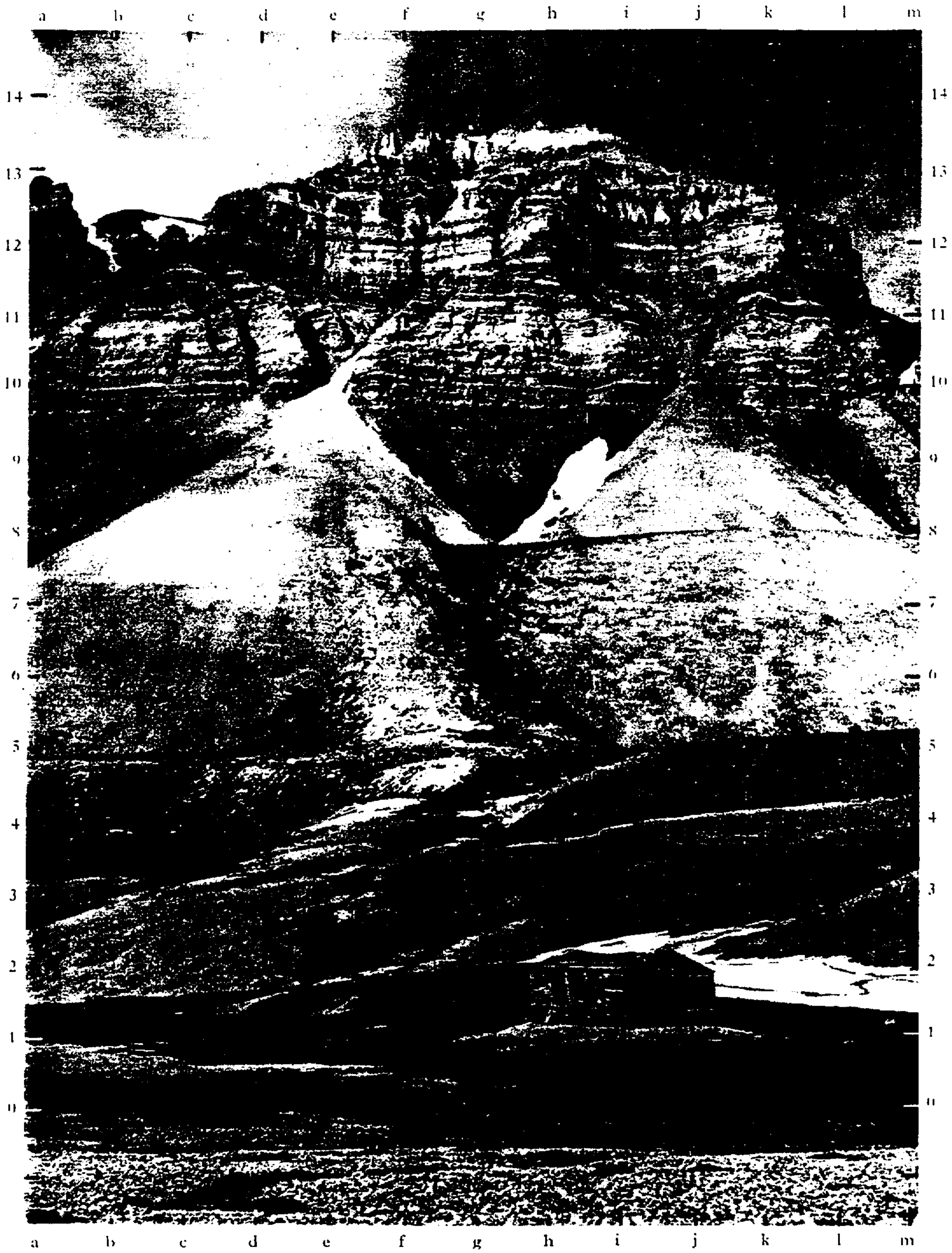


Plate XIX. Talus cones and terrace T8—T9, Bjonahamna. A. R., 21/7/1954.

Plate XVIII (a). Talus cones and terrace T8—T9, Bjonahamna. G. de Geer, 19/7/1882.

Plate XVIII (b). Talus cones and terrace T8—T9, Bjonahamna. O. Halldin, 1908.

Pl. XX.

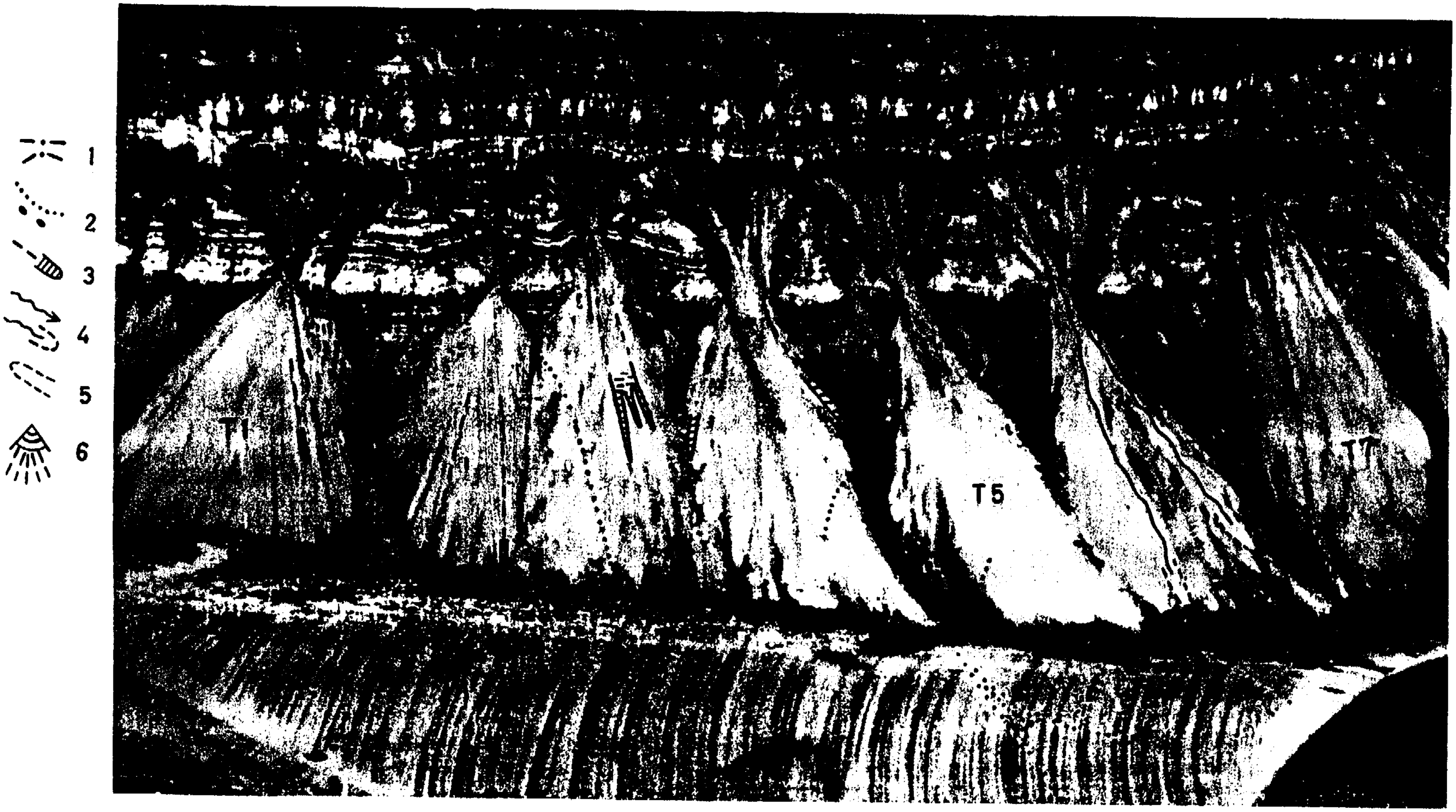


Plate XX. Talus cones T1--T7, Bjonahamna. The various mass-movements that have been observed on the photographs between 1882 and 1954 are marked on this picture. Symbols: 1, new boulders from "fresh" rock-falls. 2, bump holes from "fresh" rock-falls. 3, talus slides. 4, mudflow levées. 5, earth-slide scar. 6, close or scattered cover of "fresh" fallen débris. The photograph is an enlargement of part of Plate I, an air photograph by B. Luncke, 1936.

THIS PAGE IS AN OVERSIZED DRAWING OR FIGURE,

THAT CAN BE VIEWED AT THE RECORD TITLED: SVALBARD SINDBALLEFJELL AT BJONAHAMNA, AND SVALBARD TEMPLET AT BJONAHAMNA WITHIN THIS PACKAGE

NOTE: Because of this page's large file size, it may be more convenient to copy the file to a local drive and use the Imaging (Wang) viewer, which can be accessed from the Programs/Accessories menu.

THIS PAGE IS AN OVERSIZED DRAWING OR FIGURE,

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NOTE: Because of this page's large file size, it may be more convenient to copy the file to a local drive and use the Imaging (Wang) viewer, which can be accessed from the Programs/Accessories menu.

Cation-ratio dating of rock varnish: Why does it work?

Steven L. Reneau, Robert Raymond, Jr.
Earth and Environmental Sciences Division, MS D462, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

ABSTRACT

Cation-ratio dating of rock varnish is an empirical surface-exposure dating method based on decreases in the cation ratio (Ca+K):Ti over time. Although these changes were attributed to the preferential leaching of Ca and K from varnish, the existence of such leaching has not been demonstrated. In varnish collected from the Cima volcanic field, California, distributions of the minor elements used in cation-ratio (CR) dating reflect varnish stratigraphy as defined by the major elements Mn, Fe, and Si. In general, K is associated with Si, Ca with Mn, and Ti with Fe. Because of these associations, variations in CRs both within samples and between samples typically reflect variations in major element composition associated with varnish stratigraphy. No systematic changes with depth or age are present in the ratios K:Si or Ca:Mn as would be expected if K and Ca have been preferentially leached from varnish. Available data suggest that, instead of a leaching process, thickness-dependent changes in the amount of substrate being incorporated into varnish analyses contribute to the empirical trend of decreasing CR with increasing surface age, although further research is required to verify this hypothesis.

INTRODUCTION

Cation-ratio dating of rock varnish, first proposed by Dorn and Oberlander (1981), is an empirical method for estimating the age of a geomorphic or archaeologic surface based on decreases in the cation ratio (Ca+K):Ti over time. As Dorn (1983, p. 50) presented the cation-ratio (CR) dating method: "It is based on minor elements in varnish that are not overly sensitive to factors that affect manganese deposition. The premise of cation-ratio dating is that the leachable cations in varnish, such as Na, Mg, K, and Ca, are gradually replaced and/or depleted relative to less mobile cations, such as Ti. The decreasing cation ratio of Na+Mg+K+Ca:Ti, or any component thereof (e.g., Ca:Ti), provides an indication of the length of time that the varnish has been exposed to cation leaching." Additional assumptions of the dating method are that (1) the manganese and clay components of varnish are not remobilized after deposition, and (2) the accreting varnish has an "initial ratio" that is constant over time in a region and that can be determined from analyses of local dust (Dorn, 1983, 1989).

The method of Dorn and Oberlander (1981) and Dorn (1983, 1989) involves proton-induced X-ray emission (PIXE) analysis of varnish scraped from the substrate. The general trend of decreasing CR with increasing surface age that they reported has been independently replicated by other workers using different methods, including scanning electron microscopy (SEM) analysis (Harrington and Whitney, 1987) and PIXE analysis (Pineda et al., 1988) of intact varnish surfaces.

Despite the success of these different methods in producing similar trends of decreasing CR with increasing surface age, the main premise of the CR dating method—preferential leaching of elements from rock varnish—has not been demonstrated. Except for using the empirical trend as indirect evidence for leaching, the only approach that has been suggested to test the leaching hypothesis is to substitute depth in varnish for age and examine trends in CR with depth. As stated by Dorn (1989, p. 566): "At a simplistic level . . . (K+Ca)/Ti should decrease with greater depth (time) in the varnish." However, Dorn (1989) also noted that such trends are "not always" present, and other workers have failed to find systematic trends in CR with depth (Dragovich, 1988; Krinsley and Anderson, 1989; Raymond et al., 1991).

In this paper we use element distributions within rock varnish to demonstrate that the concentrations of Ca, K, and Ti are not independent of Mn concentration, as originally implied by Dorn (1983), and to argue against significant preferential leaching of Ca and K from varnish. We then explore an alternative hypothesis to explain the empirical relation of decreasing CR with increasing surface age.

SAMPLE SITES

Rock-varnish samples were collected from sites on five basaltic lava flows in the Cima volcanic field, Mojave Desert, California, that range in estimated age from ca. 15–20 to 460 ka (Table 1). At each site the darkest, best developed varnishes were collected in an attempt to sample varnish most closely approximating the age of the flow.

Previous research on Cima varnish has suggested that these varnishes share important characteristics with varnish studied elsewhere. Specifically, Dorn et al. (1987) presented a CR dating curve, partially calibrated using Cima varnish samples, that shows the same trend of decreasing CR with increasing surface age seen for other regions. In addition, Cima varnishes include layers displaying variations in Mn and Fe concentration (Dorn, 1984; Raymond et al., 1991) similar to layers recognized in varnishes in many other areas.

TABLE 1. CIMA VOLCANIC FIELD SAMPLE SITES

Sample site	No. of profiles	No. of analyses	Estimated age (ka)
CIA	12	681	15-20*
CIU	10	501	90 ± 70†
CII	12	840	130 ± 30†
CM3/CIE	23	781	320 ± 90†
CMG	15	1153	460 ± 80†

* Black Tank flow of Wells et al. (1990).
† K-Ar ages with 2-σ uncertainties from Turrin et al. (1985).

ANALYTICAL METHODS

Polished sections perpendicular to the varnish surface were prepared for three samples from each lava flow. Chemical analyses were performed with an ISI-DS130 SEM equipped with a Tracor Northern Series 2 energy-dispersive X-ray analytical system. The analyses utilized Tracor Northern's SQ program, which incorporates internal elemental references and a ZAF matrix correction and provides normalized element concentrations. X-ray spectra were acquired at an accelerating voltage of 15 kV and with 100 s counting times; the 15 kV voltage provides an excitation volume of about 1 μm in diameter. Analyses were typically spaced about 0.5 μm apart along line profiles that extended from the top of the varnish into the underlying substrate; this resulted in about 0.5 μm overlap between analyses. Analyses incorporating substrate were deleted from the data set discussed here. Profiles were selected to sample both thin varnish on substrate highs and thick varnish in substrate depressions, avoiding sites where there was evidence of erosion of varnish.

ELEMENT ASSOCIATIONS IN ROCK VARNISH

As viewed in cross section, rock varnish typically displays stratigraphic layers distinguished by varying concentrations of Mn, Fe, and Si (Perry and Adams, 1978; Dorn, 1984; Raymond et al., 1991). An examination of element distributions in Cima varnish indicates that concentrations of the minor elements used in CR dating are in turn related to variations in major element concentration. Variations in Ca, K, and Ti concentration typically follow variations in Mn, Si, and Fe concentration, respectively. For example, the trend of varying Mn with depth in Figure 1 is strikingly similar to the trend of varying Ca with depth. Similarly, fluctuations in K closely follow fluctuations in Si, and Ti follows Fe (Fig. 1).

The element associations shown in Figure 1 are present in the majority of our 72 Cima profiles, and are clearly evident in plots of all analyses from single rocks (Fig. 2). These associations are also present in plots of average element concentrations in each profile, equivalent to bulk varnish analyses, although more scatter exists in plots of average element concentrations due to the incorporation into varnish of varying amounts of detritus of variable composition (cf. Perry and Adams, 1978; Raymond et al., 1991).

In addition to the associations between minor elements and major elements discussed above, concentrations of Fe and Si in Cima varnish are typically inversely related to Mn concentration (also noted by Dragovich [1988] for Australian varnishes), and the minor elements used in CR dating are thus partially related, either positively or negatively, to Mn concentration. Because of these relations, CR is in turn related to the major element composition of a varnish sample. For the Cima samples, CR shows a slight positive correlation with Mn (and Ca) concentration and a stronger negative correlation with Fe (and Ti) concentration (Fig. 3), and the lowest CRs are thus at spots of relatively high Fe and low Mn concentration. Notably, our Cima sample with the lowest average CR is an Fe-rich varnish from the youngest surface sampled, although the model of cation leaching predicts that varnish with the lowest CR would occur on the oldest surface.

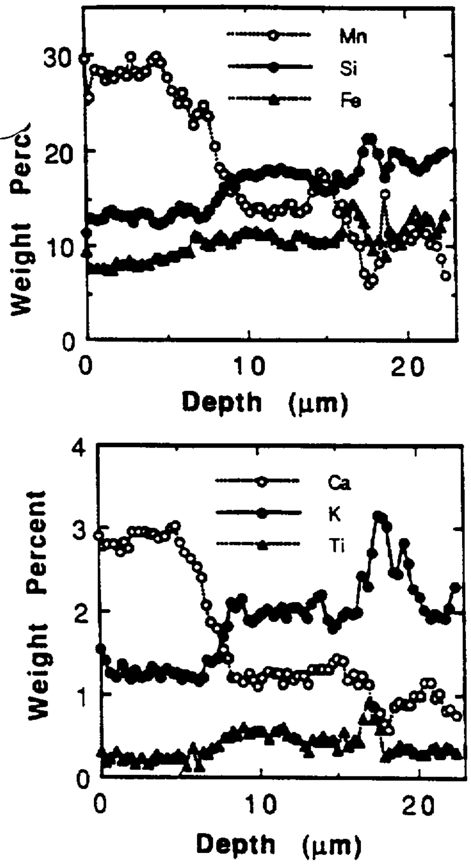


Figure 1. Plots of Fe, Mn, and Si vs. depth, and a, K, and Ti vs. depth for line profile CIE-44-1.

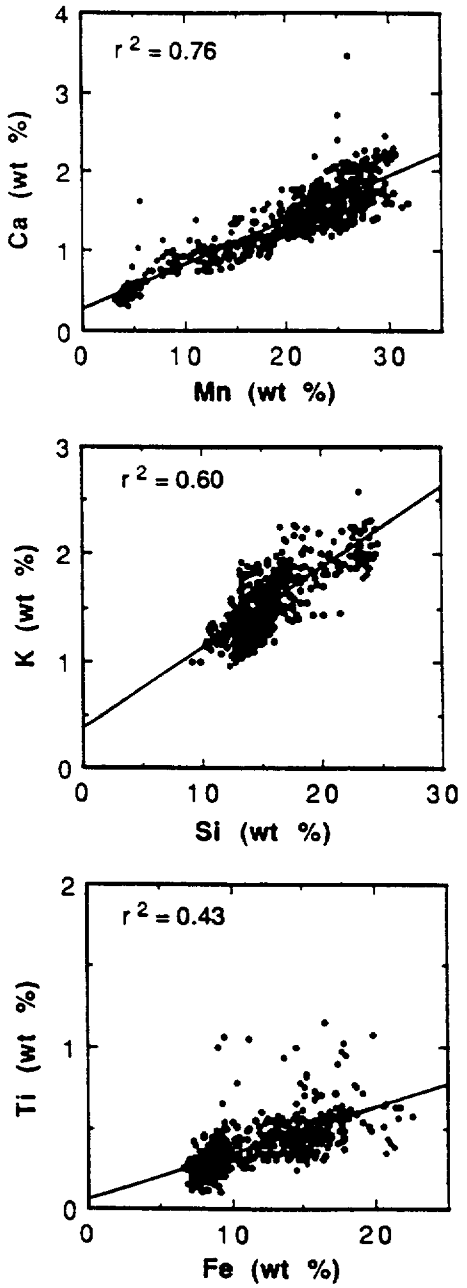


Figure 2. Plots of Ca vs. Mn, K vs. Si, and Ti vs. Fe for sample CII-17, including all 545 analyses from eight line profiles.

CATION LEACHING IN ROCK VARNISH?

The cation-ratio dating method was proposed to work because of leaching of more mobile elements from varnish, but the validity of this model has never been demonstrated. Because the ratio (Ca+K):Ti of a varnish layer is related to the major element composition of that layer, variations in this ratio with depth are related to varnish stratigraphy and thus do not, by them-

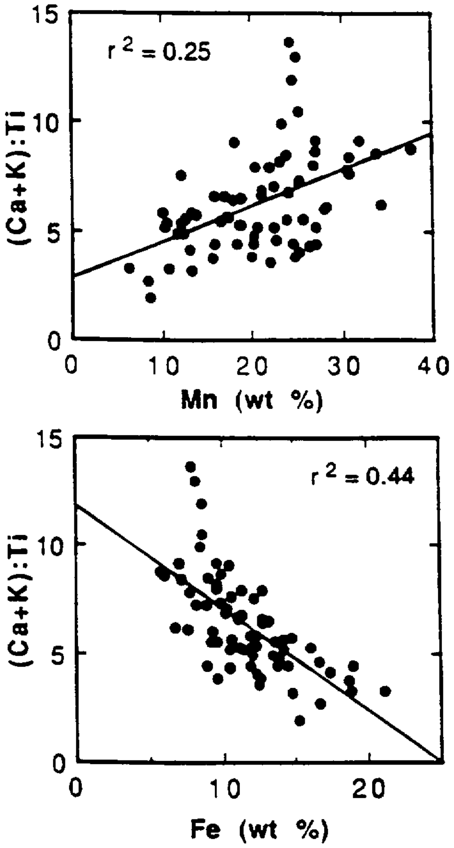


Figure 3. Plots of cation ratios vs. Mn and Fe for average values in all 72 Cima line profiles. Each point is average of all analyses in single profile, and is thus equivalent to bulk analysis of that profile. These averages are most comparable to bulk varnish analyses previously reported from Cima samples by Dorn et al. (1987).

selves, provide evidence for or against the preferential leaching of Ca and K from varnish. Instead, because Ca is generally associated with Mn, and K with Si, if Mn and Si are relatively immobile in varnish (as assumed by Dorn, 1983), then any significant cation leaching should be recognizable by systematic changes in the ratios Ca:Mn and K:Si with depth and with surface age. In particular, the model of cation leaching predicts that the uppermost (youngest) varnish should be the least leached and have the highest relative amounts of both Ca and K.

In our Cima line profiles, there is no evidence for such systematic changes in the ratios Ca:Mn or K:Si with depth in varnish or with surface age, or for consistently higher ratios in the uppermost varnish. Data from the oldest (CMG) and youngest (CIA) sampled surfaces are presented as representative examples in Figure 4. Although there is scatter in these data, Ca:Mn ratios are typically about 0.03 and K:Si ratios about 0.11 for both samples, regardless of depth. Much of the scatter and the differences between samples are related to the varnish stratigraphy. The high Ca:Mn points near the surface of CIA-14 and deeper in CMG-103 (Fig. 4) are associated with low-Mn layers. In these layers additional Ca is commonly present in Ca-rich detritus that is infrequent in the more Mn-rich layers (e.g., Raymond et al., 1991). Similarly, the high K:Si points at depth in CMG-103 reflect K-rich detritus incorporated into Mn-poor layers. In addition, low Ca:Mn and K:Si values at the surface of many samples (e.g., Ca:Mn ratios in CMG-103, Fig. 4) conflict with the prediction that the surface layer is the least leached and highest in Ca and K. In our Cima profiles, Ca:Mn and K:Si ratios near the surface may be either higher or lower than at depth, and no systematic trends are recognized that would support the model of cation leaching.

ALTERNATIVE HYPOTHESIS

Due to the dependence of Ca, K, and Ti concentrations in rock varnish on the concentrations of Mn, Si, and Fe, and due to the absence of evidence for leaching of Ca and K, an alternative explanation is required for the empirical correlation of CR with surface age, one that does not assume an initial CR of surficial varnish that is constant over time and does not depend on leaching. We have examined the effects on the empirical CR trend that may be related to (1) gradual changes in the chemistry of the accreting surficial varnish as microdepressions become filled and as the varnish surface becomes smoother, and (2) the misidentification of Ba in previous analyses of Ti in varnish (cf. Bierman and Gillespie, 1991; Harrington et al., 1991). Our Cima data suggest that neither of these effects is adequate to produce the observed empirical trend. The hypothesis that is most consistent with available data is that the empirical correlation of CR with surface age is a result of the inadvertent incorporation of varying amounts of substrate into varnish analyses.

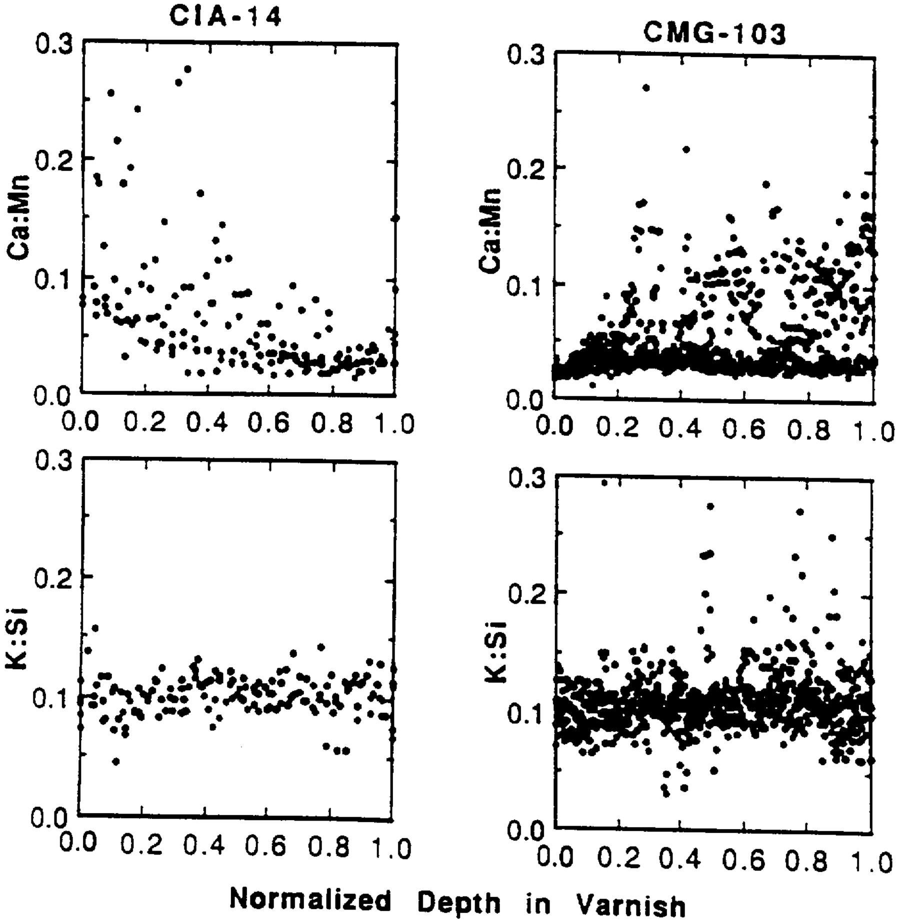


Figure 4. Plots of Ca:Mn and K:Si ratios vs. normalized depth for five profiles through sample CIA-14, including 153 analyses, and for five profiles through sample CMG-103, including 731 analyses. Depths in varnish are normalized to total profile length; base of varnish is set at 1.0.

Some substrate has probably been included in most samples analyzed for CR dating. Microtopographic highs thinly covered with varnish and areas of high local relief along the varnish-substrate interface are particularly susceptible to the incorporation of substrate both during scraping and during SEM analyses. The ratio (Ca+K):Ti is commonly greater in substrates than in varnish, and the incorporation of substrate into analyses thus typically increases CRs. The importance of this addition of substrate should vary inversely with average varnish thickness, relatively more substrate being included in analyses of younger, thinner varnishes than of older, thicker varnishes. As stated by Dorn (1983, p. 58): "As varnish thickness decreases and the surface roughness of the underlying rock increases, the purity of the scrapings decreases." The incorporation of smaller amounts of high-CR substrate in analyses of thicker varnish would provide an apparent decrease in CR with increasing varnish age that is independent of any actual changes in varnish chemistry.

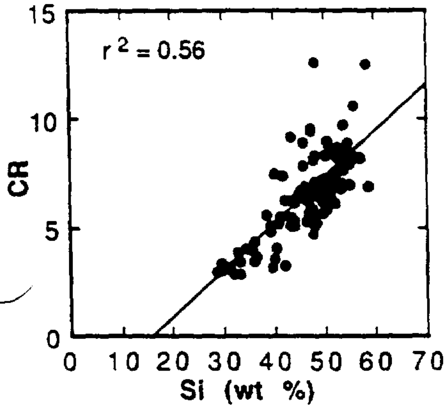
In support of this hypothesis, we have acquired SEM X-ray maps of some varnish surfaces from southern Nevada that were previously analyzed by Harrington and Whitney (1987). The substrate beneath these varnishes is a K-rich, Ti-poor rhyolitic tuff, and CRs for tuff in this area range from 6 to 105, averaging about 45 (e.g., Quinlivan and Byers, 1977), significantly higher than the reported varnish CRs of about 4.3 to 6.0 (Harrington and Whitney, 1987). In the X-ray maps, preferential penetration of the electron beam through thin varnish on microtopographic highs and into the underlying substrate can be recognized (cf. Reneau et al., 1991), and spot analyses confirm that CRs are much higher where such substrate is analyzed than in adjacent areas of thicker varnish. Furthermore, in an examination of the original data that Harrington and Whitney (1987) used to calibrate their CR dating curve, we also see positive correlations between CR and Si concentration and inverse correlations between CR and Mn concentration that are consistent with the incorporation of variable amounts of substrate into their analyses (Fig. 5).

Although the hypothesis of substrate addition into varnish analyses may not apply for varnish on some Ti-rich basaltic substrates where the ratio (Ca+K):Ti is lower in the rock than in the varnish, CRs for Cima basalts (4.6 to 6.0; Turrin et al., 1985; H. G. Wilshire, unpublished data) higher than varnish CRs (0.8 to 4.0) re-ed by Dorn et al. (1987) and used in developing their CR dating curve. The incorporation of variable amounts of substrate by Dorn et al. (1987) may thus have also contributed to their reported empirical trend at Cima.

CONCLUSIONS

The reasons for the empirical correlation of varnish chemistry with surface age have apparently been misunderstood. No evidence for significant preferential leaching of elements from varnish is available at the Cima volcanic field; instead, variations in CR between varnish layers and between varnish collected from lava flows of different age are related to variations in major element concentration. Because of the lack of evidence for leaching, referring to the calibrated dating curves as "cation-leaching curves" is inappropriate, and interpretation of microenvironmental variations in CRs in terms of local variations in leaching environments (Dorn, 1989) is questionable. In addition, because the concentrations of Ca, K, and Ti in accreting varnish are related to major element compositions that vary nonuniformly with time, use of an "initial ratio" that is assumed to be constant over time is not substantiated.

Many uncertainties remain concerning CR dating of rock varnish and the nature of the empirical correlations of chemistry with age. In the absence of significant leaching, mechanisms that cause changes in calculated CRs associated with the increase in varnish thickness over time seem more reasonable. Available data suggest that the empirical correlations may in part depend on the incorporation of varying amounts of substrate into varnish analyses, the percentage of added substrate decreasing with increasing varnish thickness and therefore with increasing age. If this hypothesis is correct, then previous sampling of varnish from compositionally variable substrates has increased uncertainties in the age estimates. Further testing of alternative hypotheses using varnish collected from other areas is required to verify the underlying cause of the empirical correlations of chemistry with age that are the basis for the CR dating method.



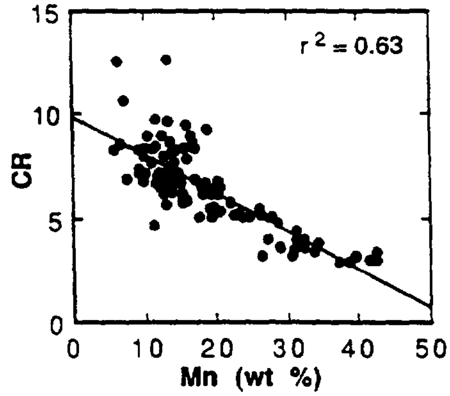


Figure 5. Plots of cation ratios (CR) vs. Si and Mn for surface analyses of varnish from clasts on Crater Flat, Nevada; alluvial surface analyzed by Harrington and Whitney (1987). In contrast to positive correlation of CR and Mn present in analyses of Cima cross sections (Fig. 3), where there is no addition of substrate, inverse correlation here suggests that gnificant amounts of high-CR substrate were cluded in analyses.

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Reviewer's comment

Challenges method (and implicitly, results) of dating geomorphic surfaces [and] archaeological sites [which is] widely used and accepted.
