10. Wave washing phenomena in the coastal district of Norrbotten

By

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1. Introduction

In connection with the survey of Quaternary deposits in Norrbotten (N. Sweden) which is now being carried out, it has been noticed to what an advanced degree the washing action of waves has left its impression on those areas which are situated below HK (the highest shoreline). In large tracts of the coastal district of Norrbotten there occur fairly frequently phenomena of wave washing which have hitherto not been seriously considered as such. There is considerable justification for the statement that wave washing has constituted one of the main factors in the formation of the present Quaternary landscape in certain sections of the area.

The object of the present investigation is to give examples of some of the more distinctive wave washing phenomena which occur in the coastal district of Norrbotten, and which have been pointed out to the author by Dr E. FROMM. Observations have been made in the coastal area between the towns of Piteå and Haparanda, the modern phenomena described in this paper having been observed in the Piteå archipelago.

In conjunction with this investigation, the formation of the esker-like gravel ridges in the country NW. and W. of Avesta (described by E. RYTTERBERG in 1943) has also been discussed.

The field work for this investigation was carried out during short periods in the summers of 1947 and 1948, partly at the same time as mapping work for the Geological Survey of Sweden. For grants towards field work expenses I am indebted to the Section of Mathematics and Natural Science of the Philosophical Faculty at the University of Upsala. As the survey of Norrbotten is not yet completed, I have been fortunate in obtaining the kind permission of the Director of the Geological Survey of Sweden, Prof. P. GEIJER, to publish data and maps prepared in connection with this survey. The author is also indebted to Dr E. FROMM, Stockholm, and Dr N. G. HÖRNER, Upsala, for valuable advice and information, and to Prof. H. G. BACKLUND, editor of this Bulletin, for complaisance in publishing my paper.

2. Present day wave washing phenomena

In order to get some sort of insight into the genetical development, a number of present day phenomena of wave washing — i. e. those met with immediately above the present sea level — have been investigated. The observations have been made within a section of Norrbotten's southern archipelago, 23 km wide and 31 km long, situated E. and SE. of the town of Piteå (see Fig. 1). Before describing the actual wave washing phenomena, a few words about the general topography and Quaternary geology of the area would be appropriate here.

The coastline within this area is very indented with bays and creeks, the majority of which lie in a SE.—NW. direction. Most of the islands and skerries have their longitudinal axes also in this direction. The archipelago is low-lying and gives an impression of comparative flatness: Vargön, which is the largest and at the same time highest island in the group, reaches a height of only about 30 m above sea level.

The flat character of the area continues also below sea level, depths greater than 30 m being — according to the charts — rather rare. Shallow banks at depths between 1 and 5 m are to be found as far as 15 km from the mainland.

On most of the islands and skerries the bedrock is uncovered, forming rock outcrops or groups of outcropping rocks of varying size. In exposed situations these outcrops show fine glacial sculpture with the side of impact mainly on the NW. face. The direction of striae is given on the map (Fig. 1) and varies between N. 80° W. and N. 35° E., with the majority of observations within the range N. 40° W.—N. 25° W. In those cases where it has been possible to determine the relative age of the different series of striae with some degree of certainty, they have indicated, with few exceptions, a clockwise shift in the direction of ice movement.

The largest islands are covered by a sandy till with wave sorted surface

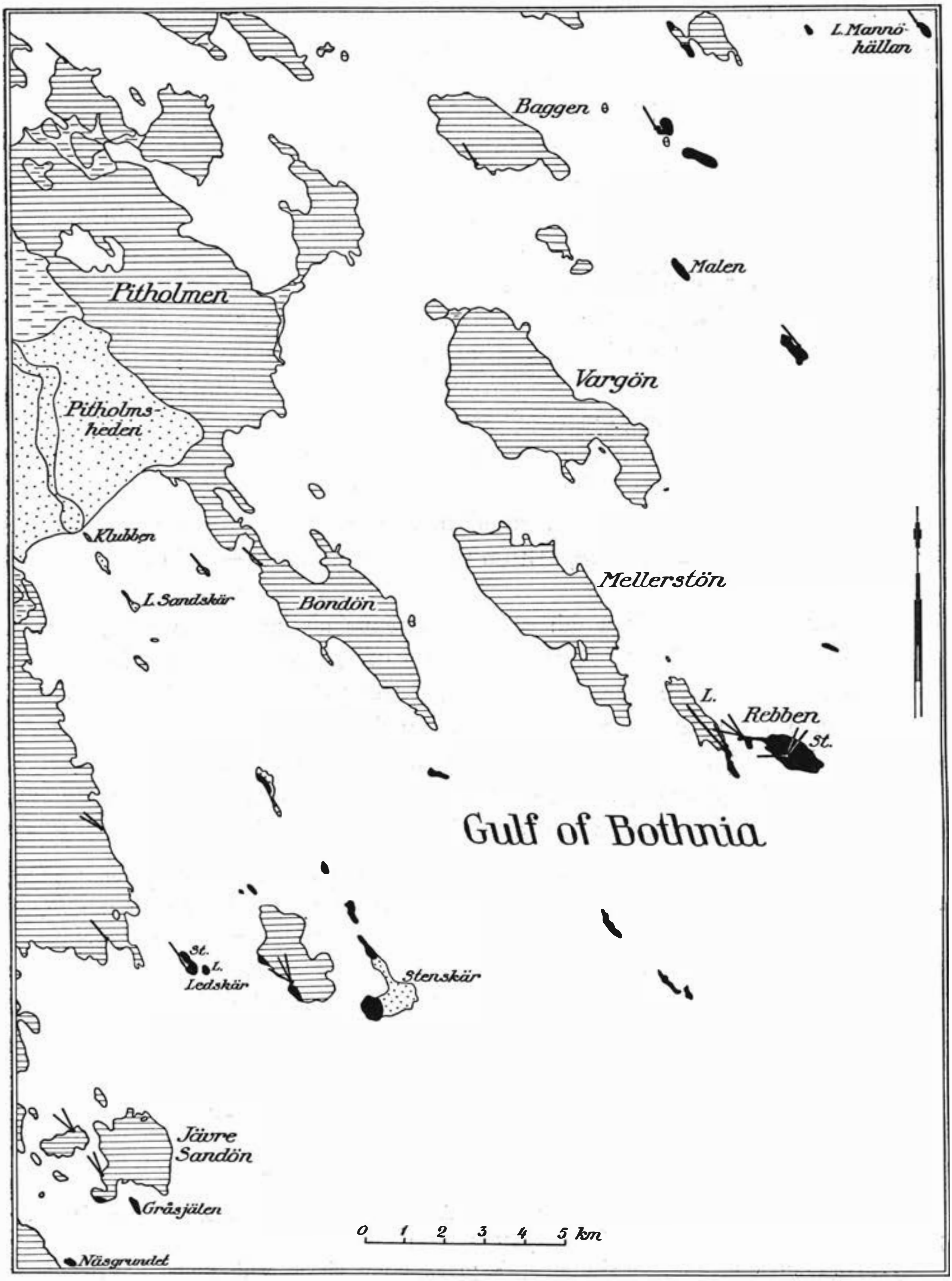

Fig. 1. Map showing localities of shingle and wave washed gravel in the archipelago E. and SE. of Piteå. Black = shingle and wave washed gravel, ruled = till with wave sorted surface layer and solid rocks, dotted = glacifluvial material, hatched = other sediments.

layer. Here and there along the shorelines occur lesser fields of sand, in many localities with traces of recent dune formation.

One of Norrbotten's largest eskers appears out of the sea first as the island of Stenskär, which is built up totally of glacifluvial material. From this island the esker continues in a northerly to northwesterly direction as a chain of islands built up of similar material, until after 14 km it reaches Pitholmen, where it merges into the thick glacial sediments on Pitholmsheden.

Islands built up of shingle and wave washed gravel. On the map (Fig. 1), a row of islands and skerries lying on the extreme seaward side of the archipelago are marked with the sign for shingle and wave washed gravel. All these islands, from Näsgrundet in the S. to L. Mannö-hällan in the N., show characteristic similarities in longitudinal profile and in appearance of and sequence of layers in the surface material.

Before continuing with the description it might be appropriate to give a definition of the terms *shingle* and *wave washed gravel.*

Both these sediments are formed in shallow water, as a result of the breakers working on and re-deposition the parent material — till or glacifluvial material.

Shingle (*"klapper"*) is a fairly homogeneous sediment consisting of well rounded pebbles and boulders[1], which are often worn to a flattish shape. Its dominating particle sizes are between 1 and 3 dm in diam. The sediment always occurs on the surface and usually forms banks and spots devoid of vegetation. Shingle often lies on top of a bed of wave washed gravel.

Wave washed gravel (*"svallgrus"*) is a markedly heterogeneous sediment, as has already been pointed out in the Bergslagen district by G. LUNDQVIST

[1] Four degrees of roundness (well rounded, moderately rounded, slightly rounded and sharply angular) in accordance with HOLMES' scale (1941, p. 1307) are used in this paper The following size classification (ATTERBERG's, 1905, pp. 195—198) is used:

Grade Limits (Diameters)	Name
> 2 dm	Boulders
2 dm—2 cm	Pebbles
2 cm—2 mm	Gravel
2—0.2 mm	Coarse sand
0.2—0.02 mm	Fine sand
0.02—0.002 mm	Silt
< 0.002 mm	Clay

This translation of the Swedish names in ATTERBERG's grade scale diverges in some points from that, published by KRUMBEIN (1938, p. 79).

ATTERBERG's method of size analysis presupposes sieves with round holes, but for practical reasons sieves with square meshes have been used for the analyses in this paper. The ratio between round holes and square meshes is 1:0.8, meaning that, when sieving a hole-diameter of 20 mm in a sieve with round holes is in effect practically equivalent to a meshwidth of 16 mm in a sieve with square meshes (found empirically at the Swedish Road Institute: BESKOW, 1935, pp. 123—124). Therefore the sievings (Fig. 3) are started at 16 mm (corresponding to 20 mm in ATTERBERG's scale).

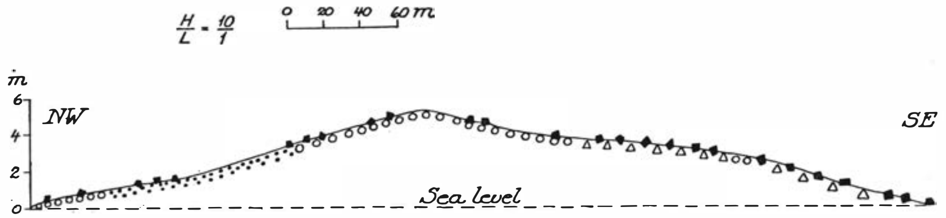

Fig. 2. Longitudinal profile of the shingle and wave washed gravel island Gråsjälen. See Fig. 9 for explanation of symbols.

(1940, p. 55). Its composition varies considerably from place to place, depending on the parent material, environment, and various other factors. The wave washed gravel observed during this investigation contained an assortment of different particle sizes from boulders (up to between 5 and 7 dm in diam.) to fine sand. Wave washed gravel is not usually layered and sorted to any great extent but can in some cases be well layered and sorted. It can generally be seen that the boulders, pebbles and grains of gravel are slightly to moderately rounded. The distribution of the finer particles in wave washed gravel from different localities is apparent from the cumulative curves in Fig. 3: see further the following descriptions.

Let us now return to the shingle and wave washed gravel islands in the Piteå archipelago. The island of Gråsjälen, just S. of Jävre Sandön, can be taken as a typical example for description.

As is apparent from the profile in Fig. 2, Gråsjälen is 490 m long and 5.5 m high, with its longitudinal axis running from NW. to SE. The windward side — i. e. the SE. side which is exposed to the sea — slopes rather less then the leeward side, so that the topographical centre of gravity of the islands is slightly displaced towards NW. The windward side is covered

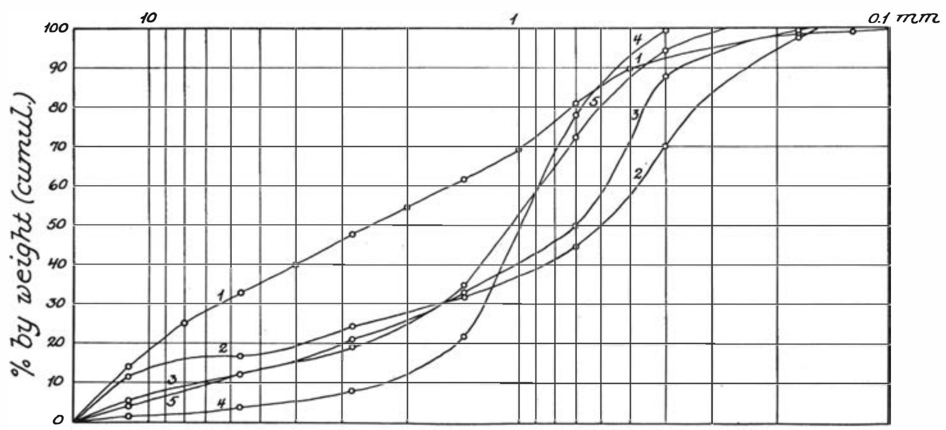

Fig. 3. Cumulative curves from sieving analyses of wave washed gravel. See text.

Fig. 4. The shingle and wave washed gravel island of L. Ledskär. Note the asymmetrical longitudinal profile and the light sediments on the leeward side. — B. Järnefors 1947.

with a drastically washed-out till, consisting mainly of angular and slightly rounded boulders (0.5—1 m in diam.). About 70 m SE. of the island's highest point this till merges into shingle (1—3 dm) which is, however, mixed in places with larger, slightly rounded boulders. The shingle zone covers the crest of the island and continues for about 65 m down the leeward slope, after which it is replaced by wave washed gravel, from the surface of which only a few larger boulders protrude. If one digs under the surface, it becomes apparent that the deeper-lying layers are considerably richer in larger boulders.

Analyses 3 and 4 in Fig. 3 give a good idea of the composition of the surface layer of wave washed gravel (samples were taken 0.5 m under the surface). The fractions "gravel" and "coarse sand" predominate, while almost all the finer particles have been washed away. The grains of gravel show throughout a distinct slight rounding.

A zone of shingle, mixed in places with wave washed gravel, appears again about 15—20 m from the leeward shoreline. It has been found that the sea bottom off the NW. tip of the island consists of sand, at least until 2 m below sea level.

In exposed parts of the shore zone there occur boulders (up to 1.5 m in diam.) in groups of different sizes and, in places, in rows parallel with the shoreline. This collection of boulders has probably come into existence partly as a result of the pressure from solid, and the movement of drift ice (cf S. THUNMARK, 1931, pp. 11—14).

The profile described above, which is particularly characterized by displacement of the topographical centre of gravity towards the leeward side, occurs frequently in smaller islands in positions exposed to the sea in those parts of the Norrbotten archipelago where rocky outcrops are scarce. According to E. FROMM, it constitutes a characteristic feature of the landscape in the archipelago S. and SW. of Haparanda. It has already been mentioned that the Piteå archipelago is unusually rich in rocky outcrops, and this results in the shingle and wave washed gravel islands in this area having an appearance which diverges from the example given above: it is best exemplified by the continous line profile in the diagrammatic sketch Fig. 18 B_2.

The highest point of those shingle and wave washed gravel islands is made up of a large rocky outcrop with the exposed side well rounded and the "leeward" side distinctly plucked by the land-ice. The windward side may consist of a rock-outcrop which is either washed bare or covered with a drastically washed-out till rich in boulders. The leeward side shows, at least in principle, the same succession of layers of sediments as was found on Gråsjälen. Closest to the rock outcrop is a zone of shingle mixed with large boulders: it is followed by zones of wave washed gravel and shingle along the present shoreline.

It is apparent from the description above that it is possible to divide shingle and wave washed gravel islands into two types, according to their morphological development. If there is no core of solid rock, the longitudinal profile is characterized mainly by the displacement of the centre of gravity towards the leeward side. If, on the other hand, there is a core of solid

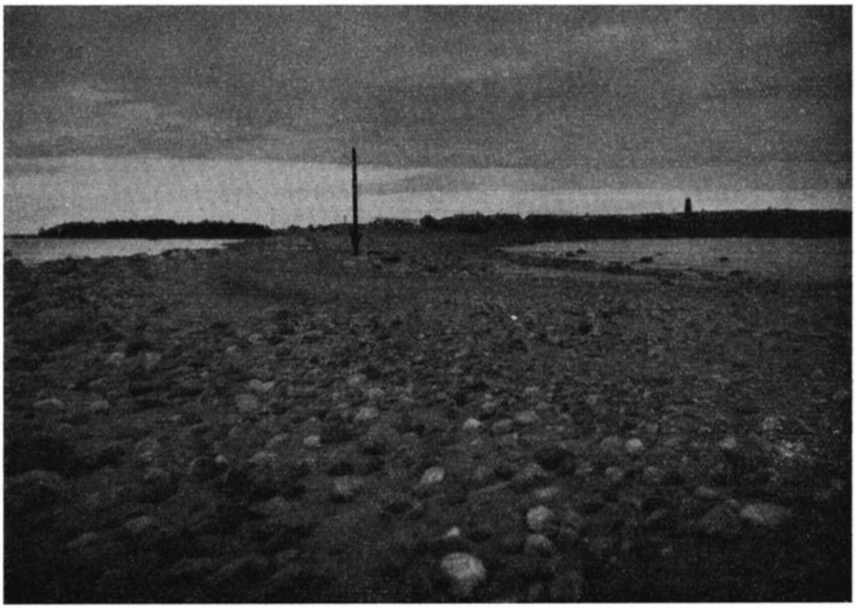

Fig. 5. Saddle-back ridge on the island of Stor-Rebben, seen from W. The arrow indicates the approximate centre of the detail map in Fig. 6 A. — B. Järnefors 1947.

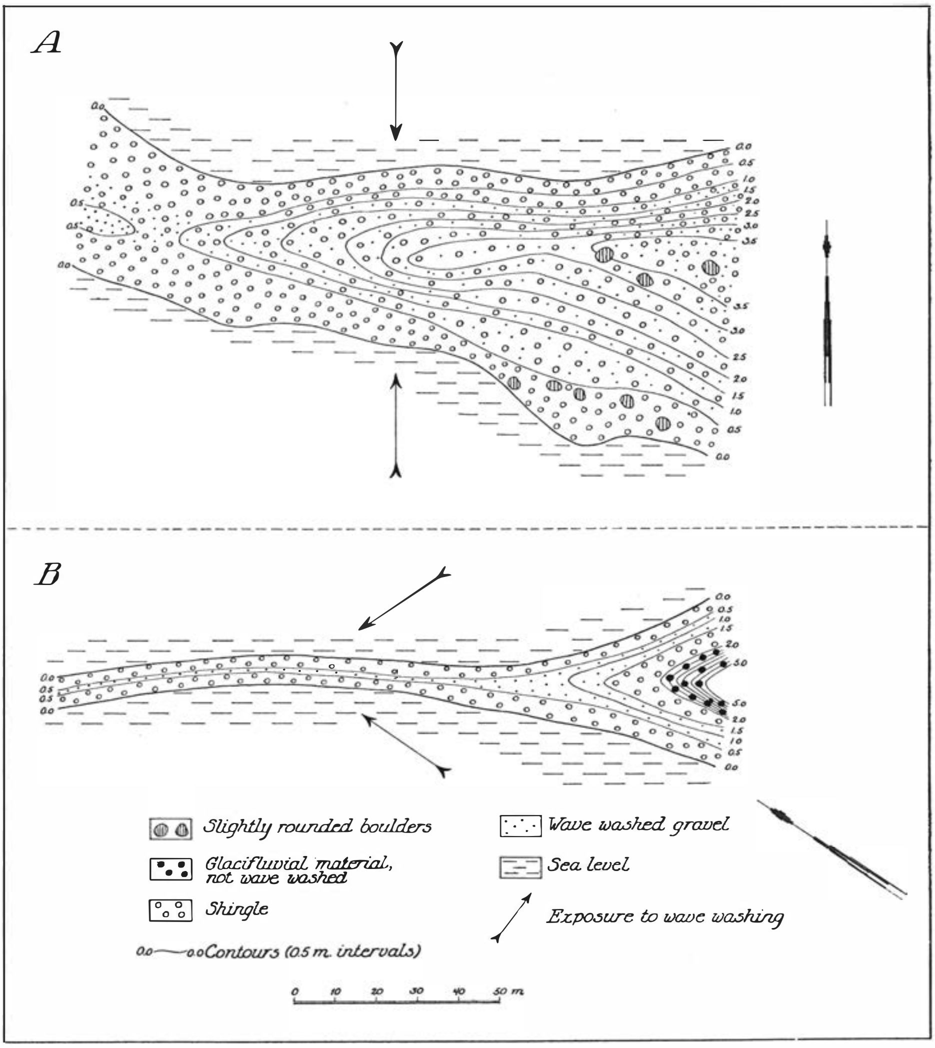

Fig. 6. A. Central part of saddle-back ridge on the island of Stor Rebben.
B. Shoreline spur on L. Sandskär.

rock, the highest point of the profile usually lies closer to the windward than to the leeward side.

The islands within the section of Piteå archipelago which was investigated are exposed to the action of the breakers mainly from N., NE., SE. and S. (see also Fig. 1).

T h e s a d d l e - b a c k r i d g e o n t h e i s l a n d o f S t o r - R e b b e n. Among the modern wave washing phenomena with till as parent material, which have been observed in the Piteå archipelago, there is one which is particularly worthy of mention. The E. and W. parts of the island of Stor-

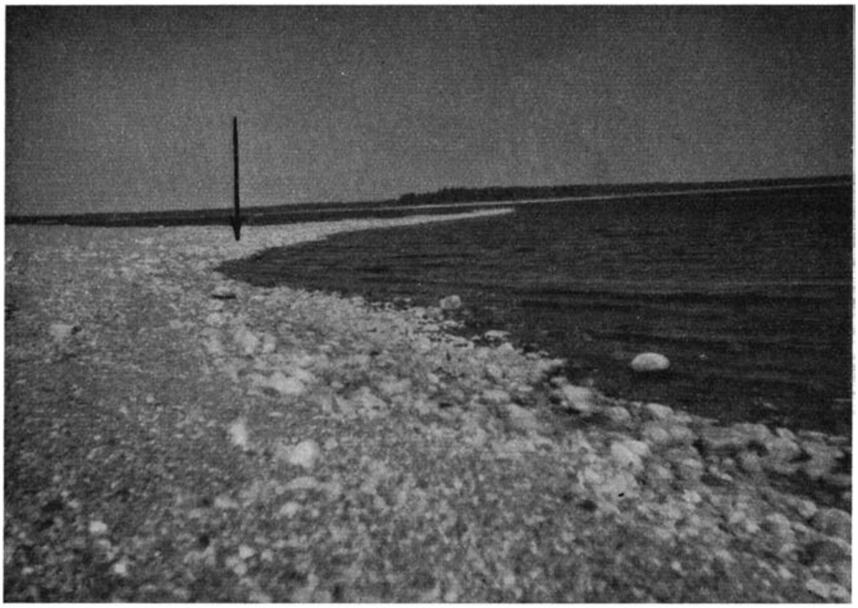

Fig. 7. Shoreline spur on the island of L. Sandskär, seen from E. The arrow indicates the approximate centre of the detail map in Fig. 6 B. — B. Järnefors 1947.

Rebben — situated SE. of Mellerstön (see Fig. 1) — consist of large protruding rocky outcrops. In the saddle between these has arisen a ridge-like formation, about 600 m long and varying between 200 and 35 m wide: from now on this will be called a *saddle-back ridge* (*"passpunktsås"*).

The saddle-back ridge on the island of Stor-Rebben (see Fig. 5) is fairly level and in general symmetrically arched in shape. The width and the height above water level diminish progressively from the E. rock outcrop and, in about the middle of the saddle, the ridge reaches its narrowest and lowest point, after which width and height increase again towards the W. outcrop.

As is apparent from the detail map (Fig. 6 A), which embraces 160 m of the narrowest part of the ridge, the highest point in this section of the ridge is less than 0.5 m above water level.[1] Along the shore and, on the whole, up to the 0.5 m contour extends a zone of completely clean-washed shingle (1—4 dm). Inside this zone the surface layer consists of wave washed gravel mixed with shingle, and here and there lie fairly large, slightly rounded boulders.

The saddle-back ridge is exposed to the action of breakers from two opposite main directions, NNE. and SSE. Such exposure from two directions is hereafter called *double exposure to wave washing*.

[1] The Swedish Meteorological and Hydrological Institute states that the water level at the time of this survey was about 5 cm below normal.

Shoreline spurs built up of glacifluvial material. As was mentioned above, a row of islands built up entirely of glacifluvial material extends from Stenskär to Pitholmen. They are elongated and flatly rounded in shape and attain a height of between 5 and 10 m above sea level. These islands presumably constitute esker centres, which have been brought above sea level by land uplift. Several finely formed beach ridges are usually to be noticed, disposed concentrically around the crest of each island.

The most obvious evidence of modern wave washing here is the presence of long, narrow spurs which often protrude in a NNW. direction from the NNW. tips of the islands. A good example is the approximately 300 m long spur protruding from the NNW. tip of the island L. Sandskär, which lies 3.5 km W. of Bondön (see Fig. 1): part of this spur is shown on the detail map Fig. 6 B and in Fig. 7.

From the 2 m contour and upwards, the triangular base of the spur — which has a plough-like form as a result of abrasion — is built up of glacifluvial material, wave washed only in the surface layer. Below this contour the material has been re-stratified and washed out, and consist of shingle (1—3 dm). A streak of wave washed gravel about 1.5 m wide runs up the centre line of the spur. With the prevailing water level[1], the spur was about 8 m wide all the way out to the rather blunt tip, and the height of the crest line above water level was about 0.7 m.

The spur had a double exposure to wave washing from S. and SE.

3. Ancient wave washing phenomena

The types of present day wave washing phenomena described in the previous chapter have also been met with as older features, i. e. situated above the present sea level, in several localities between the towns of Piteå and Haparanda in the coastal district of Norrbotten. The wave washing phenomena which have been observed lie between 15 and 60 m above the present sea level and between 1 and 10 km from the coastline.

The shingle and wave washed gravel islands in the archipelago have their counterpart in older wave washing phenomena in ridge-like formations, built up mainly of shingle and wave washed gravel and situated in exposed positions on the crest of till and rocky heights. In accordance with a term introduced during the field work by E. FROMM, such a formation will henceforth be called a *crest ridge* (*"krönås"*).

The general position of crest ridges within a section of country W. and N. of Haparanda is illustrated by the schematic map (Fig. 8), which is drawn from the rough draft of the Geological Survey of Sweden's map of Quaternary deposits of Norrbotten, reconnoitred by E. FROMM.

[1] See foot-note 1 on the preceding page.

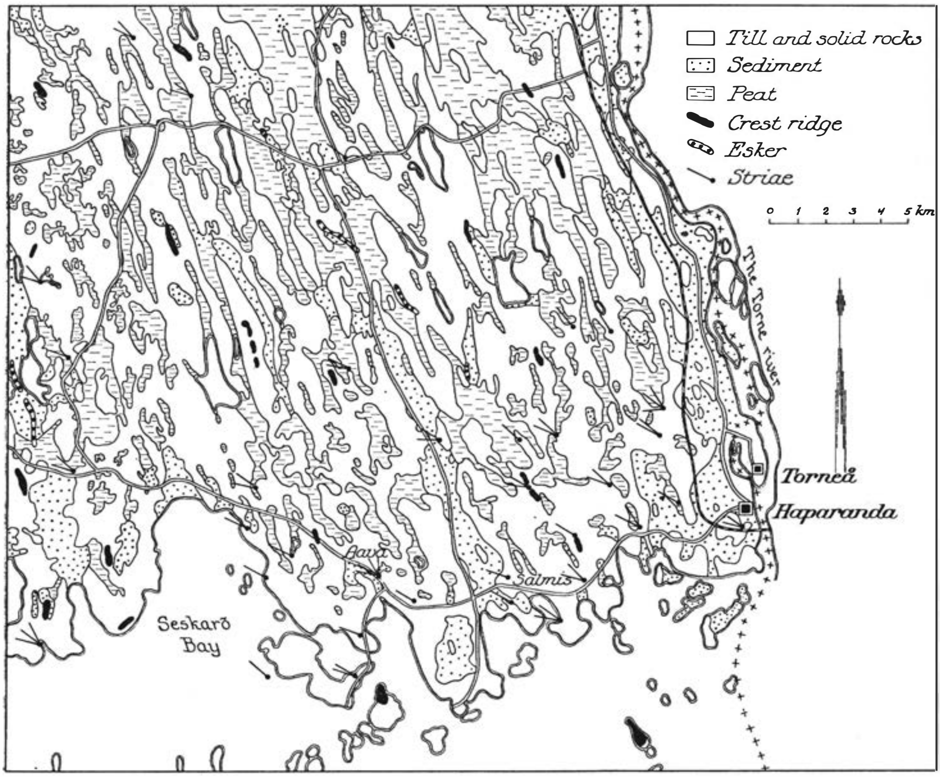

Fig. 8. Schematic map of Quaternary deposits of a district N. and W. of Haparanda. After a rough draft from the Geological Survey of Sweden, reconnoitred in 1946 by E. Fromm.

The area is fairly flat topographically with small relative differences in height, and is characterized by low ridges of till with their long axes generally lying in a NNW.—SSE. direction. The majority of hollows between the heights are filled with peat; the larger dells are covered with Glacial and Post-Glacial sediments. It seems probable that the topographical details of the landscape have been formed by an ice movement both older and of a more N. direction than the WNW.—NW. one which is generally indicated by the striae as observed and marked on the map (cf also G. HOPPE, 1948, pp. 93—96).

About 25 crest ridge formations have been observed within the area, which is about 700 km² in size. The crest ridges always lie on top of till ridges, in situations which have been well exposed to the action of the breakers: their long axes usually lie in a NNW.—SSE. direction, which is characteristic for the topography in general.

The general formation of the crest ridges can now be described by taking some examples in detail; this should also help towards the understanding of their genetical development.

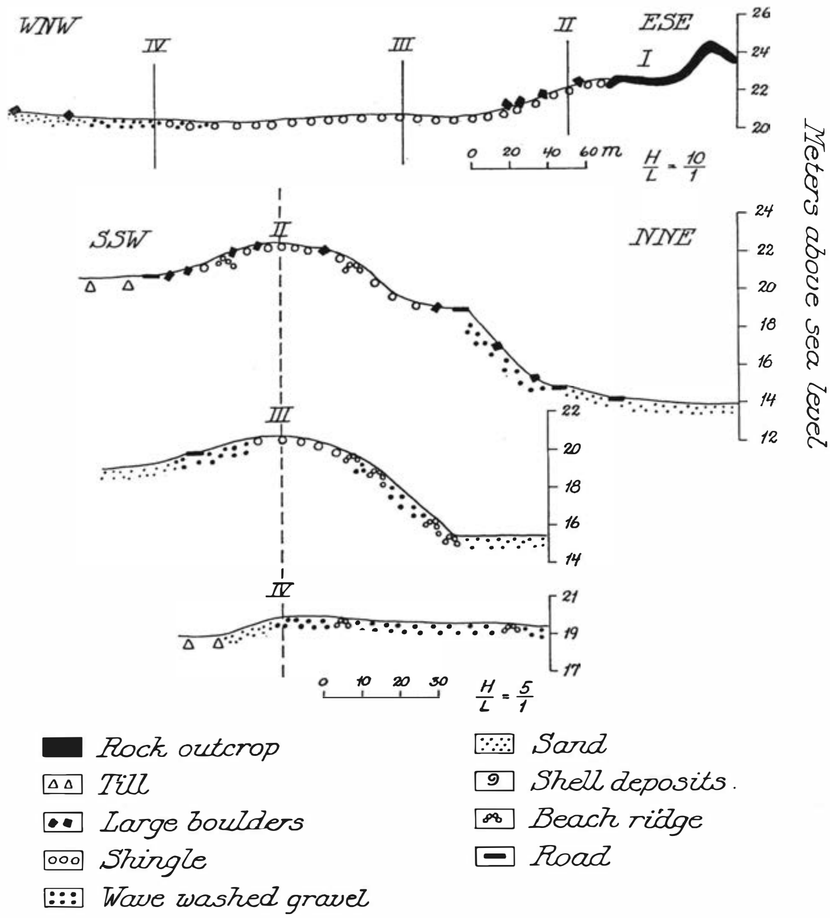

Fig. 9. Profiles of the crest ridge N. of Salmis.

The crest ridge N. of Salmis. About 2 km N. of the village of Salmis (see Fig. 8 and the official topographical map 38. Haparanda N. V.), on the till ridge immediately N. of the 18,79 m point lies a crest ridge extending for about 350 m in a WNW.—ESE. direction. In Fig. 9 are included some profiles of the ridge, which has been surveyed with a Tesdorph's level, starting from the fixed points set down by the Geographical Survey Office.

It is apparent from the longitudinal profile (I) that the crest ridge has been built up in the lee of a large rocky outcrop at the ESE. end. Thus genetically it belongs to the same type of wave washed gravel phenomena as the modern shingle and wave washed gravel islands with a core of solid rock.

For the first hundred meters the crest line of the ridge slopes down very slightly towards WNW., but continues from there almost in the hori-

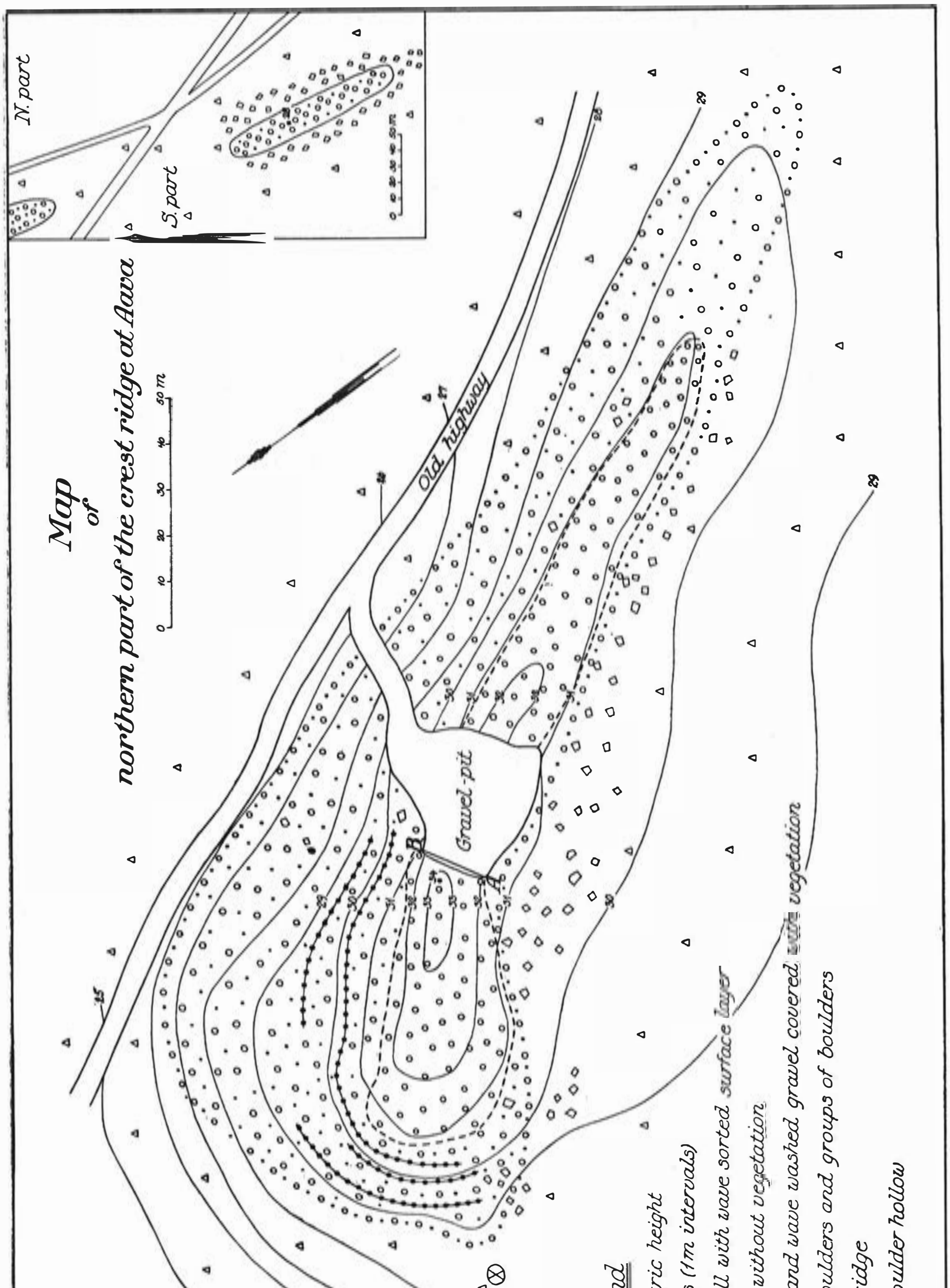
Map
of
northern part of the crest ridge at Aava
50 m
N. part
S. part
Old highway
Gravel-pit
Legend
.00 Barometric height
o~o Contours (1m intervals)
Sandy till with wave sorted surface layer
Shingle without vegetation
Shingle and wave washed gravel covered with vegetation
Large boulders and groups of boulders
Beach ridge
Large boulder hollow

Fig. 10.

zontal plane. For about 240 m in a WNW. direction from the lee side of the rocky outcrop, the crest is paved with shingle with a rich admixture of large boulders close to the outcrop. This zone of shingle merges after a while into wave washed gravel, and at the extreme WNW. the crest is of inconsiderable dimensions and built up of sand.

The transverse profiles (II, III and IV) give some impression of the form of the ridge, which is mainly characterized by the clearly asymmetrical configuration with the flat SSW. slope and the considerably steeper and longer NNE. slope. Profile II, through the crest ridge immediately behind the rocky outcrop, shows that the SSW. side is here not only flatter but is also built up of coarser material — boulders and shingle — than the NNE. slope, which is built up of shingle, wave washed gravel and, at the lowest edge, sand. The first sign of the crest ridge becoming less markedly asymmetrical comes when, after 300 m the ridge is flattened out and fades away towards WNW. (profile IV). Another characteristic of the NNE. side is the series of distinct beach ridges, built up of shingle and wave washed gravel.

The asymmetrical transverse profile of the crest ridge is probably connected to a certain extent with the slope of the underlying ground surface, but must also be considered against the background of the exposure to wave washing prevailing during the formation of the ridge. This exposure has been mainly from the ESE. and has given rise to the formation of zones of sediment in the lee of the rocky outcrop, from coarser (shingle) to finer (wave washed gravel and sand). It is possible that there has also been a severe exposure to wave washing from SE.—SSE., the action of breakers from this direction having resulted in material being washed over towards NNE. and giving rise to the asymmetrical transverse profile. The large boulders in the shingle cover on the SSW. slope of the ridge (profile II) can therefore be looked upon as a residue from this washing.

Analysis 2 in Fig. 3, which refers to a sample taken at a depth of 0.5 m in the wave washed gravel zone, gives an idea of the particle size distribution in this material, from gravel downwards.

Measurements of the direction of striae on the rounded rocky outcrops at the ESE. end have given the result N. 56° W., which indicates that the ice movement has been in the same direction as the long axis of the crest ridge.

T h e c r e s t r i d g e N W. o f A a v a. At the junction between the new and the old highway about 3 km NW. of the village of Aava (see Fig. 8 and the official top. map 38. Haparanda N. V.) lies a crest ridge, the N. part of which is shown on the detail map Fig. 10.

The long axis of the crest ridge runs from NNW. to SSE. Its N. part reaches a width of about 85 m at the N. end. The highest point lies immediately N. of the gravel-pit and is — according to barometric determina-

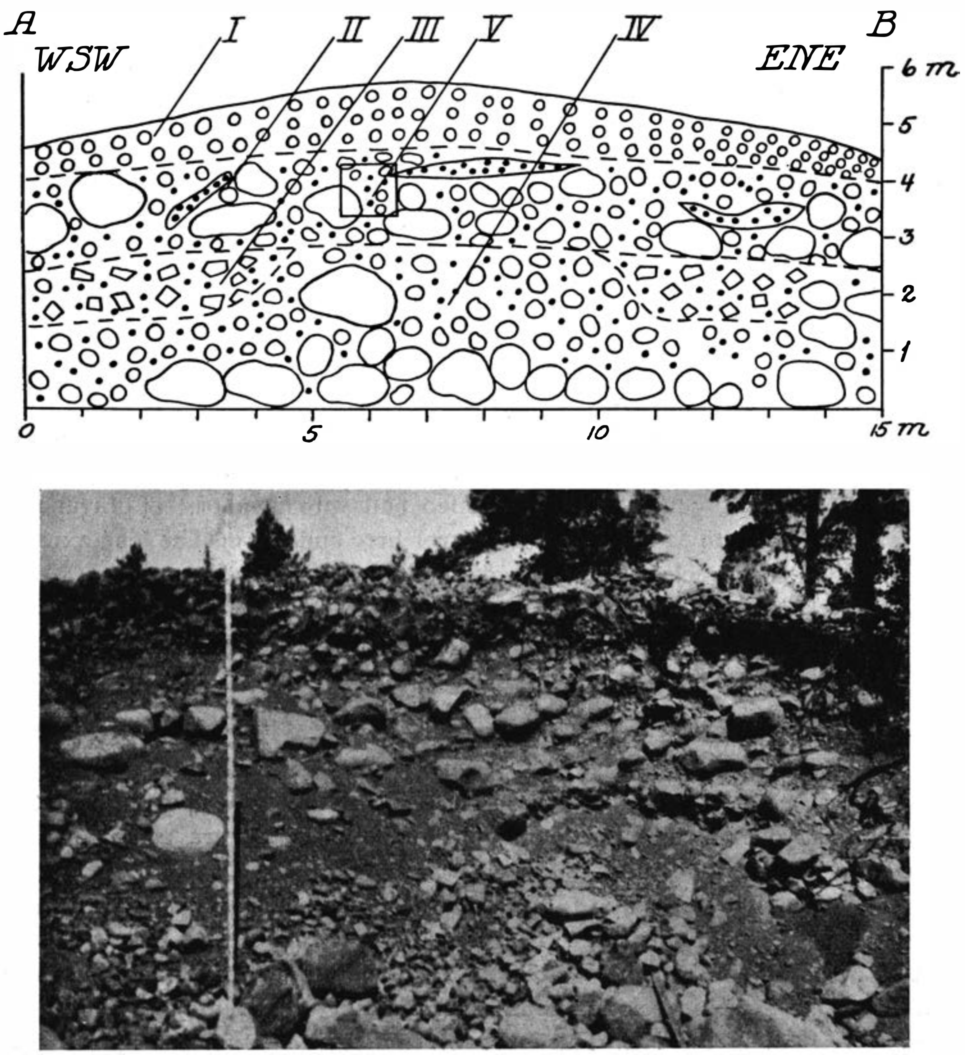

Fig. 11. Sketch and photo of the section A—B (Fig. 10) in the crest ridge NW. of Aava. B. Järnefors 1948.

tion — 33 m above sea level. The longitudinal profile is thus in principle similar to that drawn with a continuous line in Fig. 18 A_2. The crest ridge is not formed in the lee of any rocky outcrop so, genetically, it is of the same type as shingle and wave washed gravel islands without a core of solid rock.

As is apparent from the map, the crest of the ridge is covered with shingle, which forms a small field at the N. end of the ridge. The sides of the ridge consist of shingle and wave washed gravel covered with vegetation. A series of well-formed beach ridges is present in the wave washed gravel round the N. and NW. sides of the crest. A considerable number of sharply angular boulders (0.5—1 m in diam.) are strewn at the base of the ridge W. of the gravel-pit.

The gravel-pit in the middle of the crest ridge gives a good picture of its internal structure. The schematic sketch in Fig. 11 has been made on the basis of a section A—B in Fig. 10 being 15 m long and 6 m high in a nearly vertical wall of the pit. The appearance of the material is further illustrated by the photograph of a part of the same section. The figures on the sketch signify:

I. Shingle covering, particle size between 2 cm and 3 dm, predominating size 1 dm; particles generally well rounded. Particle size diminishes markedly towards ENE.
II. Upper bed of wave washed gravel. Concordant, almost horizontal layers consisting of slightly rounded boulders to 1 m in diam., and pebbles and boulders, generally well rounded and with a matrix of gravel and sand, and with larger veins of gravel here and there. The long-axes of the larger particles usually lie distinctly in a N.-S. direction.
III. Lower bed of wave washed gravel. Horizontal layers of pebbles and boulders, with a dominating particle size of 1—2 dm in a matrix of gravel and sand. The material here is considerably less rounded than in the upper bed of wave washed gravel.
IV. Part of section which has fallen down.

It can be further noted, that, in the wall of the gravel-pit opposite the section just described, the upper layers of pebbles and gravel conform to the arch of the ridge crest.

The asymmetrical shape of the crest ridge is immediately apparent from a glance at the contour lines. The crest line is displaced towards the SW., and the SW. side is considerably flatter than the NE. side, and the base of the ridge is — in relation to the surrounding till country — higher in the SW. than in the NE. This probably indicates — analogously with the case of the crest ridge N. of Salmis — a certain degree of exposure to wave washing, at least towards the end of the formation of the ridge. Powerful breakers have come from the open water of Seskarö Bay in the SW. and S. (see Fig. 8). The boulders W. of the gravel-pit are a residue of this wave washing, even though they have probably been concentrated by the action of solid and drift ice (cf p. 584). The decrease towards the NE. in the sizes of particles in the shingle field of the crest ridge is also indicative of an exposure to wave washing from the SW. The beach ridges round the N. end of the crest ridge have been built up in "backwater" which was rather quieter here, from wave washed gravel which was swept over from the SW.

One should be able to obtain some idea of the exposure to wave washing

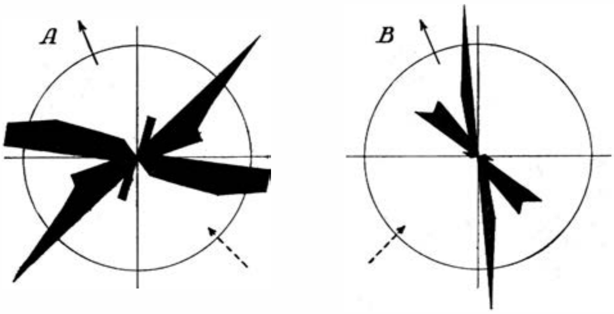

Fig. 12. Analyses of long-axis directions in wave washed gravel. A from the crest ridge W. of Bastunäs, B from the crest ridge NW. of Aava. The continuous arrow indicates direction of the crest ridge's long axis, the broken arrow shows the direction of exposure to wave washing.

which prevailed during the formation of the crest ridge by a study of the direction in which the pebbles and boulders lie. It is reasonable to expect that, due to the relatively slow and rolling movement imparted to them by the action of breakers, the pebbles and boulders will come to rest with their long-axes at right angles to the swell of the waves. G. LUNDQVIST (1948, pp. 15—17, 26) has, in a recently published paper, shown that this assumption is correct in the case of certain shore sediments.

The square area V in Fig. 11 shows where an analysis of long-axis directions according to RICHTER's (1932) method was carried out in the

Fig. 13. S part of the crest ridge NW. of Aava, seen from N. — B. Järnefors 1948.

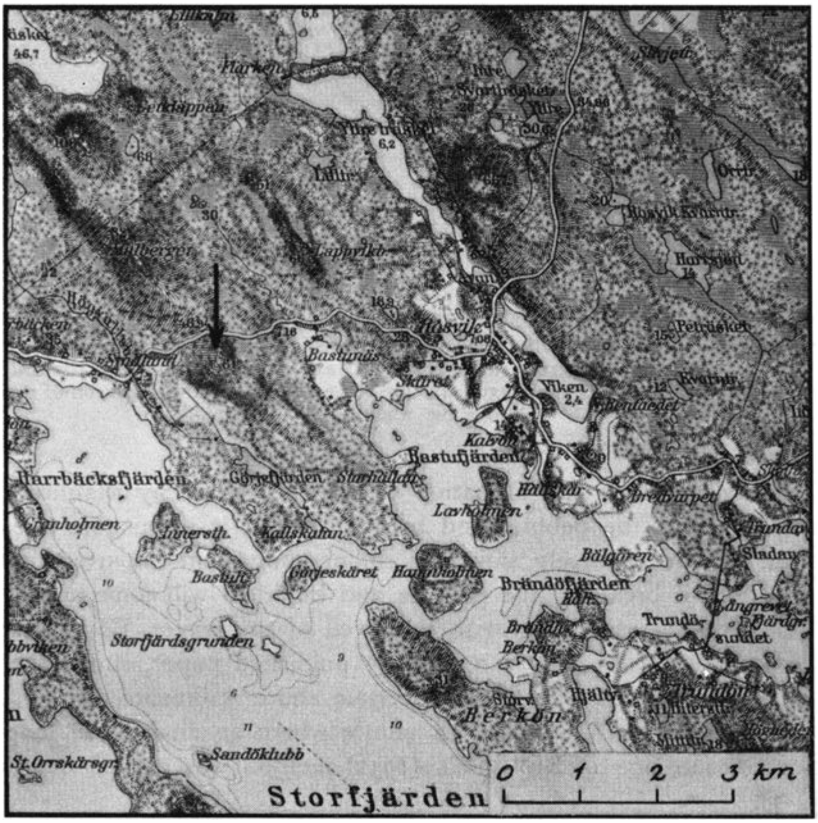

Fig. 14. Detail of the official topographical map, showing the country surrounding the crest ridge W. of Bastunäs. The arrow shows the situation of the crest ridge.

upper bed of wave washed gravel. The long-axis directions of about a hundred pebbles and boulders were determined, the result being presented in Fig. 12 B as a rose diagram of the same type as that used by LUNDQVIST. The occurrence of the secondary maximum in a NW.—SE. direction can possibly be connected with the exposure of the crest ridge, as deduced above, to wave washing from the SW. It must here be noted that a single analysis of long-axis directions in wave washed gravel in a crest ridge can only give a rough indication of the direction in which the depositing wave swell acted. Good results could probably be obtained if the number of analyses made was large enough to permit of statistical treatment.

The S. part of the crest ridge (see sketch in the upper right-hand corner of Fig. 10) has been built up in a completely different manner compared with the N. part. The ridge here is an esker-like formation about 110 m long and between 15 and 20 m wide, which rises 2—3 m above the surrounding level and runs in a NNW.—SSE. direction. The crest and sides are paved with shingle. Both to the W. and to the E. of the ridge lies a belt rich in boulders from 0.5—1 m up to 2 m in diam.

This formation of the ridge can be explained by a double exposure to wave washing from SW.—W. and SE.—E. The boulders lying around the ridge are a residue of this washing, and have been concentrated by the action of solid and drift ice.

The crest ridges N. of Salmis and NW. of Aava were observed in the 1870s by FREDHOLM (1878, p. 66), who assumed that they were a type of shore formation.

The crest ridge W. of Bastunäs. One further instructive example of crest ridge formation — from the coastal district 14 km NNE. of the town of Piteå — can be described here.

About 1400 m W. of the village of Bastunäs the coastal road passes over a till ridge, the highest point of which lies about 60 m above sealevel. On the crest of this rise, a crest ridge has been built up in a NNW.—SSE. direction (Fig. 14). It is apparent from the longitudinal profile (Fig. 15 I) that the ridge is built up in the lee of a rounded, glacially polished rocky outcrop at the SSE. end. This crest ridge thus belongs to the same genetical

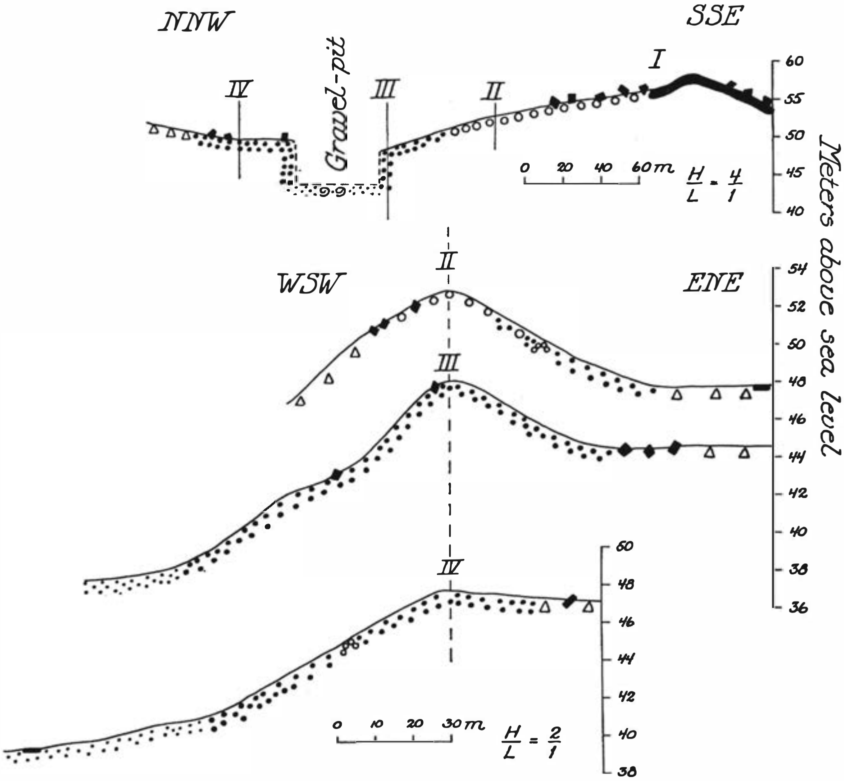

Fig. 15. Profiles of the crest ridge W. of Bastunäs. See Fig. 9 for explanation of symbols.

Fig. 16. Section in the crest ridge W. of Bastunäs, seen from NNW. — B. Järnefors 1947.

and morphological type as the shingle and wave washed gravel islands with a core of solid rock.

Below the outcrop and on its NNW. side, the arched crest is covered with shingle (1—3 dm), out of which large boulders stick up here and there. The shingle zone slopes very slightly in the direction of the crest line and, after about 100 m, merges into wave washed gravel.

A gravel-pit, about 45 m wide and 5 m deep, goes right across the zone of wave washed gravel. The central portion consists of wave washed gravel, richly intermingled with slightly to moderately rounded pebbles and boulders between 1 and 4 dm in diam. (Fig. 16). A certain degree of layering of the coarser material can be traced, as the larger pebbles and boulders appear to be deposited in the same horizons. Between 1.5 and 5 m depth the section has fallen down, and on the bottom lie slightly to moderately rounded boulders up to 0.5 m in diam. Towards the left edge of the section a certain degree of layering is visible in the wave washed gravel, and the boulders have almost totally disappeared.

Analysis 1, Fig. 3 — made on a sample of the smallest particle sizes in wave washed gravel taken at a depth of 0.5 m in the SE. edge of the section — shows that the gravel and coarse sand fractions predominate. The gravel particles are tolerably well rounded.

An excavation in the bottom of the section showed that the layer directly under the wave washed gravel consisted of sand, which contained large quantities of shells of *Mytilus edulis* and *Macoma baltica*. This must be taken as decisive evidence of the fact that the crest ridge was at one time a shore formation.

From this section the crest line rises gradually towards the NNW., the crest ridge becomes flatter and narrower, and the wave washed gravel is replaced by till with wave sorted surface layer.

The transverse profiles (II, III and IV in Fig. 15) illustrate the shape of the ridge. As is the case with the other crest ridges, this one is also asymmetrically built up. The ENE. side of the ridge is always flatter than the WSW. side, and the base of the ridge is higher on the ENE. side. It can thus be assumed here that, at least during the later stages of the formation of the crest ridge, there has been a significant exposure to wave washing from the SE. and E., and this is further confirmed by the fact that the country SE. and S. of the crest ridge is low-lying.

An analysis of long-axis directions of pebbles and boulders in the wave washed gravel in the section has been carried out, the result being presented in Fig. 12 A. The diagram shows a primary maximum in a NE.—SW. direction which, in accordance with assumptions previously made, points to an exposure of the crest ridge to wave washing from the SE.

The saddle-back ridge WNW. of Fällträsk. A saddle-back ridge in non modern situation but of similar genetical and morphological type as that on the island of Stor-Rebben has been observed 26 km N. of Piteå on the till and rock heights at point 63, about 2.5 km WNW. of the village of Fällträsk (official top. map 36. Boden S.O.).

The ridge, which is about 500 m long, is built up in the saddle between two projecting rocky outcrops at the NNE. and SSW. ends (Fig. 17). According to barometrical determinations, the central point of the ridge is 39 m above sea level. The relative difference in height between the tops of the rocky outcrops and the lowest point of the ridge is about 5 m. From the central point, the crest line rises steadily to the outcrops, as was the case with the saddle-back ridge on the island of Stor-Rebben.

The rocky outcrops in the NNE. are glacially polished and rounded on the NE. side, and the lee slopes are plucked and rich in boulders. Immediately to the NNE. of the SSW. outcrop, the crest of the ridge is richly strewn with large boulders up to 2 m in diam., in a belt about 150 m wide.

A section, about 120 m long and 1—1.5 m deep, parallel with the crest in the centre ridge, shows that the ridge is built up of unsorted wave washed gravel with a rich interspersion of slightly rounded to fairly well rounded boulders up to 0.5 m in diam.: here and there occur also slightly rounded boulders up to 1 m in diam. The particle size distribution of the finest material in the wave washed gravel is apparent from analysis 5, Fig. 3, which was carried out on a sample, taken at a depth of 0.5 m in the section.

The saddle-back ridge, which is about 200 m wide at the base of the

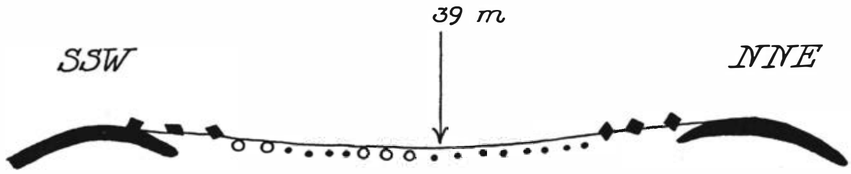

Fig. 17. Schematic longitudinal profile of the saddle-back ridge NNW. of Fällträsk.

rocky outcrops and about 70 m wide in the middle, has an asymmetrical transverse profile. The E. side of the ridge slopes gently (10—15°), and the wave washed gravel merges into till with a wave sorted surface layer. The W. side of the ridge is considerably steeper (20—30°) and longer. Below the base of the ridge the ground continues to slope down in a westerly direction with a gradient only slightly less than that of the W. side of the ridge. The surface layer of the ground here consists of washed-down sand.

The asymmetrical form of the saddle-back ridge and the sand washed down to the W. side of the till slope indicates that the saddle between the outcrops has been exposed to the action of breakers mainly from the SE. and E. This has been brought about by winds from an arm of the sea which covered the low-lying districts SE. and E. of the till heights.

The shoreline spur NE. of Pitsundet. Among the modern wave washing phenomena which have been described are the shoreline spurs built up of glacifluvial material. A non modern shoreline spur formation has been observed on Pitholmsheden about 8 km S. of the town of Piteå and 2.5 km NE. of Pitsundet (official top. map 44. Piteå S.O.).

The Pite esker shows itself here in a massive esker-centre NW. of the island Klubben. The NW. tip of the esker crown is plough-like in shape, and is not very different from that observed on the island L. Sandskär. From this tip a 5 m wide shoreline spur extends for about 150 m; this spur rises about 1 m above the fairly flat, sandy Pitholmsheden, and is built up of shingle between 1—3 dm in diam. The height above sea level at this point is — according to measurements with hand level — 15 m.

This shoreline spur has probably been built up as a result of double exposure to the action of breakers mainly from S. and E.

4. The formation of wave washing phenomena

The fact that it has been possible to observe all the above described phenomena of wave washing in modern formations has made the task of interpreting their genetical development much easier. It is only natural that the field observations hitherto carried out can not lead to a comprehensive account of this development, so only an indication of the main principles will be given here. The question of transport of material by the action of breakers, for example, would probably require thorough studies both in the field and in laboratory for its solution.

The following features are common to the general building up both of the modern wave washing phenomena found in the shingle and wave washed gravel islands in the archipelago and of their counterparts in older formations on the mainland — the crest ridges.

1.) Shingle and wave washed gravel islands always lie in situations that are well exposed to the action of the breakers, and crest ridges always lie in situations that have been thus exposed.

2.) The longitudinal profiles of shingle and wave washed gravel islands and of crest ridges have, in the main, the same form. Two main types of profiles have been distinguished: in those cases where a core of solid rock is lacking, the topographical centre of gravity of the profile is somewhat displaced towards the leeward side. If, on the other hand, there is a core of solid rock present, the highest point of the formation consists of a protruding rocky outcrop, in the lee of which lies wave washed gravel in a long esker-like formation gradually diminishing in size. The topographical centre of gravity is thus displaced towards the windward side in this case.

4.) The material from which the wave washed gravel islands and the crest ridges are built up always shows a striking similarity, both in situation and composition. The coarsest material (large boulders and the larger sizes of shingle) lies on the windward side or, if there is a core of solid rock, immediately in the lee of the protruding rocky outcrop. The finest material (the smallest sizes of shingle, also wave washed gravel and sand) lies farther down on the leeward side, with the finest fractions farthest away. In those cases where it has been possible to study the material in sections, only a certain degree of layering has been evident.

On the basis of what has just been said, together with the descriptions of different examples already given in this paper, the following general remarks concerning the genetical development of shingle and wave washed gravel islands and crest ridges can be put forward.

The parent material is till, which has been deposited by the land ice in the form of long, drumlin-like mounds of till extended in the direction of ice movement, as a drawnout tail in the lee of a protruding rocky outcrop (Fig. 18 A_1 and B_1). The author has found, in the course of the survey, that such a form of till deposition is particularly common in the coastal district of Norrbotten: the type of country which results from this type of deposition is also clearly apparent from the official topographical map (see also Fig. 8). The primary material thus deposited must have been extraordinarily rich in boulders to have been able to give rise to a final material so rich in coarser particles as that from which the wave washed gravel islands and the crest ridges are built up.

The next phase in the development was a land uplift which brought

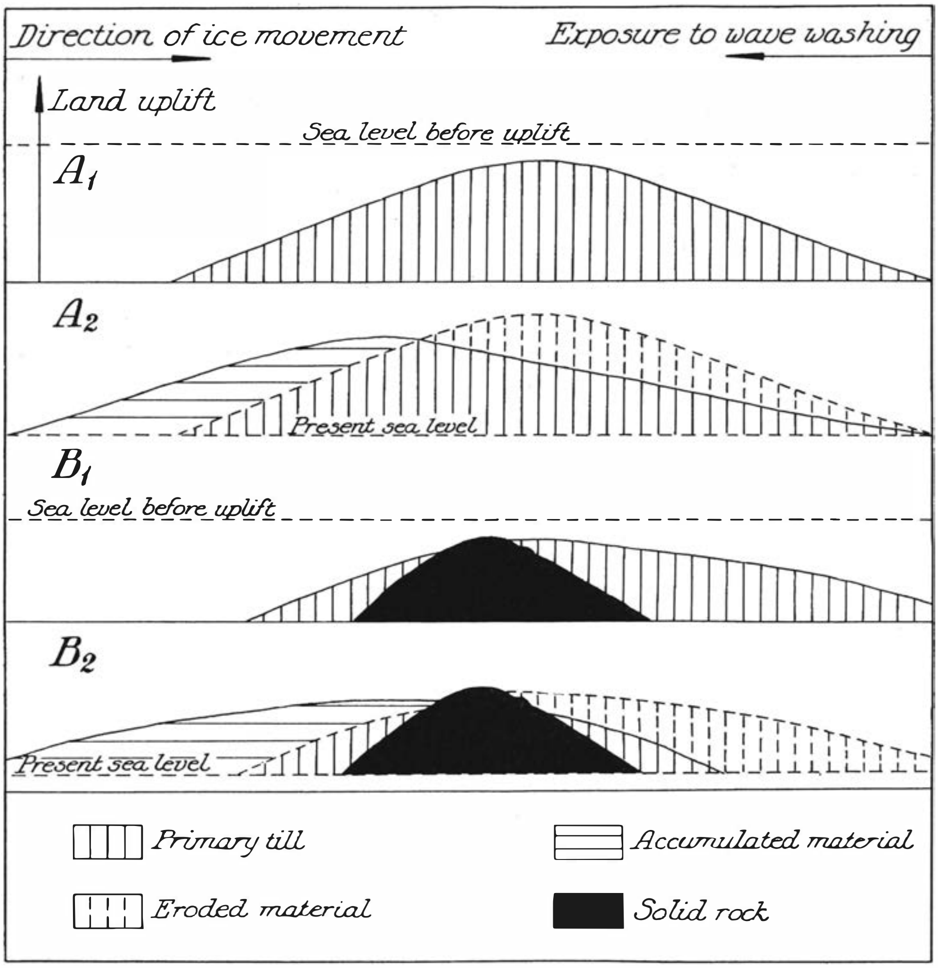

Fig. 18. Schematic sketch showing principle of the development of shingle and wave washed gravel islands.

the primary material to sea level. SW. of Piteå the HK lies at a height of 230—240 m above present sea level (A. G. HÖGBOM, 1899, and H. MUNTHE, 1900) and in Övertorneå between 200—210 m (SANTESSON, 1927), so the depth of water in what is now the coastal district must have been considerable after the land ice had melted. The primary material did not undergo any great change during the relatively long time which this phase took; on the contrary, it was probably preserved and consolidated by the deposition of a protecting layer of Glacial and Post-Glacial sediment.

And so we come to the stage where the breakers begin to work on, re-model and re-stratify the primary material. It has already been pointed out that there are many problems yet to be solved, so only a few general points will be put forward. The eroding and accumulating action of the breakers naturally depends to a very large extent on the laws of dynamics which govern the movements of the waves: it is, however, beyond the scope of this paper to probe further into the question. An outline account of this question has been given by I. HESSLAND (1943, pp. 39—43).

The breakers began to work on the primary deposit even before it came on a level with the water surface. To quote an example of this, KRÜMMEL (1911, p. 112) mentions in his handbook that sand on the Newfoundland Bank can be eroded by the waves at a depth of 20—25 m below the water surface (see also F. P. SHEPARD, 1948, pp. 46—47).

As a consequence of continued land uplift, larger areas of the deposits have been exposed so that the effect of the breakers has been intensified. The primary material has probably first been eroded, after which the eroded material has been accumulated. During these processes the material has been reduced to its present shape and particle size: some material from the windward side has been eroded away and has then been deposited on the leeward side. The longitudinal profiles of the shingle and wave washed gravel islands and of the crest ridges have thus obtained their present appearance. The course of development is illustrated schematically in Fig. 18.

The large, usually sharply angular boulders on the windward sides constitute a residue of the material which has been eroded away. Even on the leeward sides — both in the surface layer and mixed up with the wave washed gravel — can be found boulders, the sharply angular appearance of which indicates that they have not been transported very far. Their presence can probably be accounted for by the action of solid and drift ice. An indication of this is provided by the boulders, often more than 1 m in diam., which are to be found everywhere in exposed situations along the shores of wave washed gravel islands.

How, in detail, has this considerable shift of material from the windward side to the leeward side taken place? Has the material been thrown over the crest parallel with the long axis or has it been transported mainly along the shoreline zone — which has become longer and longer as a result of land uplift? What has been the speed of transport and what is it now? Many factors, such as the velocity, direction and duration of the winds, land uplift, size of material, slope of the sea bottom, etc, play a part in this complex question, which can probably be answered only with the help of careful field observations, supplemented by laboratory experiments. It can be hypothetically stated here that the main transport of material has probably taken place along the shoreline through a phenomenon — caused by the work of the breakers — which D. W. JOHNSON (1919, pp. 94—103) has called "beach drifting". The movement of the waves is often at an angle to the shoreline, so that material is washed up also at an angle. The water running out again, however, takes the material out in the direction

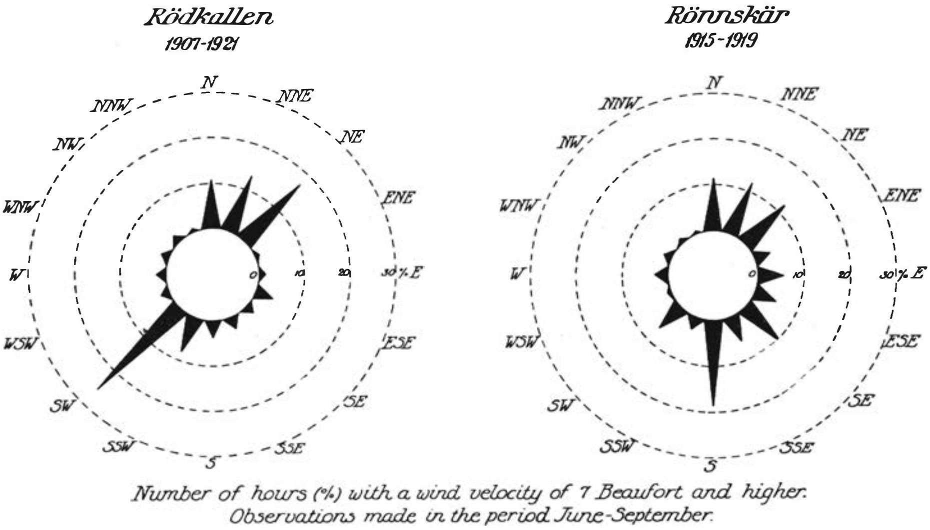

Fig. 19. Wind diagrams from Rödkallen and Rönnskär lighthouses.

of slope of the shore, so that a succession of waves causes the material to be transported along the shore in a zig-zag path. In those cases where wave washed gravel formations lie in the lee of rocky outcrops, the latter show no clear marks — scratches, etc — which might indicate that a large quantity of material had been washed over them: they are certainly polished by the water, but on the whole have a purely glacially polished sculpture.

The absence of any clearly defined stratification in the wave washed gravel in the sections studied is an indication of irregular sedimentation. Judging by the well rounded boulders — often about 0.5 m in diam. — which are to be found in certain horizons, the action of the breakers must at times have been extremely powerful.

Here we come to the question of which winds, as a result of their indirect action through the waves and breakers, can have caused this considerable transport of till material. First, it can be established that these forces of nature have had a substantial period of time at their disposal for this work. BERGSTEN (1930, p. 45) has stated that the rate of land uplift in the coastal district of Norrbotten is at the present time about 1 m per century, so one can — ignoring sources of error such as discontinuity in the land uplift — estimate the time required for the wind and waves to form an 8 m-high island of shingle and wave washed gravel as roughly 1,000 years. It is natural that only winds from a very short period can be accounted for, and some of them have been presented as wind diagrams in Fig. 19. These diagrams have been constituted from C. J. ÖSTMAN's (1922) tables, the readings having been taken at Rödkallen and Rönnskär lighthouses — which lie a few kilometers N and S respectively of the area in the Piteå archipelago which was investigated. Only winds with a velocity of more than 7 Beauforts (more than some 12 m per second) have been taken into account. It is likely that only strong winds, and in particular storms, play any significant part in the transport of material, at least where the largest particle sizes are concerned.

It is apparent from the diagrams that the most prevalent strong winds during the observation periods have come from N., NE., SE., S. and SW., and seem, above all, to have followed the same direction as the coastline. The wave swell caused by these winds has probably been directed at an angle towards the coast — a direction which, according to the assumptions put forward above, would have been particularly advantageous for the occurrence of the wave washing phenomena.

The wave washing phenomena described in this paper are certainly not peculiar to Norrbotten's coastal region, but can be expected to appear in other districts, which are below HK and which have been well exposed to the action of breakers: certain observations from central Sweden also substantiate this assumption.

From the geological map of the Hedemora district, G. LUNDQVIST (1941, pp. 87—88) has described a phenomenon resulting from wave washing, the formation of which probably agrees well — at least in principle — with that of crest ridges. Even in this case, material which the breakers have eroded away from the windward side has been transported to the leeward side, where it has been re-deposited as wave washed gravel. The situation described lies at HK, but the author says that it is apparent that the phenomenon becomes of greater fundamental significance at lower levels.

The same author (1940, p. 58, and 1941, p. 85) has pointed out instances from Bergslagen of the tendency which wave washed gravel has to collect in the saddle between two high points exposed to the action of breakers. True saddle-back ridges of the type described from the island of Stor-Rebben, however, are probably built up only under conditions most favourable to this type of formation.

The gravel ridges NW. and W. of Avesta. E. RYTTERBERG's (1943) description of the esker-like gravel formations in the district NW. and W. of Avesta (S. Dalarna) is of great theoretical interest in connection with the questions which have been dealt with in this paper. According to RYTTERBERG these gravel ridges are formed through sedimentation of material, which has been transported by powerful streams from the melting land ice. G. LUNDQVIST (1946, pp. 81—84) considers, however, that they have been built up through the action of breakers, and after investigations in the district, the author is of the same opinion. A few examples of gravel ridges which have been built up through the action of breakers are given below, after which the observations will be summarized and compared with the state of affairs in Norrbotten. For further details refer to RYTTERBERG's descriptions, profiles and illustrations.

The gravel ridge NW. of Risbyn. This gravel ridge is built up mainly in the lee of rocky outcrops. Its form and the appearance and layering of the material indicate that it has been built up as a result of wave washing from ENE. and ESE. The section in the northern end shows that the material consists of wave washed gravel, which is very similar to that occurring in the crest ridges in Norrbotten. The wave washed gravel is rather unsorted, but certain layers — which dip towards W. — can be observed. Most of the pebbles and boulders are only slightly rounded, but some with a higher degree of roundness do occur. Large boulders, 0.5—1 m in diam., are to be found here and there, and are certainly concentrated through the action of solid and drift ice in the old shoreline zone.

The gravel ridges SW. of Klintbo. The ridges lie in the lee of rocky outcrops which have been washed bare, and which have been exposed to the breakers from E. and NE. The surface layer of the W. slopes consists of wave washed gravel. As is apparent from sections, the particle size of the material diminishes from E. to W. During the period of formation, the material has probably in the main been washed round the N. and S. ends of the rocky outcrops.

The gravel ridge W. of Gåsmyrberget. This ridge has probably been formed through breakers transporting material from Gåsmyrberget round the rocky outcrops in the NW. and SE. The ridge has probably been exposed to wave washing, mainly from the N. and NE. The section in the middle of the ridge (entrance to the stone-quarry) shows tightly packed, slightly rounded pebbles and boulders lying almost directly on the outcrop rock, and thus indicates that the action of breakers has been extremely powerful.

The gravel ridge SE. of Bredmossen. This gravel ridge is very reminiscent of a crest ridge built up in the lee of a protruding rocky outcrop: both longitudinal and transverse profiles resemble those of a crest ridge. The coarsest material lies immediately S. and SW. of the rocky outcrop, and large boulders also remain as a residue from the washing of the waves. The crown of the ridge is paved with shingle and constitutes the so-called shingle zone. The large section in the northern tip shows that the ridge is built up of wave washed gravel which is, however, much better layered and sorted compared with that in the crest ridges in Norrbotten. The pebbles and boulders, which are generally only slightly rounded, indicate relatively short transport, and the varying composition in the different layers points at irregular sedimentation. The gravel ridge has been exposed to breakers mainly from the NE., and it is probable that much of the material has originally come from the till area in the NNE.

In summarizing, it can be pointed out that the esker-like gravel ridges in the district NW. and W. of Avesta have their long axes extended in the direction of the ice movement, which is analogous to the state of affairs in the shingle and wave washed gravel islands and crest ridges in Norrbotten.

The gravel ridges have been built up in the lee, SW. or S. of a protruding, bare-washed rocky outcrop, and thus belong, genetically and morphologically, to the same type as Norrbotten's wave washing phenomena with a core of solid rock. The successively decreasing height from N. to S. gives even the longitudinal profiles a similar appearance.

The appearance and exposure of the gravel ridges indicate that they have been built up through the action of breakers, caused mainly by strong winds from E. and NE. The material has probably not been washed over the rocky outcrops at the windward side to any great extent, but has rather been transported round their ends.

The wave washed gravel in the sections shows, both as regards shape and particle size, a striking similarity to that observed in the crest ridges in Norrbotten: certain differences must, however, be pointed out. The material in the crest ridges is usually more rounded, while the wave washed gravel in the gravel ridges is often better layered and sorted. The sometimes concordant and sometimes discordant pebble, gravel, and sandlayers in the sections through the gravel ridges point to an irregular, but at times intensive sedimentation, which is a characteristic feature of wave washing phenomena of this type.

Where has the material used in building up the gravel ridges in the Avesta district come from? As RYTTERBERG (p. 195) called attention to, the low degree of roundness compared with the material in local eskers, together with the very low occurrence of Älvdal porphyry point to a fairly short transport. It is significant that, E. and NE. of all gravel ridges, there are larger or smaller areas which consist of till, well washed by the waves and often containing many large boulders. Here is almost certainly the parent material of the wave washed gravel in the gravel ridges. The larger collections of boulders may be considered as a residue from wave washing.

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