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KÄRKEVAGGE. SOME RECORDINGS OF MASS-MOVEMENTS IN THE NORTHERN SCANDINAVIAN MOUNTAINS

Abstract

Since 1952 the author has followed the development of slopes in the trough valley of Kärkevagge in Swedish Lappland (fig. 1; pl. 1, 2).

The momentary mass-movements (rockfalls, eroding snow avalanches, mudflows, earth-slides) have been recorded by (1) direct observations, (2) inventories of the fresh debris deposited upon snow at the end of the spring, or (3) upon vegetation in summer, (4) comparison between old and new photographs of the same slope, (5) measurements of the quantity of fresh rockfall debris upon sack carpets.

The more continuous processes (talus-creep, solifluction) have been recorded by checking the annual position of wooden stakes and painted boulders (fig. 5).

In this article some results from three slope sections in Kärkevagge are given. (a) A steep rockwall with a gullied talus, characterized by rockfalls, mudflows and gullying (fig. 3). (b) A steep slope with a small stream, where snow avalanches are important for the morphology (fig. 4). (c) Recording of talus-creep on a talus cone and solifluction on a till-covered slope (fig. 5).

One of the excursions of the Abisko Symposium in 1960 was devoted to deglaciation morphology (cf. Holdar 1957) and recent slope processes in the valley of Kärkevagge. This is a trough valley, about 5 km long, situated 8 km SE of the railway station at Riksgränsen (lat. 68° N) near the frontier between Sweden and Norway.

Kärkevagge has been chosen as a type area for detailed continuous recordings of the actual development of slopes in the northern Scandinavian Mountains (the Scandes). These studies were started in 1952 and have been carried out mainly in accordance with the recommendations made by the I.G.U. Commission for the study of slopes (cf. Macar & Birot 1955, p. 14 f). Similar studies are also in progress elsewhere. We may for example refer to the excellent work of Starkel (1959, a. o.) from the Polish Carpathians.

In this article some recorded mass-movements (rockfalls, mudflows and gullying, dirty snow avalanches, talus-creep, solifluction) in Kärkevagge are described and discussed as representative examples of geomorphic processes in high-latitude mountains. A more detailed thesis on the work in Kärkevagge 1952—1960 is in preparation (Rapp 1961).

GENERAL DESCRIPTION OF THE VALLEY

Anyone who wishes to follow the actual denudation on slopes within a restricted area would do well to choose a place with a rapid development. That was what we expected to find in Kärkevagge, where the general climate, the steep slopes, the rocks, the soil and the vegetation conditions probably are favourable to a comparatively rapid denudation.

The mountains bordering the valley are the plateau-like Mt. Vassitjåkko to the west (1 580 m) and the smooth-ridged Mt. Kärketjårro to the east (1 400 m). The valley bottom rises from an altitude of 650 m at the mouth to 800 m in the innermost, cirque-like end at Lake Rissajaure. There are steep rock-walls both on the western and the eastern sides. The highest parts of the walls consist of fairly resistant, nearly horizontal beds of mica-schists with large garnets. It is not unusual to find *roches moutonnées* with glacial striae in these rocks above the walls in the "frost-shatter zone" and the "tundra zone" (terms translated from Büdel 1948), indicating that the postglacial destruction by frost-shattering must not be overestimated even in these zones. Lower down in the walls there are other types of grey mica-schists and black, phyllitic mica-schist. The latter rock weathers easily. In the lower parts of the walls there are also limestone (marble) beds and under these there occur "hard-schists" (banded quartzose and slaty schists, cf. Kulling 1960, p. 44).

On the eastern and north-eastern sides of Mt. Vassitjåkko are two regularly formed cirques with small, dying glaciers at altitudes of 1 100 m and 1 200 m.

The cirques and the recent small glaciers and snowfields are facing east or northeast, which is a general condition in large parts of the Scandes because of the dominant snow drifting predominantly from the west and the accumulation of snow on the lee slopes.

A small glacier cap occupies the southern part of the top plateau of Mt. Vassitjåkko above 1 400—1 500 m.

Some information on temperature and precipitation within the district is given by the values from the nearby weather station at Riksgränsen (altitude 500 m):

Table I

Mean monthly temperatures at Riksgränsen 1939—1953 (after Ekman 1957, p. 18)

J	F	M	A	M	J	J	A	S	O	N	D
−10,9	−10,9	−8,8	−3,8	+0,8	+6,9	+11,0	+9,3	+4,9	−0,2	−5,1	−7,7

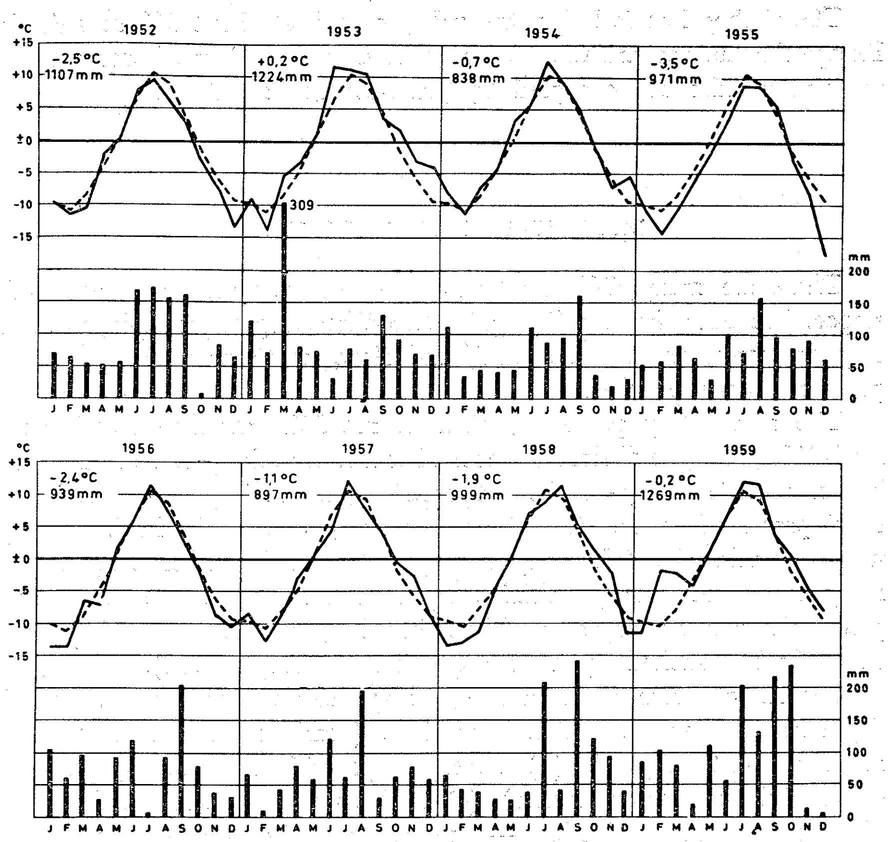

Fig. 2. Graphs of air temperature and precipitation at Riksgränsen, 1952—1959

Dashed curve shows monthly mean temperatures 1901—1930, fulldrawn curve the actual monthly mean temperatures. Mean annual temperature and annual precipitation are given in the upper, left corner of each square. Compiled by the author from the Swed. Met. Hydr. Inst. Yearbooks 1952—1959

The annual precipitation is about 1 000 mm (see further fig. 2 and Rapp & Rudberg 1960, figs. 1 and 2).

Along the foot of the rockwalls are talus slopes from 50 m to 300 m high, mostly formed as simple slopes but in some cases also forming talus cones. The talus slopes on the more "sunny" eastern side are more covered with vegetation (*Dryas*, grass etc.) than on the western side. Below the talus in section A and C (fig. 1) there are wet slopes with solifluction lobes. On the eastern side there is no corresponding solifluction zone but drier meadows upon old, gullied alluvial fans etc. below the talus (cf. fig. 3).

The timber line is below the valley mouth at about 510 m altitude. Except for the accumulations of big boulders (pl. 1) the lower parts of the valley sides are occupied by grass-covered meadows.

MOMENTARY MASS-MOVEMENTS

There are many different transport processes working on mountain slopes. We can primarily distinguish two different groups: rapid, momentary processes, on the one hand, and slow, continuous or long-lasting processes, on the other.

The momentary processes, such as rockfalls, mudflows, avalanches, land-slides, etc., are difficult to record because of their sporadic occurrence. But nevertheless they can be supposed to play an important role in the development of slopes. One of the purposes of the studies in Kärkevagge was to examine the different types of processes, their influence upon slope morphology and their quantitative importance. In this article some examples of the first two aspects will be referred to, but the quantitative aspect can only be touched upon here (see further Rapp 1961).

Recordings from three different slope sections will be discussed: (a) a rockwall and a gullied talus slope (combined action of rockfalls, mudflows and gullying), (b) a steep slope with a stream (geomorphic effect of dirty snow avalanches), (c) a talus slope and a solifluction slope (talus-creep and solifluction — see further below under "Continuous Mass-movements", p. 299).

ROCKFALLS

Rockfalls occur in mountains of all latitudes and the most fundamental, most rapid and simple transport process on steep walls. Many large rock--slides have been described and mapped (Heim 1932 and others) but this is not the case with the smaller and more numerous rockfalls. Yet the smaller falls are also worthy of study, primarily perhaps from a quantitative point of view, but also from that of their principal erosion and deposition forms, etc.

A typical rockfall in Kärkevagge is described below and later on compared with other types of mass-movements from the same slope, shown on fig. 3.

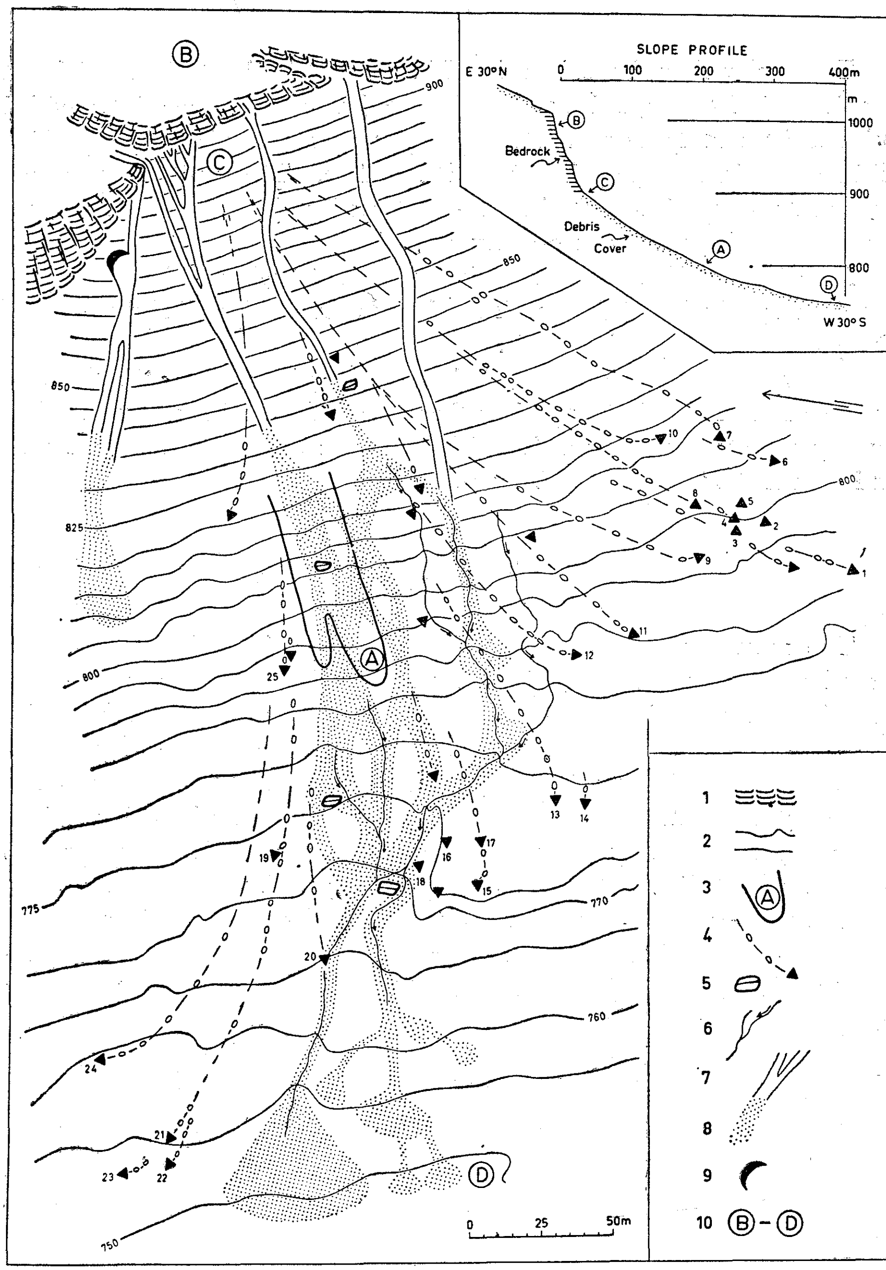

Fig. 3. Map of mass-movements in Kärkevagge, section K, 1952—1960

1. rockwall; 2. contours; 3. dirty snow avalanche of May, 1953; 4. rockfall of June (?), 1957, released from point B on the wall; ovals — bump holes from jumping boulder; black triangles — new rockfall boulders; 5. old, big boulder; 6. temporary runnels; 7. gullies, enlarged in October, 1959; 8. mudflow and alluvium deposits of October, 1959; 9. scar after earth-slide of October, 1959; 10. points on the profile

Site

The rockwall on fig. 3 is facing W 30°S and is about 120 m high. It consists of flat-lying mica-schists in the lower part, then interbedded mica-schist and limestone. In the upper part are mica-schists, which disintegrate into large, disc-shaped boulders. The wall is dissected by structural, vertical clefts in a N—S direction (see fig. 3). These are sometimes followed by temporary runnels.

Above the wall there is a moderate slope (roughly 15°—20°) up to the drainage divide at 1 200 m. This slope is covered by till and has dwarf shrubs and grass growing on it.

Below the wall there is a talus slope grading into a more gentle slope at the base. The talus slope is rather fine-grained with many boulders on a grass-covered surface. The inclination is about 38° near the wall and about 30° at the 830-metre-contour.

Methods

The mass-movements illustrated on the map (fig. 3) have all been traced after they occurred, either by inventories upon the snow cover in spring or by examination of the slope in summer or autumn. The locality has also been photographed by the present author several times since 1952. It is one of many similar localities examined in Kärkevagge. The following three different mass-movements were recorded there since 1952: (1) a small dirty snow avalanche in May 1953, (2) a boulder-fall in June (?) 1957, (3) mudflows and gullying in October 1959.

The map gives an example of how different geomorphic processes can work in combination on the same slope, each one with its characteristic range and deposition pattern. We will first discuss the boulder fall.

The rockfall boulders of 1957 (black triangles on fig. 3) were observed and reported to the author by Mr S. Areskog of Uppsala. The map was measured with tube equipment in 1958 by A. Rapp, J. Rapp and E. Rosén.

Observations and discussion

Direct observations of many rockfalls in Kärkevagge and the deposition pattern, etc., of fig. 3 give support to the following reconstruction as regards this case.

A rock segment of at least 15 m^3 of mica-schist was released from a point about 100 m up on the wall ("B" on the profile), as indicated by a fresh scar. The segment was split up into boulders, which fell down, colliding with the wall and therefore rotated. The rotation was accelerated at the first impact on the top of the talus (at "C", fig. 3). From there the boulders were moving in leaps, 5—30 m long, as indicated by the distance between the "bump holes" (Rapp 1960, p. 47) in the ground. The rapid rotation and the friction at the points of impact causes the disc-shaped boulders to move on their edges, like jumping wheels. Thus they move down the slope in bow-shaped paths and reach far out to both sides and far downslope. In this fall boulders Nos. 21—24 and 13—18 moved down to about 5° slope inclination. They were 1—2 m broad and 1—5 dm thick. Falls coming from low parts of the walls are generally not spread out so far. They are sometimes deposited in a rather narrow and short band of scattered debris, like the tongue at "A" on fig. 3.

Possibly the high, wide-spread falls tend to create more stable, concave talus slopes, while the lower falls tend to form steep, unstable talus. There is generally a combination of both types, if the walls are high enough.

It is interesting to compare the deposition pattern of this rockfall with that of another rockfall of nearly the same volume (about 10 m^3 of mica--schist debris) which fell in May 1953 at the same locality. It also landed at letter "C" of fig. 3 but fell in deep snow and relaased a small snow avalanche, which caught the boulders and deposited them in a tongue--shaped band (letter "A"), which did not reach far downslope (18° inclination at the front), nor to the sides. The contrast could perhaps not be greater between the two rock-masses mentioned, one deposited within the thick line at "A", the other spread out over a much greater area, and yet they came from almost the same height and contained about the same quantity of rock waste. This is one example of the influence of transport processes upon the micro- and macroforms of slopes.

The tongue-like deposition pattern is typical of most avalanches, but it is only the small cases like fig. 3, A, that stop high up on the slopes. The larger avalanches reach much further downslope than the boulder--falls generally do (cf. fig. 4 with description).

In all there have been about 25 m^3 of rockfalls from the wall in 9 years at this locality. Along the whole eastern wall (2,5 km) about 250 m^3 of rockfalls have been recorded during the same period. These figures give an idea of the actual recession of the walls and they can further be compared with the quantities of debris transported by mudflows etc. (see below).

MUDFLOWS, GULLYING AND RELATED PROCESSES

There are many types of transport processes started by water saturation from heavy rains or snow-melting on soil-covered slopes. In October 1959 extremely heavy rains occurred in Kärkevagge and its surroundings and gave a good opportunity to study the geomorphic effects of torrential rains in the high mountains of the North. Similar but larger forms of mass-movements in S—Lappland have been described by Rudberg (1950).

Some of the features that were formed on the soil-covered slopes in Kärkevagge on that occasion may be classified and designated as follows:

(1) Crescent-shaped or semicircular cracks, concave downslope, 5—30 m in diameter, with only slight vertical subsidence of the downslope portion. These cracks in many cases had developed into type (2) slides.

(2) Earth-slides or earth-slips, characterized by an upper crescent-shaped slip plane forming a scarp and a frontal lobe of the slide mass ("earth-flow" according to Sharpe 1938, fig. 8). A direct translation of a Swedish term for these features, which are common in many places also in southern Sweden, is *bowl-slides.* In Kärkevagge these slides had mainly occurred on solifluction slopes with rather deep till. It is probable that a surface of frozen ground can facilitate slides (Cailleux & Tricart 1950) but in these cases the slip planes were not on frozen ground.

Another type of slides (2b) consisted of sheets of soil stripped off from a substratum of underlying rock.

(3) Mudflows. These were apparently in many cases developed from type (2b) when the soil was so wet that it could move down the slope like a lava flow of debris porridge. They formed mudflow levées (Sharp 1942) sometimes ending in mudflow lobes. Mudflows (German: *Muren*) are well described by, for instance, Stiny (1910), Sharpe (1938), Sharp (1942) and Tricart (1957). "Mudflows may follow preexisting channels or, by moving down undissected slopes, determine the location of new channels confined by the levées and cut by the more liquid part of the flow and subsequent run-off" (Sharp 1942, p. 222).

(4) Gullying. As was pointed out in the sentence just quoted, the mudflows are often associated with runnel activity. This creates gullies above and alluvial sheets or alluvial fans of slightly water-assorted debris below.

All these forms were intimately combined in Kärkevagge (cf. fig. 3). But they are not solifluction phenomena. Andersson (1906) defined the term *solifluction* as "the slow flowing from higher to lower ground of masses saturated with water". It is to be regretted that the term *soli-*

fluction is also used by some authors for rapid, sporadic mass-movements such as distinct mudflows and distinct earth-slides (see further under "Solifluction", p. 304).

The rainstorm of October, 1959

The mudflows and gullying illustrated on fig. 3 occurred in connection with extremely heavy rains after three months of high precipitation (cf. fig. 2). The rains culminated on October 5—6 in connection with strong westerly winds and unusually high temperatures. Snow melting on high altitudes increased the run-off. In table II some data from these days are referred.

Table II

Diurnal precipitation and air temperature recorded at Riksgränsen, October 1—8, 1959

Date: October	1	2	3	4	5	6	7	8
Precipitation, mm	16	10	0	1	28	107* (43+64)	48	4
Air temp., 7 a.m., °C	+2°	+1°	+1°	+2°	+7°	+7°	+5°	−1°

* 43 mm from 7 a. m. until 7 p. m. on October 5; 64 mm during 12 hours before 7 a. m. on October 6. Precipitation during periods of 24 hours, read at 7 a. m. each day. Source: S. M. H. I. Weather Bulletin.

The rains released many slides and caused strong gullying and river erosion in the Narvik district and in the mountains to the climatic divide, where the precipitation decreased rapidly. This is seen, for instance, in the precipitation figures of October 5—6: Riksgränsen 107 mm, Björkliden 65 mm, Abisko 25 mm. The three stations are situated in W—E direction. Distances: R.—B. 24 km, B.—A. 7 km.

Three earth-slides and one broken railway bank were reported from the railway line from Riksgränsen to Narvik between 3 and 6 a.m. on this day, probably indicating the culmination of the rain.

Geomorphic effects in Kärkevagge

Fig. 3 gives an example of the geomorphic effect of the heavy rains in Kärkevagge. The fresh mudflows, etc., were sketched by the author in October 1959 and the map was revised in the field by G. Larsson, Uppsala, in 1960. For a description of this site see above under "Rockfalls" (p. 290).

Much debris was released from the till covering the slope above "B" on fig. 3, where many earth-slides had started and continued as mudflows (cf. also the slide to the left on fig. 3). From the talus crest down to the 820—840 m contours there were gullies 1—2 m deep and 2—6 m wide following older furrows.

Mudflow levées occurred along the gullies from about 850—890 m down to about 775 m. They were 3—4 m wide and up to 1 m high, consisting of mixed debris. In many cases mudflows had also moved over the grass cover without causing any erosion. Many levées ended downslope in a terminal lobe, similar to those photographed by Sharp (1942, p. 222) and Baird & Lewis (1957, p. 94, unfortunately called "solifluction tongues").

Small mudflows have been observed in motion by the author during snow melting in Kärkevagge. They moved at a rate of up to 0,5 m per second and stopped suddenly when they came upon snow, possibly because they lost water.

In fig. 3 there is also another type of deposit in the form of small alluvial fans. These consisted of more assorted debris - gravel and pebbles which had probably been washed down secondarily by longer-lasting water transport. They occpied small depressions or formed new sheets of debris upon old, vegetation-covered alluvial fans, etc.

A large part of the deposits on the lower slopes of the eastern valley side is probably accumulated by repeated processes such as those of October, 1959. It is also possible that most of this old and overgrown alluvium and mudflow debris was deposited in late-glacial times when the eastern valley-side had just been freed from the ice and the till on Mt. Kärketjårro was not yet stabilized by vegetation (cf. observations from vegetation-free, periglacial areas by Büdel 1960 and by Sharp 1942 a.o.).

In 1959 at some places the talus slopes were supplied with mudflows of a thick porridge of debris which came to rest at an inclination of 35° or lower. Evidently much of the material in the talus slopes there is old re-deposited till from the slope above the wall. Thus the recession of the wall has not been as great during postglacial time as the talus slopes at some places suggest when they are interpreted exclusively as strongly weathered rock waste from the walls.

Discussion

The total quantity of fresh debris deposited as mudflow or alluvial sheets on the slope (fig. 3) is estimated at about 500 m^3 if the average thickness of the new layer is put as low as 0,10 m.

Along 2,5 km of the eastern valley side of Kärkevagge there occurred in all 7 larger and many small mudflows. Together they carried at least 2 000 m^3 of debris from the higher to the lower slopes. This corresponds to a transfer of roughly 500 m^3 of material per square km of the eastern valley side or to an average accumulation of a 1 mm thick sheet of debris on the lower 50% of the slopes.

The mudflows and gullying in October 1959 are together the largest scale events recorded there since 1952. They are many times greater than the total volume of all rockfalls in the valley recorded since 1952 and they are also far greater than the momentary mass-movements recorded during the periods of most rapid snow-melting.

But the figures from Kärkevagge are small in comparison with the many hundred thousands m^3 of debris carried to the deltas by the rivers of the Norwegian side on the same occasion. Their debris load was, however, mainly cut from riverbanks of glacifluvial material (R. Dahl, personal communication).

The figures from the mudflows in Kärkevagge are also small as compared with similar processes reported from the European Alps (Stiny 1910, p. 38; Matznetter 1956, p. 54). It is possible that the mudflows in the Alps are larger and more frequent primarily because of climatic reasons (heavier rains), secondarily due to topographic reasons (higher and more dissected mountains). Also in the highlands of Great Britain the mudflow catastrophes seem to be stronger and more frequent than in Lappland to judge from many descriptions (cf. Baird & Lewis 1957, p. 91).

By referring to these few examples the author wishes to call attention to a question which is of great importance within climate-morphology, i.e. the regional distribution of torrential rains and their geomorphic significance.

We can end this discussion by quoting Washburn (1947, p. 86): "Mudflow is not usually associated with arctic regions. Yet it occurs in them and locally at least may be of considerable importance."

DIRTY SNOW AVALANCHES

Snow avalanches probably cause great denudation in many high mountain areas (cf. Allix 1924; Peev 1957; Pillewizer 1957; Jäckli 1957). It is quite evident that they do so in the highest massifs within the amphibolite mountains of Lappland, where deposits of avalanche rock debris are frequent ("avalanche boulder tongues", Rapp 1959).

In the mica-schist mountains of Lappland as represented by Kärkevagge and its surroundings the avalanche deposits are not so conspicuous, but here we still must consider avalanche erosion as one of the most important forms of mass-movement, as will be shown below.

Site

Fig. 4 is a map of the distal part of an avalanche track coming from the NE-facing slope of Mt. Vassitjåkko. The general form of the slope is shown by the profile in fig. 4. It follows a stream which starts from a small lake in an over-deepened cirque at about 1 120 m altitude, descends the back wall of a lower cirque and passes over its floor. At 900 m it reaches the rim of a still lower cirque-like wall, where it forms a second waterfall. The stream is nowhere incised. In winter the two falls are frozen into large masses of ice. When rapid melting starts in early summer the second waterfall sometimes bursts its ice dam with such violence that it is observed from the railway 3 km away. The catastrophic breaking of the waterfall occurred on June 12 in 1956, July 7 in 1957 and between June 19 and June 22 in 1958. In 1956 and 1958 it released large avalanches.

The avalanches in section V

The dirty snow avalanche of June, 1956 reached 350 m out on gently sloping ground and carried about 200 m^3 of rock debris. In 1958 a still larger avalanche was released. It moved 450 m out onto the valley bottom (5° average inclination, see fig. 4, C—D) and transported more than 300 m^3 of debris.

The traces of this avalanche were examined later on. Possibly it had been released from the first waterfall, as there were broad, oblong strips of turf-covered soil torn off in a 50 m broad zone on both sides of the stream at B in fig. 4. As an example of the transporting capacity of this avalanche it may be mentioned that one boulder, measuring $5 \times 3 \times 2$ m with an estimated weight of 75 tons was moved from point "a" to point "b" (fig. 4), that is, about 120 m down a slope with 5° average inclination.

Some characteristics of this avalanche tongue as well as of many others are as follows. No sorting of material according to size, but all the "fresh" debris — boulders, pebbles, soil, plant waste — is mixed up and loosely deposited upon the ground in the avalanche track. The debris is also deposited upon the surface of high boulders, showing that they were buried under the avalanche snow before it melted off. Erosional marks such as pits, scratches and parallel grooves in the ground are numerous in the upper and middle part of the track but can occur near the margins too, indicating that the avalanches can erode along their whole track if they move in direct contact with the ground. This ability of avalanches to erode in broad, straight tracks tends to create trough-shaped ravines above, ending in tongues with a border of boulders below.

Avalanche boulder tongues can be very distinct and conspicuous forms as in the "roadbank tongues" and "fan tongues" described from slopes in Lappland, rich in boulders and poor in vegetation (Rapp 1959). They can also be more diffuse tongues of scattered debris, like those in Kärkevagge.

Discussion

The type of dirty avalanches described from section V and preliminarily called torrent avalanches can be briefly characterized as follows. Very wet avalanches, released by swelling streams on steep or moderate slopes at the beginning of the spring flood. They consist of snow, blocks of ice, water and in many cases also great quantities of earth and rock debris.

This type is not at all unique to the locality mentioned. Similar avalanches, released from steep or moderate sloping rapids in streams have been recorded, for instance, at the following localities: E of Lake Rissajaure, Kärkevagge; in a small stream at Rakkaslako, Björkliden; and at Mt. Kaisepakte, E of Abisko, where they have hit the railway line repeatedly.

Possibly it is this type that Nobles (1959, p. 1652) terms "slush avalanches" and characterizes as "an effective mechanism of downslope transport of rock debris in arctic regions". This brings us to the question of regional distribution. Are the "torrent avalanches", as described above, typical only of high-latitude mountains or are they frequent and of geomorphic importance also in mountains in middle and low latitudes?

CONTINUOUS MASS-MOVEMENTS

Under this heading the two processes of talus-creep and solifluction are discussed.

TALUS-CREEP

This has been defined as "the slow downslope movement of a talus or scree or any of the material of a talus or scree" (Sharpe 1938, p. 30). It is considered to be most rapid in cold regions "where the major cause is the expansive force of the alternate freeze and thaw of ice in the interstices of the rock waste" (op. cit., p. 30). Another cause of movement is supposed to be "the removal of fine interstitial material by the drainage of water falling on the talus or flowing through it, thereby allowing a settling of the overlying blocks" (p. 31).

It is necessary to know the rate and type of transfer and removal of talus debris for a correct understanding of the continued development of slopes. The best method to acquire knowledge seems to be by direct recordings and observations of the types and rates of movements on talus slopes in various rocks and climates.

Site

The position and general arrangement of two recording areas called C1 and Cb are shown on fig. 5: I (cf. also pl. 2).

The recordings at C1, which will be discussed below, are probably representative of very active talus cones with relatively rapid creep movements. The talus cone C1 is situated on an E-facing slope at 900—980 m altitude. The corresponding rock-wall is about 60 m high and the cone is supplied with rock waste from an irregular funnel in strongly tectonized mica-schist.

The talus cone C1 is about 65 m high and as steep as 37° (profile in Rapp 1957, fig. 1: A) in the upper part and 38° in the lower part. It is a pure gravitational ("dry") cone, only slightly influenced by temporary runnels and not at all marked by snow avalanches. The supply of rock waste from the wall to the top of the cone has been measured on sack carpets (op. cit., p. 188). It corresponds to a new top layer of 1—3 cm thickness every year, which is the highest value of supply through annual pebble falls recorded in Kärkevagge.

The material of the cone is mainly black phyllitic mica-schist which splits up into oblong, thin slabs. Near the top they are mainly 2—10 cm in diameter, lower down on the cone mantle they are about 2—25 cm and at the base there is a fringe of boulders up to 2 m. The pebbles and cobbles on the surface are conspicuously lying like roofing-tiles, many of them with their long axis pointing down-slope.

The cold and humid climate of the valley and the observed rich supply of debris are two factors, which, according to Sharpe (1938, p. 31), both facilitate talus-creep. Schists and slates are thought to be the most mobile types of talus, for example, by Jäckli (1957, p. 29) who considers that talus cones of this material can be completely removed by rain wash. Dylik

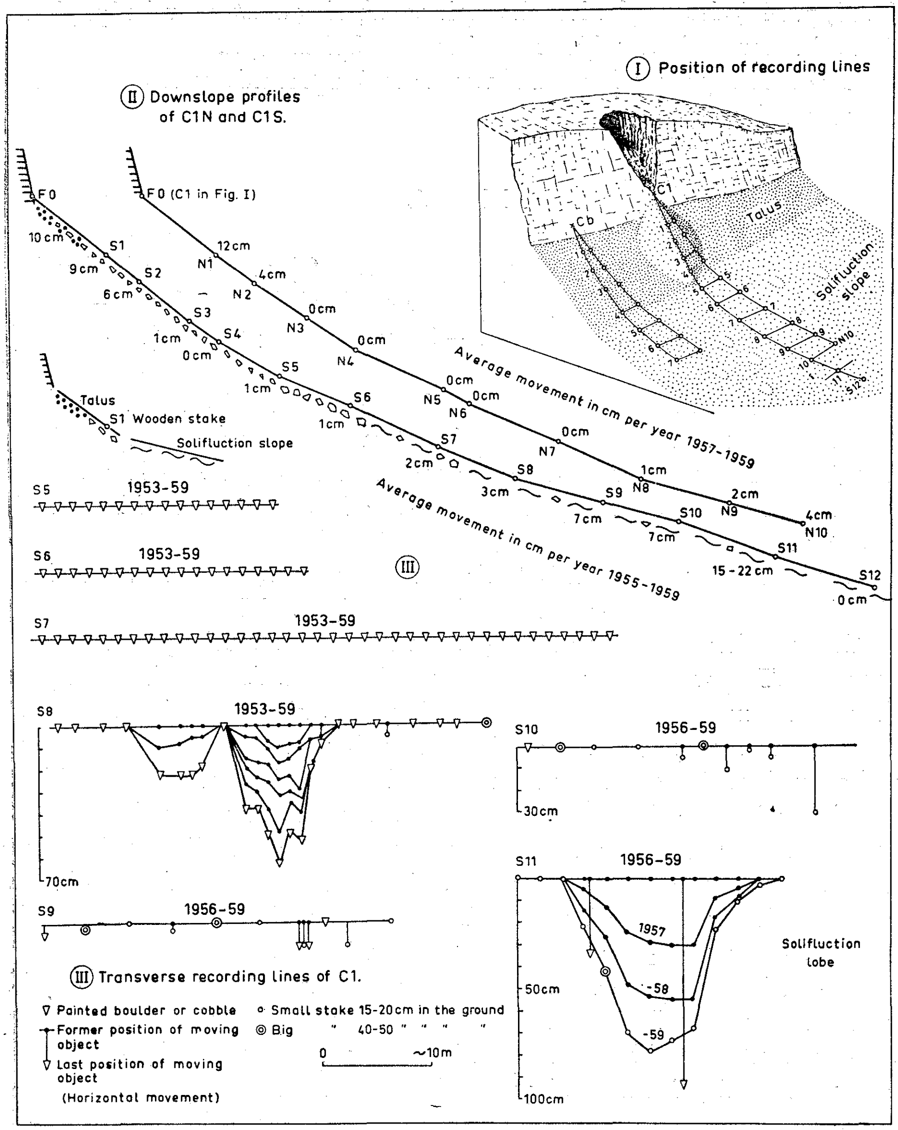

Fig. 5. Creep movements on a talus cone and solifluction slope in Kärkevagge, section C
There are three different parts in the figure:

I — sketch showing the position of the downslope lines C1 and Cb and their transverse lines; II — the two downslope lines C1. The average downslope movement of the stakes is given in cm per year; III — seven transverse recording lines of C1. Three of them (S5, S6, S7) have shown no relative movement at all during a 6-year period. The remaining four lines show various movements, most rapid on the solifluction lobe at S11. As a whole the slowest movements are at base of the talus

(1958, p. 141) also emphasizes the rapid weathering and removal of phyllitic slates in comparison with dolomites on Spitsbergen.

Consequently there is good reason to look upon this cone as one with rather rapid creep.

Methods

Three types of markings have been used: (a) markings of oil paint on boulders and cobbles, (b) wooden stakes buried vertically 40—50 cm in the ground, (c) stakes buried 15—20 cm in the ground (called small stakes below).

On fig. 5: I the stakes of C1 are drawn as small circles. They form two downslope lines over the talus down on the solifluction slope below. The interval between two stakes in each line is about 20—40 m. The total length of the downslope line FO—S12 is 431 m, that of FO—N10 is 344 m.

Between the two downslope lines there are several transverse lines of paint on stones or small stakes in soil (fig. 5: III).

The position of the markings was checked with a steel tape once every summer. The measurements were started from a fixed point (FO) in the wall 1,5 m above the talus top. It is not suitable to read the distance directly on the upper, free part of the stake, because some stakes are more and more tilted downslope by the creep and further there are often boulders etc. disturbing the tightening of the tape. By using two plumbs hanging on threads, one at each end of the steel tape, the accurate distance between the stakes can be measured 30 or 40 cm above the ground, which eliminates the difficulties mentioned above. The accuracy of the measurements is estimated at about $\pm 0{,}5$ cm per measured length.

Corrections for thermal expansion or contraction of the tape should be borne in mind. If there are outcrops of firm bedrock somewhere near the lines these should be used as fixed points too. It is especially favourable to have a fixed point at the lower end of each line.

Observations and discussion

Some observations and measurements on talus cone C1 are referred in table III and in fig. 5.

There are at least three types of movements recorded. They can be termed: (1) true talus-creep, (2) individual rolling or gliding, (3) small talus-slides.

(1) The recorded movements of the stakes and the boulders 1—3 embedded in debris on the upper part of the cone indicate a fairly continuous creep movement of about 10 cm/year, decreasing towards stability at the talus base. Boulders 1—3 are more than 1 m large. Undisturbed patches of moss and lichens close to their down-facing side indicate that they are moving at the same rate as the stone mass around them. Movements of this type can be termed true talus-creep. The thickness of the moving layer has not been determined.

Table III

Examples of recorded movements on talus cone C1

Boulder No.	Distance from FO in 1959	Movement in cm							
		1953 1953 17/6 11/9	(1954)	1955 1956 13/8 31/7	1957 3/8	1958 6/8	1959 1/8	Total	Movement per year
1	22,35 m	9	14	8	7	10	12	60	10
2	38,99 m	5	12	5	7	5	10	44	7
3	43,15 m	3	12	6	5	6	8	40	6,5
4	25,18 m	15	265	10	20	12	21	343	
5	43,46 m	4	23	11	12	9	12	71	

Boulders 1—3 are more than 1 m large and are embedded in debris. Boulders 4—5 are superficial and intermittently glide.

(2) All cobbles and pebbles in two transverse (horizontal) lines 21 m and 42 m, respectively, from the wall had moved down 0,5—10 m in two years. Most of these had been rolling or sliding individually on the surface. See also Nos. 4—5, table III.

These movements are similar to those recorded by Michaud (1950, p. 188) in the Alps. During two years 15% of the boulders marked by him moved 5—450 cm.

But these individual movements also cease towards the base of the cone. On a 25 m long transverse line between the stakes N3—S3 on the lower, steepest part of cone C1 there have been only very slight individual movements during the last 2 years. It is especially remarkable that the line was intact and straight even after the very heavy rains of October, 1959. This indicates that sheet wash can be of little significance even on phyllitic talus cones.

(3) On some basal parts of the cone there are unstable "slide tracks" of pebbles. On the line N3—S3 such a slide 2,80 m broad had moved the pebbles about 1 m or less downwards. Similar features are very characteristic of many talus cones on Spitsbergen (Rapp 1960, p. 61).

The measurements on other talus slopes in Kärkevagge have shown approximately the same characteristics as those described above.

Thus we may summarize by saying that the measurements of talus--creep of various types in active gravitational talus in Kärkevagge indicate movements as rapid as about 10 cm per year near the top, decreasing towards nil at the base. There is no conspicuous evidence of removal in solid form away from the cone, neither in the recording lines at the base nor in the surface forms. Consequently these slopes are probably in a growing phase (postive talus regime).

It would be of great interest if similar recordings could be done in other climates and on other rocks for comparison.

It may be stressed once more that the removal of debris from gullied talus slopes can be very effective, as is shown by, for instance, fig. 3.

SOLIFLUCTION

Solifluction (or congelifluction) in the proper sense of slow, creep--movements of soil is generally considered as the most important form of denudation in cold climates. Even fifty years ago the need of quantitative measurements on solifluction was well recognised. "The importance of solifluction on the general denudation can naturally not be determined before we have made measurements of how fast the soil does move in different localities" (Frödin 1914, p. 263).

Site

The most rapid solifluction movements recorded in Kärkevagge are from the lines C1N and C1S, partly described under "Talus-creep" above and shown on fig. 5 and pl. 2.

The solifluction slope in section C consists of a mica-schist till that is partly very fine-grained. In solifluction lobe S11 the percentage of silt and finer grains is about 30%. In the material finer than 40 mm higher up near the base of the talus the corresponding percentage is 5—10%. The soil is well saturated with melt-water from many snowdrifts which accumulate in depressions on the slope (pl. 2). During normal years the slope is very wet and washed by sheets of melt-water for some weeks from June to the last part of July. The average inclination of the slope is about 15—25°. There are many solifluction lobes, generally about 1 m high and about 5—10 m wide. The vegetation is mainly grass and herbs (*Saxifraga aizoides*, and others) with patches of bare ground. The whole slope also has scattered boulders.

Methods

The movements have been recorded by annual measurements of the position of stakes and painted boulders in downslope and transverse lines as described above under "Talus-creep" (p. 302). The movements of the stakes in the downslope lines were measured parallel to the ground, but the movements in the transverse lines were measured horizontally from the original position of the marking (see fig. 5).

The moving stakes have gradually become more and more tilted down--wards and also frost-heaved 1—2 cm per year. After some years the stakes will be completely loosened and fall down on the ground, so the lines cannot be left without checking for intervals of many years.

The method described here is a fairly approximate one, but it is rather easy to arrange and check, which is an advantage under field conditions. It is certainly necessary to develop more and more accurate methods of recording solifluction and other mass-movements, but there will always be room for simple methods too.

Some references to descriptions of various methods for recording soil movements may be summarized as follows.

Stakes or painted boulders checked with steel tape measurements: Washburn (1947), Michaud (1950), Schmid (1955), Jahn (1960), Smith (1960).

Theodolite measurements of stakes etc.: Klinger (1959, p. 52 f), Washburn (1960, p. 60).

Photogrammetric measurements have been tried on Spitsbergen in 1960 by Büdel (oral communication).

Different methods of recording the vertical gradient of solifluction movements are described by Rudberg (1958), Williams (1957, see also article in this volume, p. 353), Washburn (1960).

Observations and discussion

The recordings along the two C1 lines show movements of nearly nil at the talus base. The stability there is also confirmed by the transverse lines S5—S7, which have been straight for 6 years. Downslope the movement is increasing to 4—7 cm per year and as an extreme maximum 25—30 cm per year in the lobe S11. It is interesting to see that the movements have not varied so much from year to year (cf. lines S8 and S11, fig. 5:III). Probably the development of a lobe such as S11 is cyclical, starting with a slow differential movement, increasing to an optimum for a number of years and then decreasing, sometimes by a bursting and runnel dissection. There are indications of such a development of lobes on the same slope.

The increasing rate of movement downwards along the two lines is probably caused by increasing saturation of water and higher percentage of fine grains in the soil.

The line S8 affords an example of the effect of water saturation. The painted cobbles of this line have moved 1—10 cm per year in two small depressions where there is surplus water trickling in early summer. Frost-heave and ice-needles may have contributed somewhat to the movements here as in the cases described by Smith (1960, p. 77). Two boulders on lobe S11 have moved faster than the soil there as is seen in fig. 5. These boulders are embedded in soil and have a size of 1,5 m (left) resp. 0,3 m (right).

The inclination at the transverse profile S8 is 15°; at S11—18°; and on the ridge of the lobe S11, 25°.

The heavy rains of October 1959 released numerous rotational slips about 5—30 m wide on this slope (See above under "Mudflows...", p. 294) but it did not cause any gully erosion. It is also most remarkable that there were no noteworthy creep movements to measure in the lobe S11 and the other transverse lines 4 days after the rains. It is possible that the different reactions of the slope can be expressed thus: water saturation in spring upon a layer of frozen subsoil causes solifluction but no slides; water saturation in autumn without frozen subsoil causes slides but no solifluction.

The recordings of solifluction movements on other slopes in Kärkevagge have shown rates of about 0—8 cm per year. In the vicinity of the valley Rudberg[1] has measured rates of about 0—5 cm per year.

During the last few years several detailed investigations of solifluction movements have been carried out elsewhere under arctic conditions. We may, for instance, mention the very valuable contributions by Büdel (1960), Jahn (1960), Smith (1960) and Washburn (1960).

The recordings of solifluction movements in Kärkevagge and its surroundings show approximately the same rate as those measured by Jahn (1960, p. 56) on slopes with clayey soil in Spitsbergen. His values are at most 5—12 cm per year on slopes of 7°—15° inclination. In South Georgia Smith recorded the solifluction on a 21° slope covered by a till of fine-sandy loam mixed with boulders. The upper layer of the soil

[1] S. Rudberg — A report on some field observations concerning periglacial geomorphology and mass movement on slopes in Sweden. In the same volume of *Biuletyn Peryglacialny*, p. 311.

(0—25 cm) moved 2,5—5 cm in one year, but the pebbles on the surface moved 25—71 cm (op. cit., p. 75).

So far as the direct recordings show until now, we may conclude that many earlier authors have overestimated the capacity of recent solifluction in the arctic regions. For example Högbom's view (1914, p. 369) that the movement generally varies from "one or some decimetres to one or some metres" seems to be a tenfold overestimation.

A most interesting aspect of this question is further the rate and capacity of solifluction in the Pleistocene periglacial periods in Central Europe and similar sites elsewhere. Has the solifluction under these conditions also been overestimated? We cannot enter a detailed discussion of this question here. But it should be kept in mind, by comparisons of this kind, that the moving soils in the Arctic of to-day are more or less coarse-grained till, left behind by the inland ice, and that these soils are perhaps less favourable to solifluction than the clayey or silty soils of Central Europe (cf. Büdel 1959, p. 303, 306).

ACKNOWLEDGEMENTS

The author wishes to express his thanks to Professor F. Hjulström of Uppsala, who initiated the investigations in Kärkevagge and later always gave strong support in all respects to the work. Teachers and colleagues from Uppsala, Gothenburg and Stockholm have given valuable opinions and suggestions. Mr N. Tomkinson, B. A. has revised the English text. Mr W. Tiit has drawn figs. 1—5.

Financial contributions have been received from Matematisk-naturvetenskapliga fakulteten, Uppsala, Jernkontorets Lundbohmsfond, Stockholm and The Swedish Touring Club, Stockholm.

To all these persons and institutions the author expresses his thanks.

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Map H

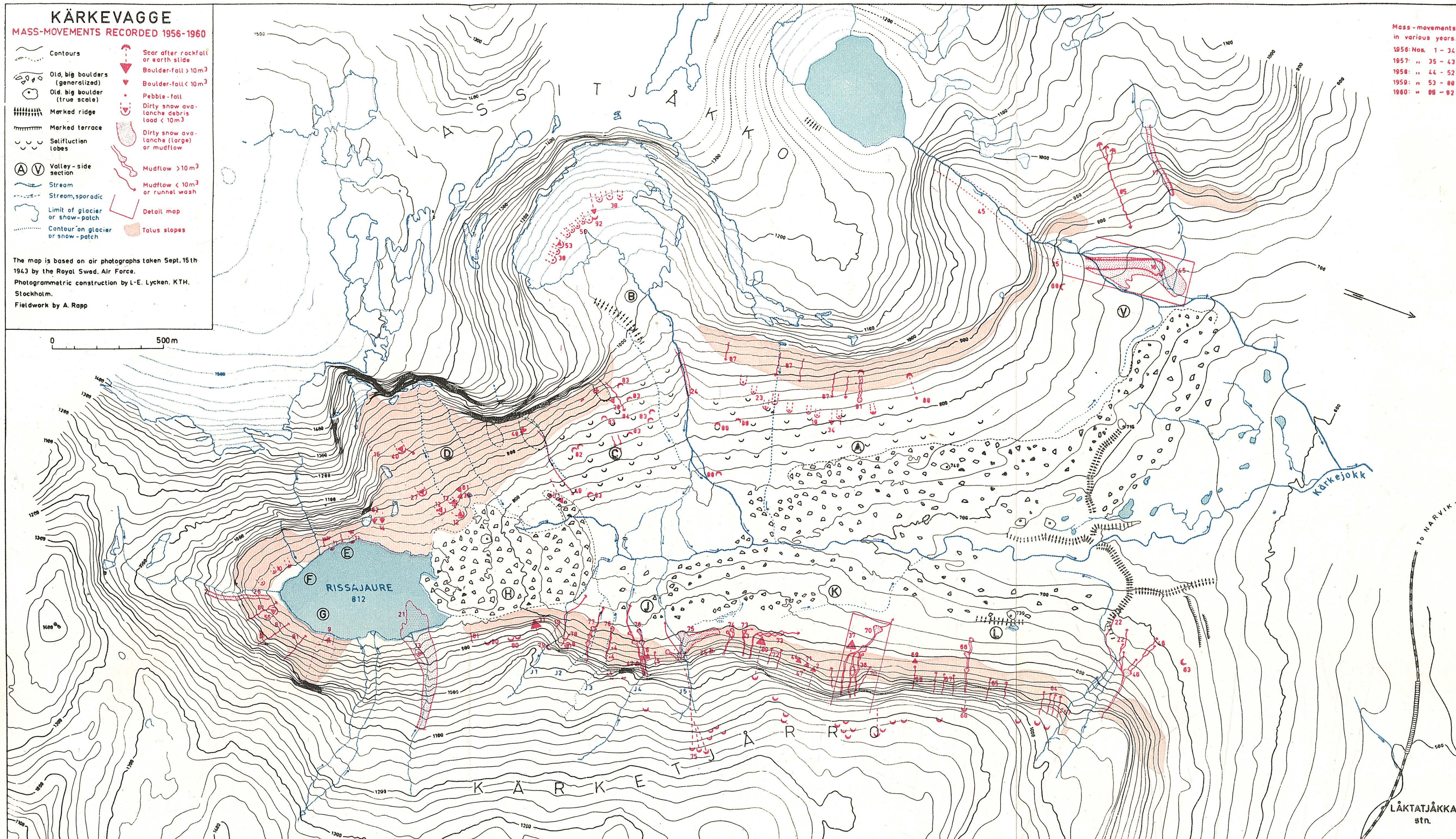

Fig. 1. Map of Kärkevagge and the momentary mass-movements recorded 1956—1960

Two localities discussed are marked by red rectangles. Cf. fig. 3 — rectangle in section K with rockfall No. 37 etc., fig. 4 — rectangle in section V with snow avalanche Nos. 16 and 45

Air photo by A. Rapp, 21, 8, 1959

Pl. 1. View south from the mouth of the valley. Deposits of big boulders and morainic ridges in the valley bottom: Mt. Vassitjåkko with Kärkereppe cirque to the right. Lake Rissajaure at the upper end of the valley

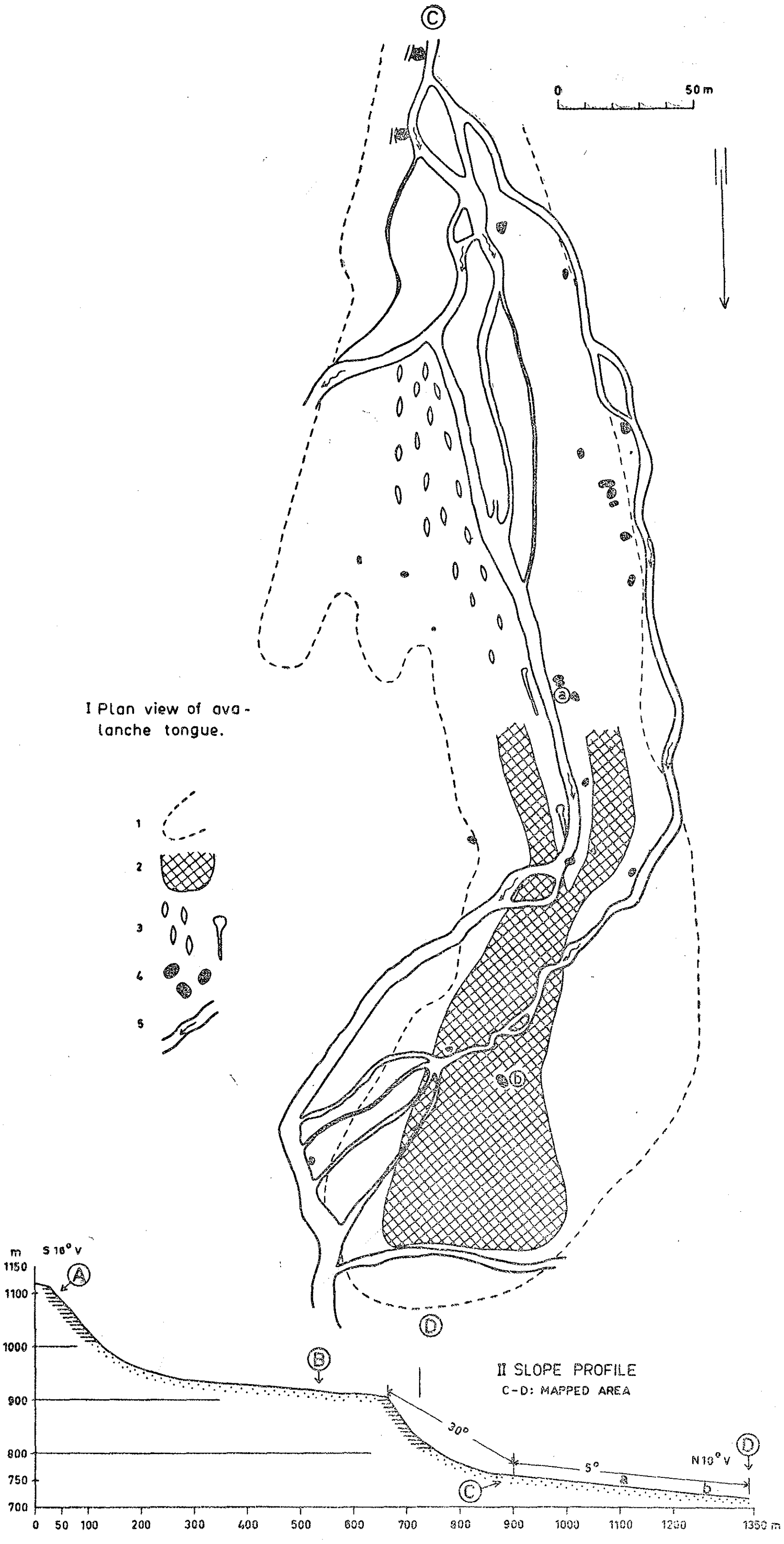

Fig. 4. Map and profile of dirty snow avalanche in Kärkevagge, section V
1. outer limit of avalanche tongue of June, 1958; 2. zone of maximum deposits of fresh debris; 3. erosion scars and grooves; 4. big boulders; one of these moved from "a" to "b" with the avalanche; 5. stream with anastomosing branches