DOWNSLOPE MOVEMENT OF SOLIFLUCTION LOBES IN ICELAND: A TEPHROSTRATIGRAPHIC APPROACH

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Abstract Excavatins of the turf-banked solifluction lobe at 28 localities in Iceland have revealed dislocated and deformed volcanic ash layers composing solifluction lobes. Tephrostratigraphy and tephrochronology present much information about the rate and the mechanism of downslope movement of solifluction lobe which probably extends over the last 7,000 years. Downslope movement during the period between *ca.* 4,000 yBP and 2,000 yBP was faster than that in the last 900 years. The rate of downslope movement of solifluction lobe front is strongly associated with the gradients of slopes. However, environmental conditions, particularly those related to the existence of permafrost may have been favorable for the downslope movement. Concerning the mechanism of movement, the solifluction lobes have not moved as a slab slide, but as a viscous flows, because no shear plane was found.

Key words: solifluction lobe, tephrostratigraphy, moving rate of solifluction lobe, rolling over phenomena

1. Introduction

Downslope soil movement in periglacial regions has attracted much attention, particularly since the study of Rapp (1960). The current rates of solifluction have been measured at various places under periglacial environments of the world (*e.g.* Williams, 1959; Washburn, 1967; Benedict, 1970; Harris, 1972). Consequently, it is now possible to compare the studies and to relate them to the environmental factors which influence them. However, one of the most fundamental problems related to data obtained from such investigations is the long-term validity of the rate. Even though the measurements have been carried out over the last 30 years, the geomorphological significance of them still remain difficult to elucidate. As Worsely and Harris (1974) stressed, alternative methods are requiered to discuss the significance of downslope soil movement since the end of the last Glaciation.

A variety of lobate and terrace-like landforms due to the downslope soil movement are produced in Iceland. These micro-landforms are composed of various sediments from place to place containing more or less of volcanic ashes mainly from the Hekla volcano. Particularly well known pumice layers such as the Hekla 1, the Hekla 3, the Hekla 4 and the Hekla 5 are excellent marker layers to offer not only absolute dates but also information about their deformation and dislocation due to the soil movement after the fall of each pumice.

The purpose of this paper is to introduce a new idea, that is the thephrostratigraphy and tephrochronology, used for the study of the long-term downslope soil movement, and then to tentatively discuss the rate and the mechanism of solifluction lobe movement.

The solifluction lobes were excavated at 28 sites in the four regions under different environmental conditions in Iceland. Only three excavations will be introduced in this paper. The others will be illustrated by figures and discussed more detail in near future.

2. The Study Area and Survey Method

The study area

The areas to be described are the Laxardalheidi, the Holtavorduheidi, the Thorskafjardalheidi, and the Thjofafell and its surroundings, at an altitude of 100-150 m, 250 m, 340-450 m and 650-850 m above sea level, respectively (Fig. 1). The former three areas are geologically situated on the Tertiary basalt, while the last on the Quaternary paragonite. Near the Thorskafjardalheidi and the Thjofafell, there exist the ice caps of Drangajökull and Langjökull, respectively. At the meteorological station, Hveravellir at an altitude of 642 m asl., near the Thjofafell, the mean annual air temperature is around $-1°$ to $-2°$ C. In the boggy area over *ca.* 450 m asl. in the central highlands, many palsas are developed, indicating the presence of discontinuous permafrost (Schunke, 1975; Hirakawa, 1986).

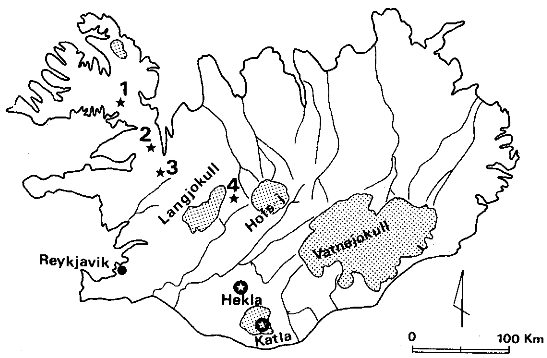

Fig. 1 Regions chosen for excavations of solifluction lobes
1: Thorskafjardalheidi; 2: Laxardalheidi; 3: Holtavorduheidi; 4: Thjofafell

The survey method

The occurrence of buried humic layers beneath solifluction lobe and terrace has beens much noticed in the literature (e.g. Williams, 1957). However, there are only several localities where radiocarbon dating has been systematically applied; the Colorado Front Range (Benedict, 1970), the Snowy Mountains, Australia (Costin *et al.*, 1967), the Okstindan Mountains, northern Norway (Worsely and Harris, 1974), and the Jotunheimen, south-central Norway (Matthews *et al.*, 1986). We have to always consider in these studies that the radicarbon date of a humic layer indicates the average period of the organic material at a given level as well as the contamination. The author observed in almost all the excavations that the present vegetation spreads the roots into the buried humic layer up to the depth of 30-50 cm, or particularly from the riser. This fact implies that it is unreliable to calculate the moving rate of last several hundred years on the basis of radiocarbon dates from the buried humic layer. Consequently we have to always put into consideration such problem for the discussion of the moving rate of solifluction lobe in the past.

Are there any possibilities to use a marker bed having an absolute date, instead of the buried organic material, in order to obtain the moving rate of the solifluction lobe? We can use several layers of volcanic ashes for this purpose in Iceland. A volcanic ash layer, which falls down to cover a moving solifluction lobe, will be displaced according to the downslope movement of the lobe. This means that the structure of displaced volcanic ash layers accurately record information not only about the rate but also about the movement-mode or -process represented by an internal structure of the lobe or a changed facies of each volcanic ashes. In addition to these advantages, we can avoid the difficulty about financial resourses to permit sufficient datings to be discussed, because the moving rate of solifluction lobes can be directly calculated from the excavation.

Using the tephrostratigraphy and the tephrochronology, the solifluction lobes were excavated at 28 localities in the above described areas. Excavated solifluction lobes were sketched as accurate as possible at the scale of 1:10—1:20.

In every excavation several volcanic ash layers were identified. Approximate absolute dates of marker volcanic ash layers are as follows (Larsen & Thorarinsson, 1978): Hekla 5: 7,000 yBP; Hekla 4: 4,500 yBP; Hekla 3: 2,900 yBP; Hekla 1: 880 yBP (by the eruption in A.D. 1104). Several characteristic scoriae layers are also distributed, of which the Katla (A.D. 1721) and the Settlement Succession[1)] are particularly remarkable.

3. Description of Excavated Solifluction Lobes

Of 28 excavations, two typical examples will be illustrated by figures in this paper.

Excavation 840731 at the Thjofafell (Fig. 2)

Solifluction lobes and terraces are well developed in the Thjofafell (Photo 1). This excavated solifluction lobe is located on the south-east facing slope of *ca.* 10° (Photo 2). As shown in Fig. 2, the excavation is about 2.4 m long and 2 m deep.

First of all, tephra layers of the Katla, the Hekla 1 and the Settlement Succession show

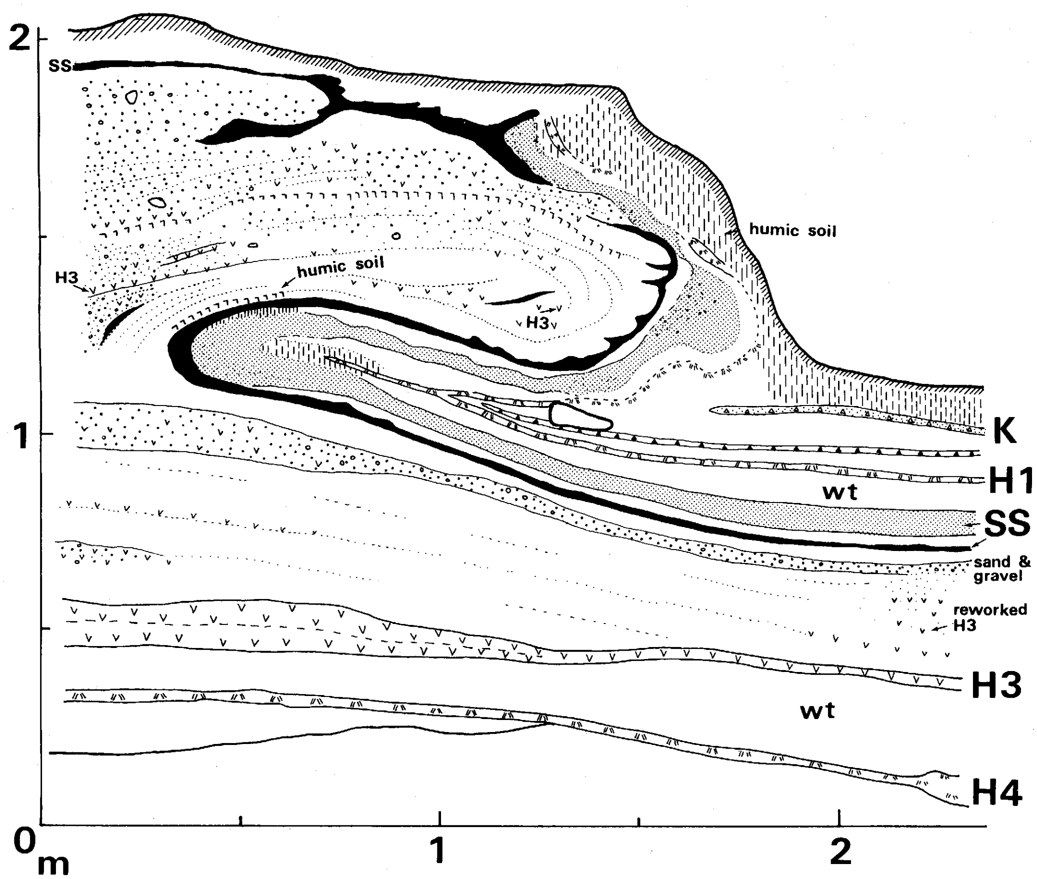

Fig. 2 Sketch of the excavated solifluction lobe 840731 indicating the dislocation of constituent materials
wt: weathered tephra containing pebbles and sand

an apparent inverted structure, while the lower Hekla 3 and the Hekla 4 layers do not indicate such structure at least within this small excavation. The part beyond the riser (uppermost part of the lowernext tread) mainly consists of volcanic ashes intercalating marker beds showing the normal stratigraphy and a layer of sand and gravel. The tread behind the riser is composed of coarse sand with pebbles containing the reworked Hekla 3 pumice grains and a displaced layer of humic soil, in addition to volcanic ashes.

Volcanic ash layers are clearly traced back from the lobe front: the Katla 1721; 20 cm, the Hekla 1; 120 cm, the Settlement Succession; 160 cm, respectively. As the Hekla 1 erupted in A.D. 1104, the front of this solifluction lobe has advanced at an average rate of *ca.* 1.3 mm per calender year during the last *ca.* 900 years and 0.7 mm/year during the last 270 years.

It is noticiable that there are no traces indicating a shear plane resulted from the movement of slab slide-type and occurrence of colluviation associated with a collapse of the lobe front. The downslope movement of this solifluction lobe has occurred to the

Photo 1 Well developed solifluction lobes and terraces at the Thjofafell

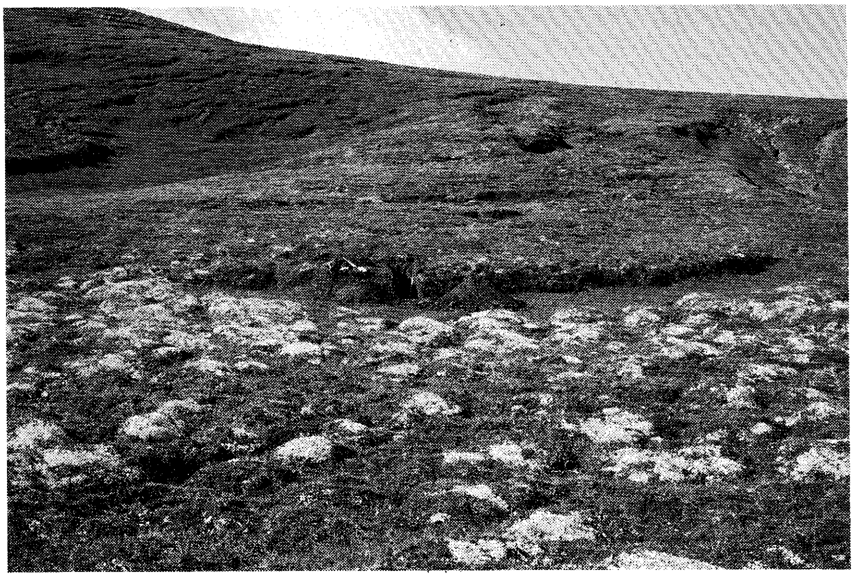

Photo 2 The excavated solifluction lobe (840731) at the Thjofafell
Trench is in the center of the photo

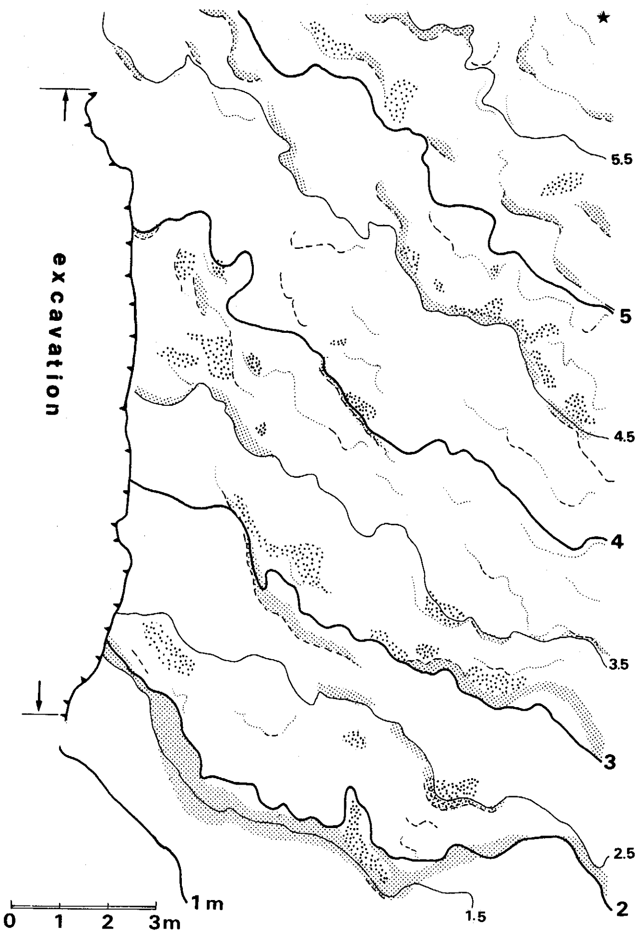

Fig. 3 Topography of the slope where the solifluction lobe 8507-1 was excavated (prepared by Mr. K. Kanzawa)
coarse dot: non-vegeteted surface with stripe; dashed line: small steps of minor solifluction terrace 15-25 cm in height; dotted line: small steps of minor solifluction terrace, 5-15 cm in height; star indicates the bench mark for leveling

depth of *ca.* 80 cm —1 m.

Excavation 8507-1 (Figs. 3, 4 and 5)

This solifluction lobe is developed on the northwest facing slope of *ca.* 20°. The excavation is relatively large, *ca.* 12 m wide and 2.5 m deep (Photo 4). However the direction of excavation is about 20° diagonal to that of the maximum slope gradient (Fig. 3). Solifluction lobes and terraces are very well developed around this excavation (Photo 3).

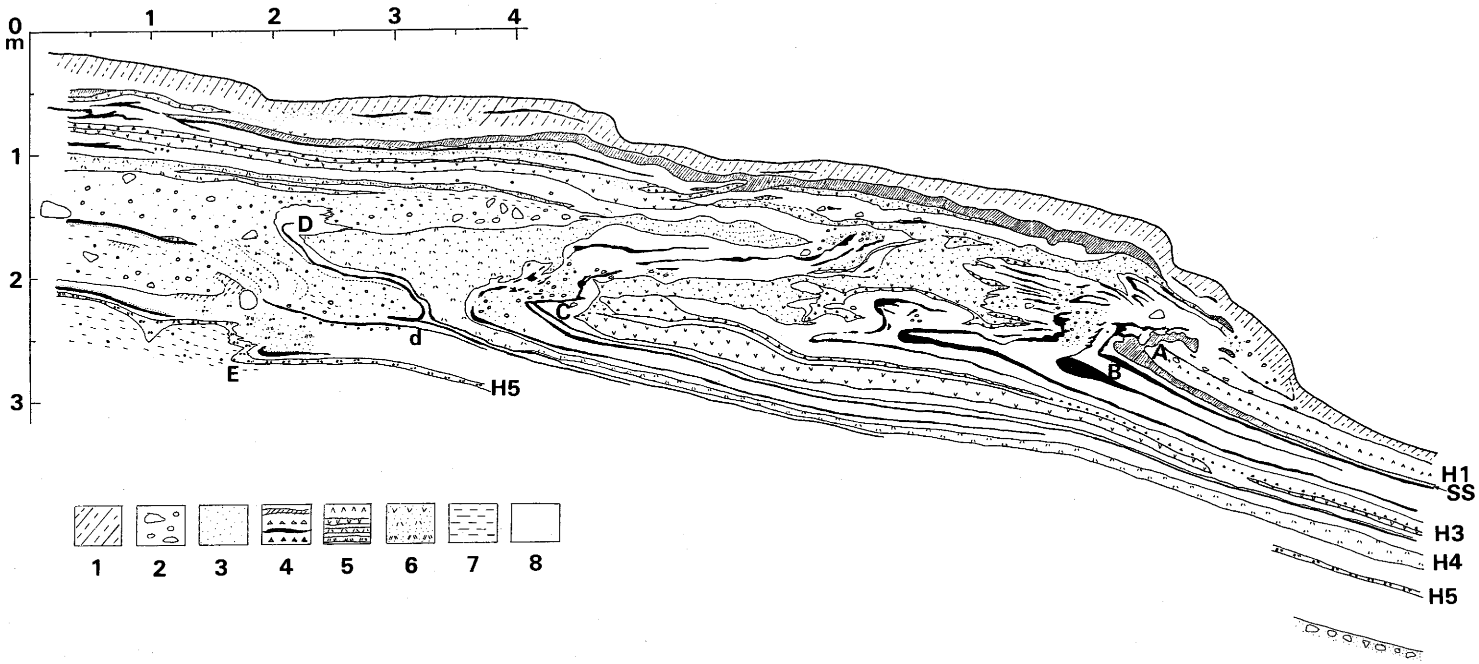

Fig. 4 Sketch of the excavated solifluction lobe 8507-1 indicating the dislocation of constituent materials
1: top soil and present vegetation cover; 2: cobbles; 3: sand; 4: scoriae; 5: pumice; 6 reworked pumices; 7: reworked volcanic ash containing granule; 8: weathered volcanic ashes

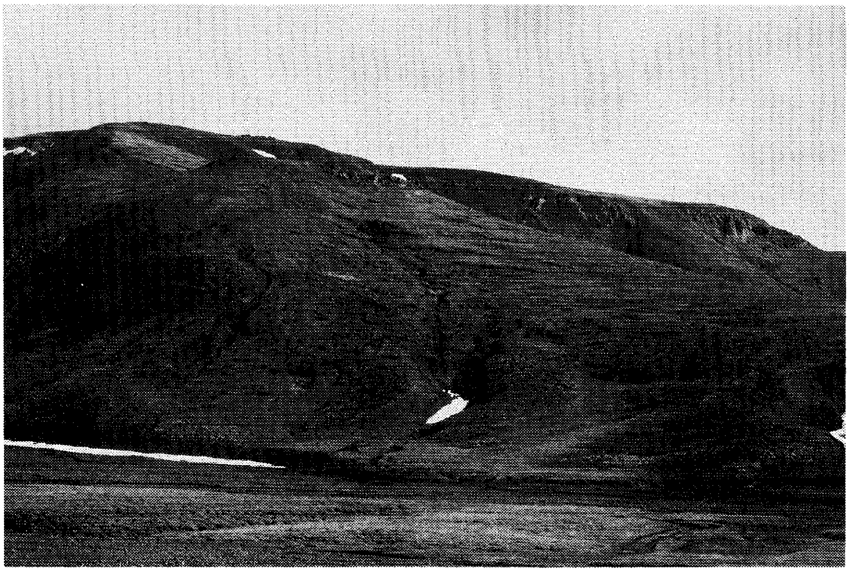

Photo 3 Solifluction lobes and terraces including the excavated site 8507-1 (arrow) at the Thjofafell

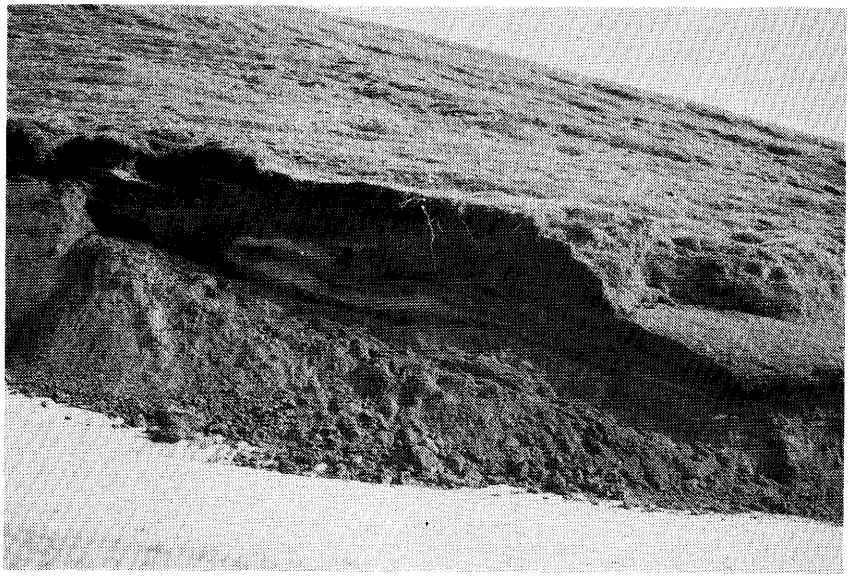

Photo 4 The excavation 8507-1.
An overturned structure and resulted reversed stratigraphy of volcanic ash layers are easily noticed

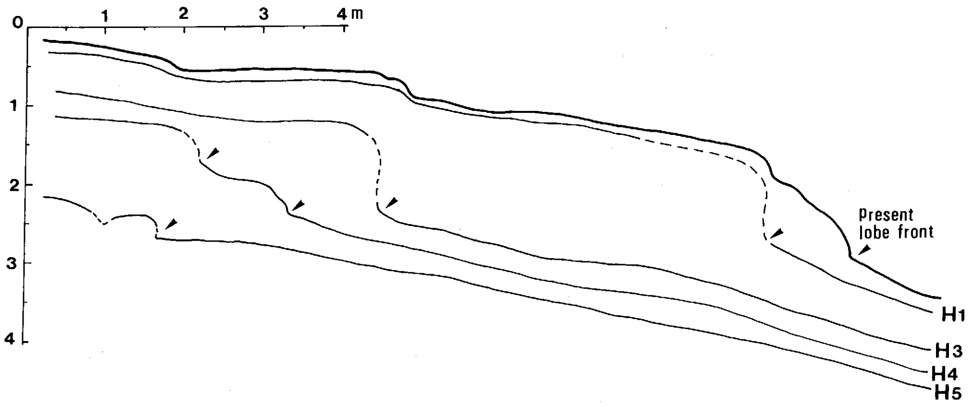

Fig. 5 Reconstructed longitudinal profiles of the solifluction lobe 8507-1 at each period just before the falls of the Hekla 1, the Hekla 3, the Hekla 4, and the Hekla 5, respectively

It is, as a whole, easily noticed that almost all tephra layers indicate the inverted structure, reflecting the rolling-over phenomena of the solifluction lobe front. On the basis of this structure, the position of solifluction lobe front at the time when each tephra layer fell can be easily traced as follows (Figs. 4 and 5): the Hekla 1: at A in Fig. 4, the Settlement Succession: at B, the Hekla 3: at C, the Hekla 4: at d and D, and the Hekla 5: at E. Consequently, the front has advanced at an average rate of 1.4 mm per calender year during the last 900 years (1.25 m since A.D. 1104), 2.4 mm during the period from the fall of Hekla 3 to that of Hekla 1 (4.8 m/2,000 years between *ca.* 2,900 yBP and 900 yBP; 2.6 mm/y = 4.4 m/1,700 years between the Settlement Succession and the Hekla 3), 1.6 mm/y from the Hekla 4 to the Hekla 3 (2.6 m/1,600 years between *ca.* 4,500 yBP and 2,900 yBP), and 0.6 mm/y from the Hekla 5 to the Hekla 4 (1.6 m/2,500 years between *ca.* 7,000 yBP and 4,500 y BP), respectively, as shown in Fig. 6. The average rates obtained from the another excavation (8507-2) in the Thjofafell are shown in Fig. 7, in which the average rate of front advance was the largest during the period from the fall of the Hekla 4 to that of the Hekla 3.

If we observe the internal structure of this solifluction lobe in detail, there are many phenomena to be noticed:

(1) The riser just before the fall of the Hekla 5 was not so well developed as that around the time of the Hekla 4 fall to the present;

(2) The riser prior to the fall of the Hekla 4 was two-stepped, of which the lower one (at d in Fig. 4) was buried by the Hekla 4 pumice and did not advance more;

(3) The left half of the tread in Fig. 4 mainly consists of tephra layers showing the normal stratigraphy, at least in the uppermost 1 m, except a minor disturbance of the Hekla 3 in the uppermost part of the tread. We can see the normal accumulation of volcanic ashes without any inverted stratigraphy related to the solifluction movement. Whereas the part just beyond the riser corresponding to the uppermost end of the lowernext tread has a perfectly normal stratigraphy of volcanic ashes without any slope

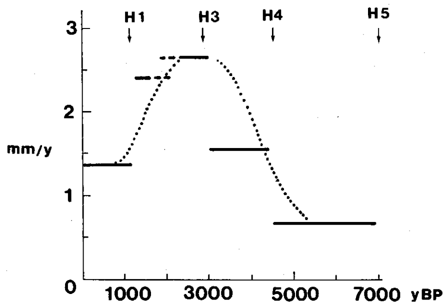

Fig. 6 Changes of the moving rate of the solifluction lobe front at the site 8507-1 since *ca.* 7,000 yBP

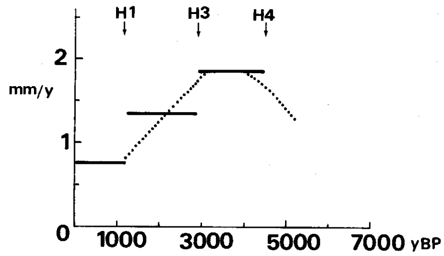

Fig. 7 Changes of the moving rate of the solifluction lobe front at the site 8507-2 since *ca.* 4,500 yBP

deposits, covering an original fluvio-glacial gravels beneath of them;
(4) There is no evidence that movements by shearing have occurred along distinct shear planes;
(5) It appears that an abrupt collapse or slumping of the riser had not occurred.

4. Discussion

Internal structure

Solifluction always indicates the overriding and burial of land surfaces immediately in front of the risers of solifluction lobes. Consequently, at the base of such landforms there often occur buried phenomena which display characteristics inherited from the land surface by forward movement of the lobe front. Washburn (1947), Troll (1958) and Benedict (1970) described inverted soil profiles, reflecting the rolling over-phenomena of the solifluction lobe front.

Using some volcanic ash layers as the marker beds, instead of buried humic layers, excavations of solifluction lobes in Iceland has revealed an excellent record indicating an integrated dislocation of deposits by solifluction movement in the last *ca.* 7,000 years.

It must be stressed that shear planes can not be found. Therefore the slab slide did not occur in the downslope movement of solifluction[2]. The internal structure shown by volacanic ash layers represents a good example that failures leading to movements of solifluction on the slope occur under conditions by viscous flow rather than by slip failure. The rolling over-phenomena as well as the inverted stratigraphy are so evident in the excavations of solifluction lobes that an abrupt collapse and resulted colluviation in front of the risers appears not to have been primarily significant for the movement of the solifluction lobe. Matthews *et al.* (1986) stressed that colluviation plays a major roll for the formation and movement of solifluction features. We can discuss this problem on the basis of the internal structure, particularlly the dislocation pattern, of constituent material of the solifluction lobe, that will be in detail done in the future.

The fact to be described is that the constituent layers of solifluction lobes represent a normal statigraphy at the uppermost part of treads which correspond to the place just in front of the riser (see Fig. 4), while they are remarkably dislocated beneath the lower half of the tread. If such stratigraphic relation is established in the other solifluction lobes, a lot of solifluction lobes on a extensive slope as shown in Photo 3 could initiate to be formed in the different places on the slope, not always gradually from the upslopes.

Rate of downslope movement of solifluction lobe

Volcanic ash layers with radiocarbon dates rolled over by the solifluction lobe make it possible to obtain information on the timing, amount and the long-term average rates of movements.

Figure 8 shows the average rates of downslope movement since the fall of the Hekla 1 (during the last 900 years) obtained from 28 excavations in Iceland. It is likely, as a whole, that the downslope movement basically depends on the gradients of slopes.

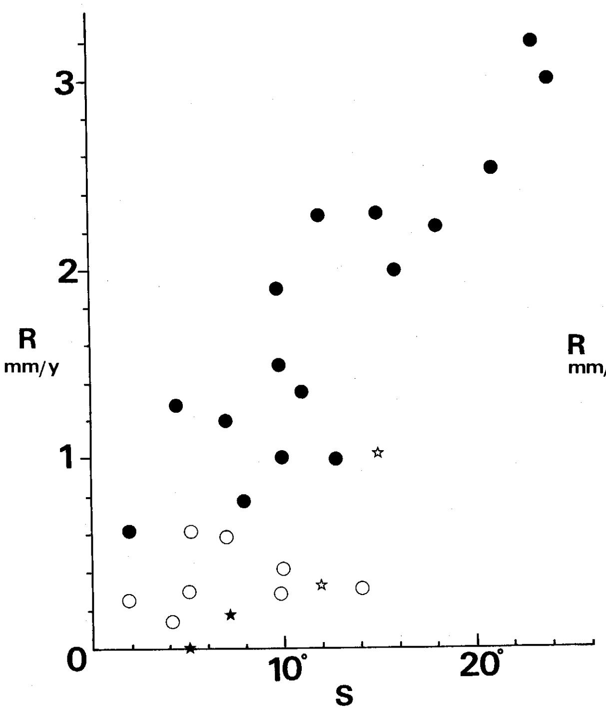

Fig. 8 Relation between the rates of downslope movement of solifluction lobes and gradients of slopes since the fall of the Hekla 1 erupted in A.D. 1104. solid circle: rates in the Thjofafell and its surroundings, 650-850 m asl.; circle: the Thorskafjardalheidi, 340-450 m asl.; star: the Holtavorduheidi, 250 m asl.; solid star: the Laxardalheidi, 100-150 m asl.

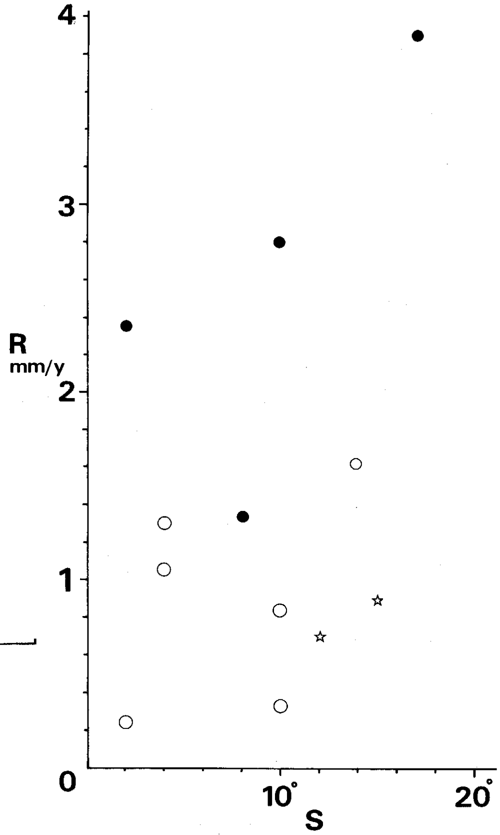

Fig. 9 Relation between the rates of downslope movement of solifluction lobes and gradients of slopes during the period of 2,900 yBP to *ca.* 900 yBP

Particularly on slopes steeper than 10°, this relation becomes clear. However, restricted to the rates from higher areas (650-850 m asl.) such as the Thjofafell and its surroundings in the central highlands, the rates apparently depend on the steepness of slopes even on the slopes less than 10°.

In the lower elevations, such as the Laxardalheidi (100-150 m asl.), the Holtavorduheidi (200-250 m asl.) and the Thorskafjadalheidi (350-400 m asl.), there is no distinct relation between the rates and the slope gradients. Particularly in the Laxardalheidi, the downslope movement seems to have not occurred on the slope less than *ca.* 5° since the fall of the Hekla 1. Consequently no clear rate-slope gradient relation under 10° in Fig. 8 is mainly due to the data from these regions with a lower altitude. It should be noticed that the rate of downslope movement by solifluction appears to be influenced through an altitude of individual regions. The rates from the region higher than 600-850 m asl. are obviously larger than those from the other regions with lower altitude. These differences of the rate in accordance with the altitude may reflect the local environmental condition whether the permafrost exist at present.

The rates during the period between the fall of the Hekla 3 and that of the Hekla 1 are larger than those in the last 900 year (compare the rates in Fig. 8 with those in Fig. 9), although the moving rate-slope gradient relation is not so clear as that in the last 900 years.

Changes of the rates of downslope movements can be also discussed by means of the tephrostratigraphy. The results obtained from two large excavations are shown in Figs. 6 and 7. It is apparent that the moving rate has changed at least since the fall of Hekla 5. The largest rate was recorded at about 2,000-3,000 years ago in the excavation of 8507-1 and at about 3,000-4,000 years ago in the excavation of 8507-2. The rate during *ca.* 2,000-4,000 yBP is about 2 fold larger than that in the last 900 years. On the contrary, the rate prior to 4,000-4,500 yBP is smaller than that in the last 900 years. It can be said that the fastest downslope movement of solifluction lobes had occurred during the Neoglaciation, in contrast to the slowest during the Climatic Optimum. Mass movements indicated by solifluction lobes should have been strongly affected by the climatic changes during Holocene.

Radiocarbon dates suggest that conditions were favorable for the lobe formation in periglacial environments throughout the world between about 3,000 and 2,500 yBP (Benedict, 1976). Tephrostratigraphic observation in Iceland reveals that the solifluction lobe has already existed at about 7,000 years ago. However, it seems that not only the higher rate of downslope movement during the Neoglaciation, but also the difference of the rate at each altitude during the last 900 years are significantly reflect the condition whether the permafrost was developed.

Benedict (1976) stressed that long-term average rates of frontal advance, ranging from 0.6 to 3.5 mm per calender year, are significantly slower than maximum rates of movement measured on the surfaces of active lobes in comparable environments. He also pointed out that estimates of sediments transport by solifluction lobes will be an order of magnitude too high, if they are based on velocity measurements obtained in midtread positions. Although there is no direct measurement of current rate of solifluction downslope movement on a tread in Iceland, non vegetated tread with active gravel

Photo 5 Vegetated lobe front and sparsely vegetated tread of solifluction lobe near the Thjofafell

Photo 6 Stripes on the midtread of the solifluction lobe at the Thorskafjardalheidi

stripes (Photo 5) probably moves downslope at similar rate as those gained in various periglacial regions of the world.

Current downslope movement by solifluction, frost creep, and slope wash on the tread surface mostly stops at the upper edge of vegetated risers (Photo 6). This surficial movement seems to be significant for the downslope movement of solifluction lobes, because the rolling over-phenomena can be caused by the supply of sediments toward the risers, and because no collapse of riser or no marked colluviation in front of the riser occurred.

Factors affecting the rates of downslope movement

Harris (1972) concluded that maximum soil movement in turf-banked solifluction lobe occurs where saturated conditions persist longest, not where the slope is greatest. He stresses at the same time that where soil moisture conditions during spring were similar, greater movements were recorded on steeper slopes, and the slope gradient was clearly a secondary factor. These conclusions were led from the measurement of current downslope movement.

On the basis of rates obtained in Iceland, gradient of slopes seems to be the primary factor, not a secondary, if we discuss the average rate of the long-term (several hundred years) downslope mass movement. Because solifluction lobes were excavated at 28 sites with various conditions each other in respect to the following factors: constituent materials from tephra itself to fluvioglacial sand and gravel or Tertiary basalt deteritus with silty matrix, water content, vegetation cover, slope gradient and direction of slope and clmate, particularly precipitation and temperature related to the freeze-thaw regime, and the presence of permafrost.

Although soil moisture content, vegetation cover and winter frost heave should be major factors controlling the rate of current soil movement on the tread, they appear to be represented by differences of moving rates on the almost same gradient of slopes. For instance, the rate of an solifluction lobe influenced by the meltwater from a snow patch upslope, is relatively large. In order to discuss such influence of local condition, the other 26 excavations of solifluction lobes in Iceland will be individually examined in the near future.

5. Concluding Remarks

1. Tephrostratigraphic studies of solifluction lobes should be more reliable ways in which the features can be used for discussions of paleoclimatic reconstruction, the calculation of moving rate and the the mechanism of movement of solifluction lobes.
2. Fronts of solifluction lobe have advanced at an average rate of 3.2 mm at maximum since the fall of the pumice Hekla 1 erupted A.D. 1104, and of 4 mm between 2,900 yBP and 900 yBP.
3. Excavations of lobes at 28 localities represent that the downslope movement basically depends on gradients of slopes, particularly on the steeper slopes than 10°.
4. In the central highlands, however, with an altitude over 650 m asl, where the

discontinuous permafrost is developed, the rate depends on the gradient of slopes even on the slopes less than 10°.

5. The rate of downslope movements has changed at least since the fall of Hekla 5, in the last 7,000 years. The largest rate was recorded during the period between 4,000 yBP and 2,000 yBP. This rate is two fold larger than that of last *ca.* 900 years.

6. Environmental conditions particularly related to the existence of permafrost may have been much favorable for the downslope movement of solifluction lobes.

7. As no shear planes can be found, the slab slide has not occurred in the downslope movement of solifluction.

8. The tephrostratigraphic and tephrochronological examination of the solifluction lobe will be further useful for a variety of discussion, for instance, how the solifluction lobe initiates to be formed, how it moves to displace its constituent sediment layers, and so on. Instrumentation for the measurement of present movement of solifluction lobes must be, at the same time, installed in relation to the annual and the daily freeze-thaw cycles and the timing of movement.

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Notes

1) Mr. Skuli Vikingsson taught the author that the characteristic scoria with two fall units of an upper grey and a lower black color, respectively is called as the Settlement Succession, that is the fall at around the time of the Settlement of people in Iceland in the middle of 9th century.

2) The author observed such type in Spitzbergen, which represents a wholly different internal structure.

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