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Solifluction resulting from one-sided and two-sided freezing: Field data from Svalbard

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Abstract: Two years of observation of soil movement on three Arctic slopes underlain by permafrost demonstrate convex downslope profiles at two depths, corresponding respectively to the middle and basal parts of the active layer. The absence of superficial movement reflects the paucity of diurnal freeze-thaw action throughout the year and soil desiccation in summer. The middle layer movement is attributed to annual frost creep/gelifluction associated mainly with frost heave during downward freezing and subsequent thaw subsidence. This type of movement prevails where the lower part of the active layer is composed of coarse materials that reject ice lensing, and over the long term eventually develops typical solifluction sheets or lobes. In contrast, the basal layer movement represents plug-like flow originating from thawing of ice lenses developed during upward freezing from the top of permafrost. Plug-like flow occurs where the whole active layer consists of muddy sediments. Such a deep movement is rarely accompanied by a specific surface feature, despite causing large mass transport.

key words: solifluction, two-sided freezing, frost heave, permafrost, Svalbard

1. Introduction

Frost heave followed by thaw consolidation results in slow soil movement, broadly called solifluction, which acts widely over cold-climate slopes. Frost heave normally accompanies downward freezing from the ground surface (one-sided freezing). Recent studies have also addressed frost heaving in the opposite direction, which is associated with upward freezing from the top of permafrost (*e.g.*, Rein and Burrous, 1980; Mackay, 1984). Upward freezing occurs mainly in cold permafrost regions, since freeze-back from the base of the active layer (seasonally thawed layer) requires a significant thermal gradient in the uppermost permafrost. As a consequence, two-sided freezing (from both the ground surface and the top of permafrost) may govern mass movements on many High-Arctic slopes (*e.g.*, Mackay, 1981; Egginton and French, 1985; Lewkowicz, 1992). Large heave associated with upward freezing, which causes desiccation of the upper part of the active layer, tends to be compensated by very small heave associated with downward freezing (Mackay, 1981).

The difference in the heaving direction affects the distribution of ice lenses formed in the frozen active layer Producing ice lenses near the base of the active layer, upward freezing possibly leads to deeper soil movement and thus thicker landforms than downward freezing Nevertheless, field data highlighting such a difference have so far been very few

Solifluction and associated parameters were observed on three Arctic slopes during geomorphological expeditions to Svalbard in 1990–1992 Although the technical level at that time limited the accuracy of data, observations revealed significant spatial variation in the type of solifluction, partly affected by two-sided freezing This paper aims at describing the nature of solifluction on these slopes and discussing factors governing spatial variability

Solifluction has been observed in some locations in Svalbard The earliest observations in the late 1950's provided data on surface movements on slopes dipping at 2–25° (Budel, 1977, Jahn, 1985) More recently, Repelewska-Pękalowa and Pękala (1993) argued the effects of aspect and active layer thickness on the surface velocity Long-term observations over 23 years revealed the inter-annual variation in the surface velocity in relation to climatic fluctuations as well as the spacial variation in movement reflecting surface periglacial features (Åkerman, 1993, 1996) These studies have revealed solifluction having surface velocities on the order of centimeters per year and reaching several decimeters depth, and presented empirical relationships between climate and solifluction However, they are lacking in detailed observations of ground temperature and frost heave, both of which directly control solifluction processes, in addition, the effect of two-sided freezing has rarely been evaluated An exception is a recent study by Sawaguchi (1995) who discussed the origin of subsurface velocity profiles based on monitoring of ground temperature and frost heave With regard to two-sided freezing, however, he argued that its effect is negligible at his measurement sites Most previous studies have virtually lacked observations of soil movement at depth, because only shallow sensors (<80 cm) were used In our study, deeper sensors (100–150 cm) were installed down to the frozen layer, so that movement in the basal active layer was detected

2. The study sites

Observations were undertaken at three slopes (KL, AL and AH sites) in central Spitsbergen, Svalbard (Fig 1) The KL site (elevation 30 m a s l) is situated in a coastal region near Kapp Linné, the southern cape located at the mouth of Isfjorden Colluvium derived from a schist rockwall has been advancing on a marine terrace exposed during the early Holocene, developing a turf-banked solifluction sheet with a front 50–100 cm high (Fig 2) The colluvium is composed mainly of sandy loam including a number of angular clasts, and overlies the marine sand and gravel layers (Fig 3) One third of the matrix (finer than 2 mm) of the colluvium comprises silt and clay, which indicates high frost susceptibility in contrast to the underlying coarser marine sand (Fig 4)

The other two sites were established in Adventdalen, a wide U-shaped valley, located 25 km east of Longyearbyen The AL site (90 m a s l) lies on a riverbank slope where a turf-banked solifluction sheet with a front ~50 cm high extends toward the present river bed (Fig 5A) Excavation of the frontal part of the sheet revealed that the colluvium (sandy loam) ~60 cm thick overlies fluvial sand, producing a buried organic layer between the two layers (Fig 6A) In addition, caterpillar-like advance is indicated by the overturning loamy

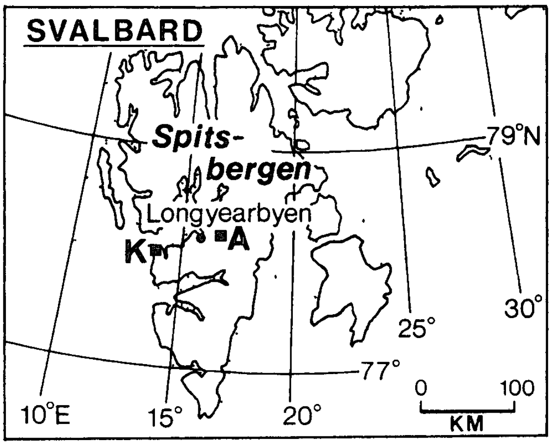

Fig 1 Location of the study areas K = Kapp Linné and A = Adventdalen

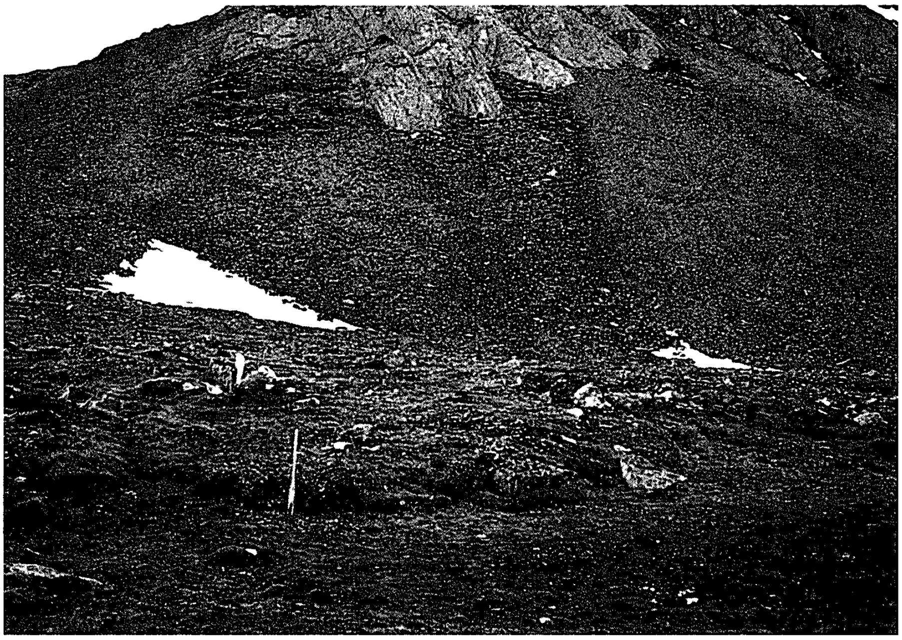

Fig 2 A turf-banked solifluction sheet in Kapp Linné (KL site) Loamy sediments derived from the schist rockwall have been advancing on the marine terrace The stake at the front is ~1 m high

layer (Figs 5B and 6A) On the upper part of the slope lie lobate features exhibiting a different sedimentary structure Instead of an overturning layer, the frontal part indicates a number of shear planes along which the colluvium appears to have slipped (Fig 6B) Upslope from the lobes lies a scarplet from which the sliding mass has detached The thickness of the sliding mass is similar to that of the solifluction sheet, which suggests that the slip occurred over the thawing plane in early summer Accordingly, two kinds of mass movements, solifluction and active layer glide (*e.g* , Lewkowicz, 1988), govern this river-bank slope Both processes occur in the colluvium originating from the till and shale bedrock exposed near the top of the slope The reason for the operation of multiple processes despite the material being the same is unclear, but during the thawing period a

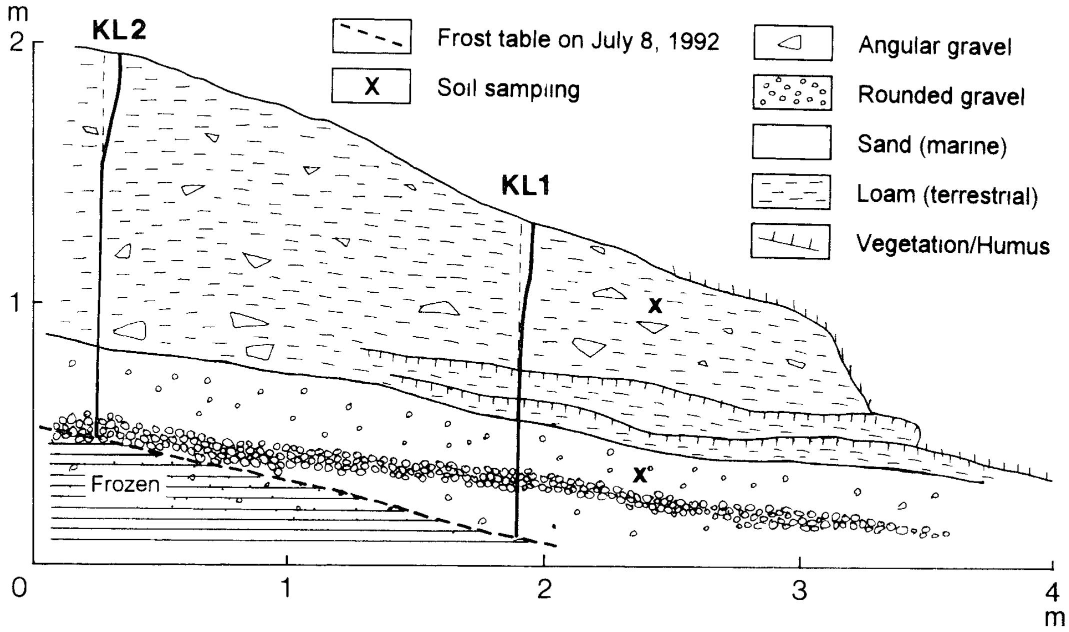

Fig 3 The longitudinal section of the frontal part of a solifluction sheet at the KL site, showing deformation of strain probes (KL1 and KL2) over two years

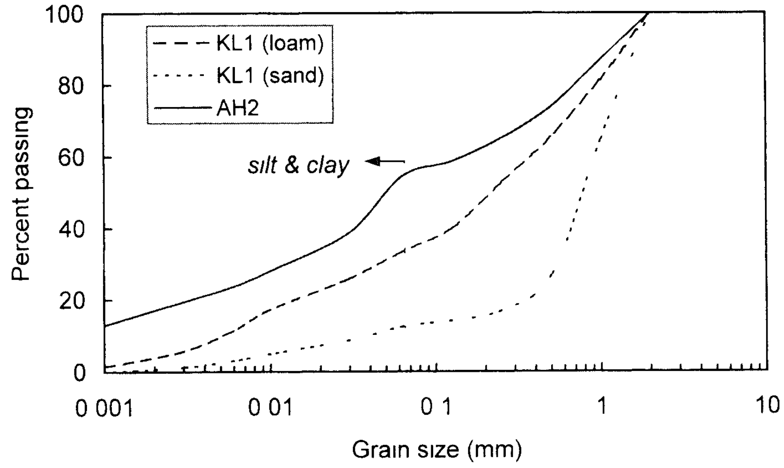

Fig 4 Grain size distribution of sediments (<2 mm) at the KL and AH sites

more unstable soil condition is expected from the upper slope where the steeper slope results in larger shear stress, and meltwater from the late-lying snowbank upslope may lower the shear strength

The AH site (270 m a s l) was constructed on a rock-controlled bench formed on the northern slope of Mt Skolten Muddy sediments derived from till and shale bedrock compose the superficial layer thicker than 120 cm Clasts are few in the uppermost 50 cm of the sediment, but increase in the lower layer Half of the matrix (<2 mm) of the upper sediment comprises silt and clay fractions (Fig 4) This suggests that the sediment has a high plasticity as well as frost susceptibility This slope lacks any lobate forms, but displays wide non-sorted stripes spacing at ~250 cm (Fig 5C) Beneath the vegetated

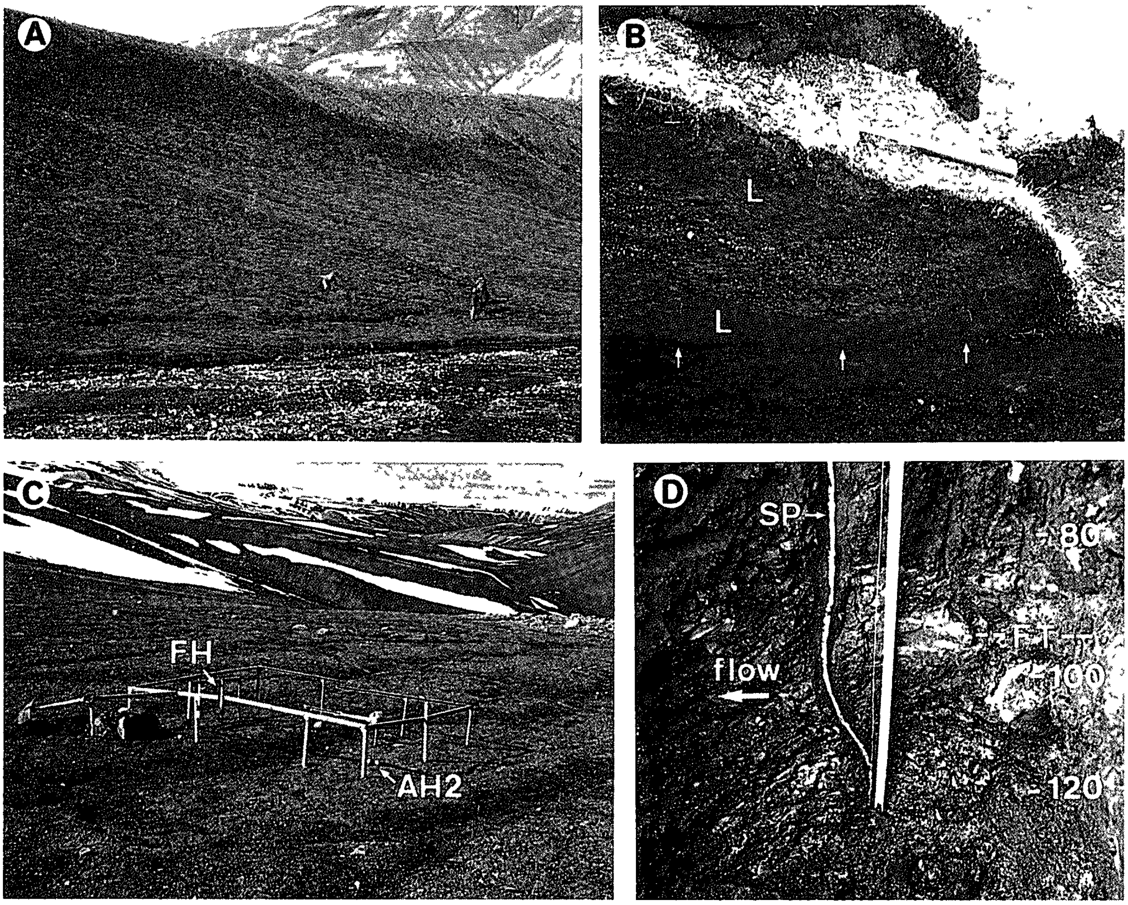

Fig. 5. The measurement sites in Adventdalen. (A) A turf-banked solifluction sheet at the AL site, advancing on the present river bed. (B) The longitudinal section of the front of the solifluction sheet at the AL site, displaying the overturning loamy layer (L) and the buried organic layer (arrow). (C) Instrumentation on non-sorted stripes at the AH site, showing the dilatometer for recording frost heave (FH) and the location of Probe AH2. (D) Deformation of Probe AH2 (SP) over two years, representing plug-like flow in the basal active layer. Approximate depth in centimeters below the ground surface is shown on the right margin. Ice lenses were observed over 105–115 cm depth, below the frost table (FT) on July 15, 1992.

furrows lies a soil wedge 50 cm in the vertical dimension (Matsuoka and Hirakawa, 1993).

Climatic conditions are slightly different between Kapp Linné and Adventdalen. Summer temperatures are not dissimilar, but the more continental location leads to a ~5°C colder winter in the latter area (Åkerman, 1987). The mean annual air temperature (MAAT) at Kapp Linné (Isfjord Radio Station) is −4.9°C (Åkerman, 1996), which suggests that the KL site belongs to a transitional area between the continuous and discontinuous permafrost zones. The active layer thickness is on average ~1 m, but ranges from 0.4 m to 2 m dependent on vegetation and ground materials (Åkerman, 1996). MAAT in Adventdalen can be estimated from the long-term mean value (−6.5°C) at Longyearbyen (Svalbard Lufthavn). Assuming a lapse rate of 6°C km^{-1}, MAAT was computed to be ~−7°C at the AL site and ~−8°C at the AH site. Thus permafrost at the two sites seems to be nearly continuous. Reflecting the similarity in the summer temperature, the active layer in Adventdalen is also 1±0.5 m thick.

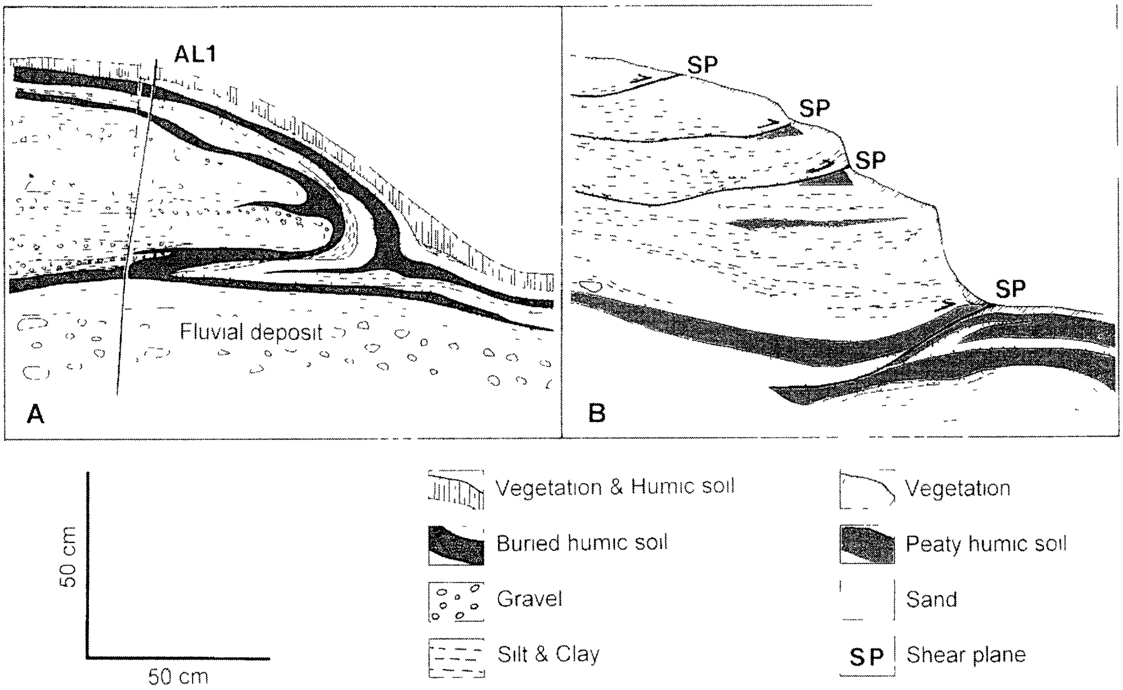

Fig. 6. *Two kinds of soil deformation at the AL site, showing the longitudinal section of the frontal part of lobate features. (A) Solifluction. Deformation of a strain probe (AL1) over two years is illustrated. (B) Active layer glide.*

The observation period, from July 1990 to July 1992, experienced slightly higher (~1–2°C) MAAT in comparison with the long-term mean value (Table 1, see also Åkerman, 1996, for the Kapp Linné records). This was caused mainly by the warm winters, apart from a short cold period in February 1992 when significant thermal contraction cracking was observed in Adventdalen (Matsuoka, 1999). The summer temperatures showed normal values, suggesting that the active layer thickness in the observation period represents the average condition.

3. Instrumentation

Downslope soil movement was measured with a strain probe made of a flexible spring steel strip 0.3 mm thick, 15 mm wide and 100–150 cm long, on which strain gauges were attached at 20–30 cm intervals and coated with silicon rubber (see for details Matsuoka, 1994; Yamada and Kurashige, 1996). During the summer of 1990, five probes were installed into a 6 cm-diameter hole dug perpendicular to the slope surface. The base of the probes was placed 10–30 cm below the frost table. The initial linearity of a probe was achieved by attaching the probe to the downslope side of the hole. Then, the space between the hole and probe was backfilled with the same soil. The probe responds only to movement in the longitudinal direction. The original plan was that manual reading with a strain meter once per year will provide an annual increment in soil movement. However, data from three probes were partly missing due to the breakage of cables by animals or incomplete waterproofing. Accordingly, all probes were excavated in 1992 to acquire the cumulative movement for two years. The soil movement was represented by three parameters: the surface velocity V_S, volumetric velocity V_{VL} and maximum depth of movement D_M.

Ground temperatures at various depths were recorded at 3-h intervals with platinum probes connected to a multi-channel data logger. The probes were installed in a 6 cm-diameter hole as well. The thermal disturbance caused during the installation probably vanished within a few weeks. At the KL site, temperatures at six depths (0, 5, 20, 60, 120, 180 cm) were recorded for one year from July 1991 using a Hakusan Datamark LT2001 logger, one of the earliest field data loggers, having relatively low accuracy (~±0.5°C). Ground temperatures at the AH site were monitored at five depths (0, 20, 60, 100, 150 cm) from August 1990 to July 1992, using a Hakusan Datamark LS3000ptv logger that provides better accuracy (~±0.2°C). However, data stored in this logger showed abnormal values after December 1991, thus records in 1992 were unavailable. Temperature was not monitored at the AL site, but records at an ice-wedge site lying 500 m west of the AL site (see Matsuoka, 1999) can be used in place of data at the AL site.

Frost heave of the ground surface was monitored only at the AH site (near Probe AH2), using a dilatometer (see for more details, Matsuoka, 1994, 1999) connected to the Datamark logger. The dilatometer was fixed to the angle-iron bedstead (Fig. 5C). Upheaving of the bedstead was minimized by attaching a timber to the base of the legs and anchoring the base in permafrost. The base was initially placed at 115 cm depth, that is, 30 cm below the frost table on the installation (August 6, 1990). However, unexpected thawing to a depth of 100–120 cm in the late summer led to significant upheaving of the bedstead during freeze-back; hence, data analysis required a correction with reference to the upheaving. The data logger recorded frost heave concurrently with ground temperature, heave data were also valid from August 1990 to December 1991.

4. Results and discussion

4.1. *Kapp Linné solifluction sheet (KL site)*

Two probes (KL1 and KL2) installed near the lobe front showed similar movements (Fig. 3). The cumulative surface movement during the two years reached ~5 cm, in terms of the surface velocity, $V_S = \sim 2.5$ cm yr^{-1}. The maximum depth of movement D_M was 40–60 cm. The velocity profile showed downslope convexity above 20–30 cm depth and concavity below (Fig. 7). The D_M value is half the thickness of the colluvium near the front (Fig. 3), which appears to reflect overturning of the moving soil mass. No deformation was observed in the marine sand. The velocity profile is comparable with that commonly observed on solifluction sheets and lobes in the Arctic and Subarctic regions (*e.g.*, Williams, 1966, Harris, 1972, Jahn, 1991, Price, 1991, Sawaguchi, 1995).

The mean annual ground temperature (MAGT) in the upper part of the active layer was −4.3°C during the second year (from the 1991 summer to 1992 summer) (Table 1). Since MAAT in the first year (1990–1991) was 1–2°C higher than that in the second, MAGT in the first year would have been ~−3.0°C. The active layer thickness was estimated from the isotherms to be ~150±20 cm; the validity of this estimation was partly confirmed by excavation showing consistency between the logger data and observed thaw depth on July 8, 1992 (Fig. 8).

Diurnal freeze-thaw cycles took place about 20 times a year at the ground surface (Fig

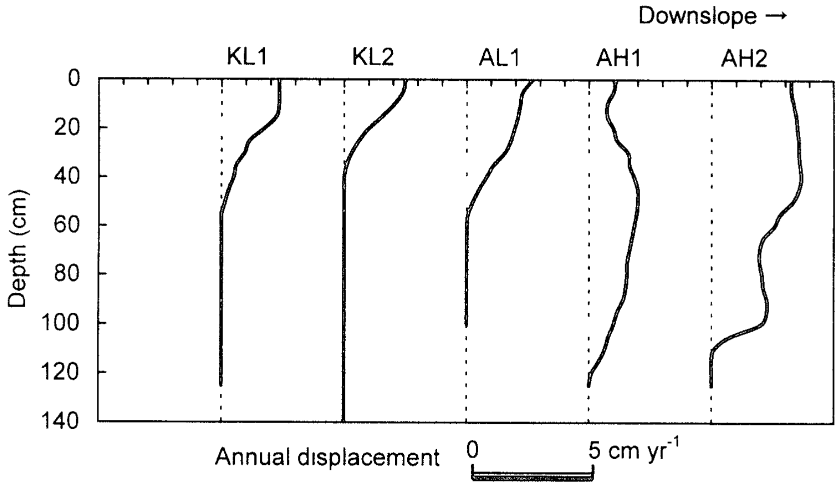

Fig 7 Deformation of strain probes, shown in terms of the annual displacement

Table 1 Ground temperature and frost heave data

Site	MAGT/MAAT (°C)		Freeze-thaw frequency (yr^{-1})[a]		Active layer depth (cm)			Maximum frost heave (cm)	
	1990/91	1991/92	1990/91	1991/92	1990	1991	1992	1990/91	1991/92
KL	—	−4 3[b]	—	24	—	145	>105	—	—
AL	−4 0[b]	−5 7[b]	7	23	55	60	>40	—	—
AH	−5 2[b]	—	15	—	105	115	>93	5 0	>1 3
Lufthavn	−4 2[c]	−5 4[c]	—	—	—	—	—	—	—

[a] Number of temperature oscillations across the zero curtain (between −0 5 and 0 5°C) at the ground surface

[b] Average of the mean annual ground temperatures at depths of 0, 20 and 60 cm

[c] Mean annual air temperature

8), but they seem to have rarely, if at all, contributed to soil movement This is because, first, of the small temperature ranges (2–3°C at the ground surface) and second, of possible desiccation of the near-surface soil during the autumn freeze-thaw periods The lack of diurnal freeze-thaw action is mirrored by downslope convexity in the upper velocity profile (Fig 7), whereas concave profiles prevail in regions dominated by diurnal action (*eg*, Pérez, 1987, Matsuoka, 1998) In other words, annual freeze-thaw action dominates solifluction If excess ice is most responsible for raising soil mobility on thawing, the velocity profiles would indicate that ice lensing occurred mainly at 10–50 cm depth where the greatest differential movement was observed The penetration of the 0°C isotherm implies that the seasonal ice lensing in 1991 occurred mainly between the end of August and early September, on thawing, the soil moved downslope in mid- June or slightly later (Fig 8) Consequently, the movement recorded on the probes is considered to have resulted from seasonal ice segregation accompanying downward freezing, followed by thaw consolidation that induced solifluction in a classic sense, *ie*, annual frost creep and/or gelifluction

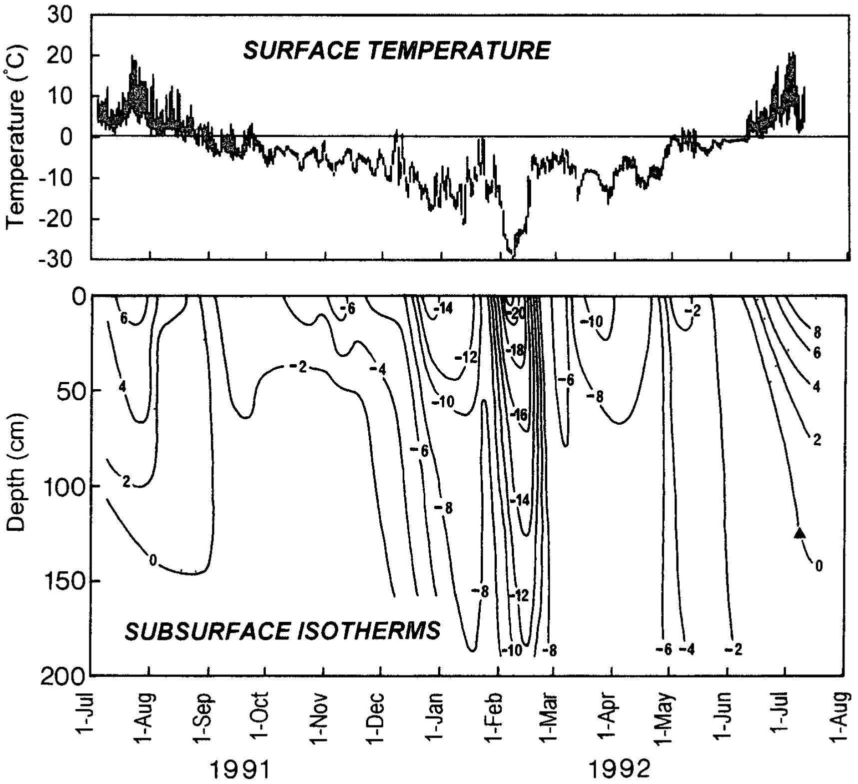

Fig 8 *Annual variation in ground temperature at the KL site Isotherm intervals are 2°C The dotted area represents the active layer The triangle indicates the depth of the frost table confirmed by excavation*

4.2. Adventdalen solifluction sheet (AL site)

Probe AL1 installed near the lobe front showed $V_S = 2.5$ cm yr^{-1} and $D_M = 55$ cm, both were comparable with values at the KL site, despite the slightly gentler slope at the AL site (Table 2) The velocity profile was on the whole convex downslope (Fig 7) The D_M value was slightly shallower than the base of the colluvium at 60 cm depth (see Fig 6A)

The active layer at the ice-wedge site near the AL site was 55-60 cm thick, considerably thinner than that at both the KL and AH sites (Table 1). The low value mainly originated from the peaty sediment which has low thermal conductivity in summer (*e.g*, Williams and Smith, 1989, p 112). The active layer thickness at the ice wedge site may thus slightly underestimate the value at the AL site In fact, excavation on July 16-17, 1992 showed some disparity in the frost table depth. 51 cm at AL site compared with 40 cm at the ice-wedge site. On the assumption of the 25% underestimation, the active layer thickness at the AL site is estimated to be ~70 cm Thus, the active layer nearly represents the thickness of the colluvium near the front, and the upper 75% of the active layer is in motion

Diurnal freeze-thaw cycles are infrequent and of small ranges at the AL site (Table 1), suggesting that they are almost inadequate to produce soil movement The convex velocity profile probably indicates the prevailing annual freeze-thaw action. In summary, the solifluction sheets at both the KL and AL sites are moving downslope at similar rates,

Table 2 Solifluction data

Probe ID	Slope angle (degrees)	Elevation (m a.s.l.)	Probe lengh (cm)	Observation period (years)	Surface velocity (cm yr^{-1})	Volumetric velocity (cm^3 cm^{-1} yr^{-1})	Maximum depth of movement (cm)	Landform[a] type
KL1	13	30	125	2	2.4	68	56	TBS
KL2	22	30	150	2	2.5	45	39	TBS
AL1	8	90	100	2	2.5	82	55	TBS
AH1	15	270	150	2	1.1	165	120	NSP
AH2	7	270	150	2	3.2	216	110	NSP

[a] TBS: turf-banked solifluction sheet, NSP: non-sorted stripes.

mainly by annual frost creep/gelifluction resulting from downward freezing.

4.3 *Adventdalen non-sorted stripes (AH site)*

The ground temperature data indicate that MAGT in the upper active layer was −5.7°C during the first year (1990–1991), and possibly fell to ∼−7°C in the second year (see Table 1). The significant fluctuation in temperature during the winter (Fig. 9) suggests that the thickness of the snow cover rarely exceeded several decimeters, which permitted upward heat flow and promoted ground cooling. The active layer thickness was 105 cm in 1990 and 115 cm in 1991, although the values may involve an error up to ±10 cm. Such a thick active layer despite a low MAGT reflects the warm summer (see Fig. 9) and lack of vegetation, both of which favor downward heat flow in summer. Diurnal freeze-thaw cycles were infrequent (15 events yr^{-1}) despite the lack of vegetation.

The infrequent freeze-thaw cycles were mirrored by frost heave activity (Fig. 9). Only a few short-term events took place annually, which agrees with heave data reported by Sawaguchi (1995) from the upper part of this slope (700 m a.s.l.), but contrasts with the high frequency on mid-latitude alpine slopes (*e.g.*, Matsuoka, 1998). In both years, a small heave event in the early winter was followed by larger seasonal heaving. The seasonal heave apparently amounted to 1–2 cm and ceased when the freezing front reached 30–50 cm depth. However, heaving is most likely to have continued slightly longer. Heaving in this period, occurring mainly below 50 cm depth, is considered to have produced simultaneous upheaving of the bedstead and dilatometer, which led to the apparent termination of seasonal heaving. The subsurface 0°C isotherm indicates that upward freezing and associated ice lensing would have occurred also in this period (Fig. 9), if the seasonal heave amount involved this component. The annual upheaving of the bedstead was computed from changes in the heights of both the angle iron and dilatometer above the ground surface between 9 August 1990 and 22 June 1991. By subtracting the heaving of the bedstead, the seasonal heave of the ground surface during the first winter was estimated to be 5.0 cm (Table 2). Accordingly, the frost heave below 50 cm depth amounted to ∼3–4 cm, although it is impossible to separate downward and upward heaving components.

The two probes (AH1 and AH2) experienced downslope movement which was much deeper than expected and displayed velocity profiles similar to "plug-like flow" (Mackay,

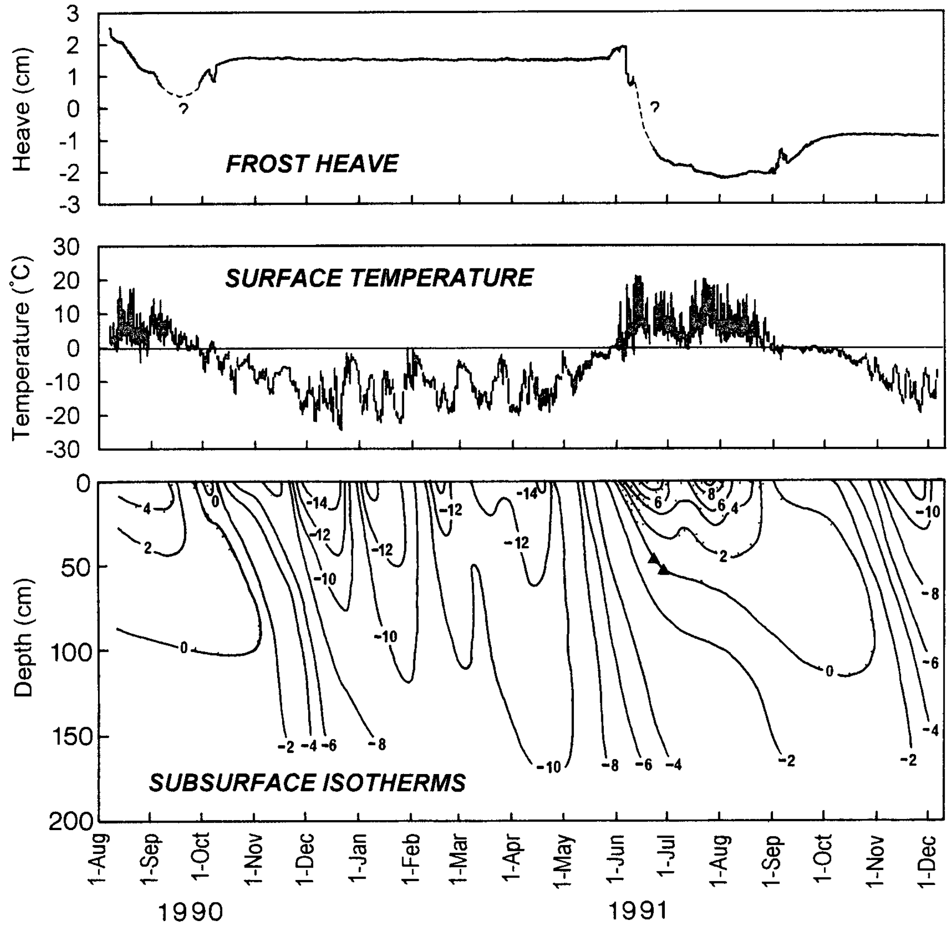

Fig 9 Frost heave and ground temperature data at the AH site. Isotherm intervals are 2°C The dotted area represents the active layer The triangle indicates the depth of the frost table confirmed by excavation Note that frost heave in early winter is significantly underestimated by upheaving of the bedstead

1981, Egginton and French, 1985). Although the base of the probe was located 5-10 cm below the permafrost table, it was difficult to identify the datum line, which is commonly given by the straight segment on a probe (Fig. 7). The velocity profile was then determined on the assumptions that the datum line was perpendicular to the slope surface and that no downslope movement occurred at the base of the probe These assumptions may yield some errors in the values of V_S and V_{VL}, but the shape of the probe can indicate mechanisms involved in the soil movement

The two probes considerably differed in the vertical velocity distribution, despite showing similar values of V_S (1-3 cm yr^{-1}) and D_M (110-120 cm) Probe AH1 indicates that movement occurred largely in the lower active layer (between 50-120 cm depth), where the velocity profile showed downslope convexity (Fig 7) The reason for the depressed velocity in the uppermost 40 cm is unclear, but in early summer the uppermost 20 cm of sediment was composed of a dry, cohesive muddy layer that may have resisted the movement that occurred in the wet lower layer Since the frost table lay at 83 cm depth on excavation (July 15, 1992), further thawing in late summer may have promoted movement below 83 cm depth However, such a movement at the basal active layer was unlikely to be significant, because ice lenses were rarely found below the frost table (over 80–125 cm depth) on the excavated section The depth and profile of movement may be indicative of ice lensing accompanying upward freezing from the permafrost table, but evidence for this is so far insufficient

Probe AH2 displayed two-step movement at depths of 40–60 cm and 95–110 cm, where on the whole there was a convex downslope velocity profile (Fig 7) Whereas the depth of the lower deformed zone was similar to that of AH1, AH2 recorded greater differential movement within a narrow zone The lower deformed zone occurred below the frost table on excavation (July 15, 1992), suggesting that subsequent thaw penetration probably resulted in further downslope movement in late summer However, this does not necessarily mean that the observed profile underestimates the total displacement for two years, because some movement must have taken place also in the late summer of 1990, as indicated by the thaw subsidence in this period (Fig 9)

The most important observation regarding AH2 was that the still-frozen active layer contained a number of ice lenses, each a few millimeters thick, over 105–115 cm depth, although there was a frozen but ice-poor layer between 93–105 cm depth (Fig 5D) This evidence also supports the occurrence of the late summer movement Similar ice lenses below the thawing front were found in a number of excavated sections in Adventdalen, in particular, where a muddy sediment originating mainly from weathering of shale was more than 1 m thick These ice lenses are considered to, at least partly, thaw in late summer and redevelop annually All of these facts suggest that the ice lenses accompanied upward freezing from the permafrost table The depth of the ice-rich layer in 1992 (105–115 cm) did not coincide exactly with that of the lower deformed zone (95–110 cm) The disparity probably reflected inter-annual variation in the active layer thickness (*cf* Lewkowicz and Clarke, 1988)

The upper deformed zone occurred in the middle of the active layer, slightly deeper than the deformed zones observed beneath the two solifluction sheets (KL and AL) A possible source of the deformation is seasonal ice lensing associated with downward freezing, followed by thaw subsidence If this assumption is valid, the two-step movement would correspond to two-sided freezing Sawaguchi (1995) also reported similar convex downslope movement from nearby slopes, he attributed it to slow gelifluction which occurs within a nearly saturated horizon below the uppermost desiccated horizon 30–40 cm thick Whether such soil saturation resulted mainly from thawing of ice lenses or from another moisture source (*e.g*, snow melting) remains unclear, the evaluation will require further detailed observations

Finally, the potential frost creep (PFC) was computed to be 0 7 cm yr^{-1} on the 7° slope where Probe AH2 was located, using the annual cumulative heave of ~6 cm (the seasonal heave plus short-term heave) PFC significantly underestimates the observed surface velocity (3 2 cm yr^{-1}), implying a large gelifluction component (*cf* Harris *et al*, 1993)

4.4. Factors affecting plug-like flow

Why does only the AH site experience solifluction originating from two-sided freezing ? Two factors, the thermal and material conditions, should be taken into account First, the lower ground temperatures at AH site may favor upward freezing The differential temperature between 100 cm and 150 cm depths indicates that the mean thermal gradient at the top of permafrost was $\sim$2°C m^{-1} in late summer when upward freezing possibly took place. In contrast, the top of permafrost at the KL site experienced a mean gradient of 0.5–1°C m^{-1} in late summer, which was computed from the differential temperature between 120 cm and 180 cm depths. The larger gradient at the AH site possibly reflects the lower permafrost temperature at depth, but it can also result from the muddy sediment having low thermal conductivity in the uppermost permafrost. Although it is unclear that such a difference in the gradient is critical in delimiting the presence or absence of upward freezing, the gradient at AH site is close to that reported from the Canadian Arctic, where ice lensing due to upward freezing has actually been observed (Mackay, 1981).

Even if the thermal condition is favorable at the KL and AL sites, the lack of fine materials near the base of the active layer would impede ice lensing. Thus, the presence of a thick muddy sediment derived from the shale bedrock or clay-rich till must be critical in ice lensing due to upward freezing, because of the need for both high frost susceptibility and low thermal conductivity.

Plug-like flow results in a large volumetric velocity V_{VL} depending largely on the active layer thickness. The V_{VL} value can significantly rise during an episodic warm summer, when the active layer deepening induces melting of the top of ice-rich permafrost (Egginton and French, 1985, Lewkowicz and Clarke, 1998). Previous observations reported V_{VL} ranging from 20–80 cm^3 cm^{-1} yr^{-1}, where the active layer is $\sim$60 cm thick (Mackay, 1981, Lewkowicz and Clarke, 1998). Much voluminous movement, $V_{\mathrm{VL}} = \sim 200$ cm^3 cm^{-1} yr^{-1}, occurred at the AH site, in response to the deeper active layer ($\sim$110 cm). This value is one of the largest volumetric velocities so far recorded as solifluction (Matsuoka, submitted), although a similar large mass transport has also been reported by Sawaguchi (1995) from the present study area.

The non-sorted stripes developed on the AH site are unlikely to be associated with plug-like flow. Rather, they seem to be preserved under deep soil movement (*cf.* Egginton and French, 1985). In this context, despite large volumetric transport, plug-like flow may not be indicated by any of the surface features. This condition contrasts with shallow movement by normal solifluction (annual frost creep/gelifluction), which is commonly associated with lobate features. However, significant downslope deceleration of plug-like flow may cause bulging that produces a lobate feature thicker than the common solifluction lobes (*cf.* Mackay, 1981). The geomorphic significance of plug-like flow is an important target of future studies.

5. Conclusions

Solifluction on three permafrost slopes in Svalbard is devoid of superficial soil movement, reflecting the lack of diurnal freeze-thaw action and soil desiccation. However, movement in the middle to basal active layer shows spatial variability between the three slopes. Both the KL and AL sites mainly undergo annual frost creep/gelifluction in the middle active layer, in association with frost heave during downward seasonal freezing and subsequent thaw subsidence. In contrast, the AH site experiences plug-like flow in the basal active layer, which originates from thawing of ice lenses developed during upward freezing from the permafrost table. The difference in the depth of movement arises mainly from the material composition in the lower active layer the coarse sediment (sand/gravel) at the KL and AL sites rejects ice segregation, whereas the muddy sediment in the whole active layer at the AH site favors ice segregation accompanying two-sided freezing Plug-like flow yields large mass transport, despite being rarely associated with a specific surface feature

Although the field observations have highlighted the role of two-sided freezing in solifluction, further improvements in the monitoring technology will be needed before a substantial conclusion is reached First, soil temperature should be measured at least at 10–20 cm vertical intervals in order to detect upward freezing in detail Second, the upheaving of the bedstead has to be avoided by anchoring the legs firmly in permafrost Finally, the use of longer tubes or strain probes will permit determination of the datum line for downslope movement

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References

Åkerman, H J (1987) Periglacial forms of Svalbard a review Periglacial Processes and Landforms in Britain and Ireland, ed by J Boardman Cambridge, Cambridge University Press, 9–25

Åkerman, H J (1993) Solifluction and creep rates 1972–1991, Kapp Linnē, West Spitsbergen Solifluction and Climatic Variation in the Holocene, ed by B Frenzel Stuttgart, Gustav Fisher Verlag, 225–249

Åkerman, H J (1996) Slow mass movements and climatic relationships, 1972–1994, Kapp Linnē, West Spitsbergen Advances in Hillslope Processes 2, ed by M G Anderson and S M Brooks Wiley, Chichester, 1219–1256

Budel, J (1977) Klima Geomorphologie Stuttgart, Gebruder Borntraeger, 304 p

Egginton, P A and French, H M (1985) Solifluction and related processes, eastern Banks Island, N W T Can J Earth Sci, **22**, 1671–1678

Harris, C (1972) Processes of soil movement in turf-banked solifluction lobes, Okistindan, northern Norway Polar Geomorphology, ed by R J Price and D E Sugden London, Institute of British Geographer, 155–174 (Inst Br Geogr Spec Publ 4)

Harris, C, Gallop, M and Coutard, J-P (1993) Physical modelling of gelifluction and frost creep some results of a large-scale laboratory experiment Earth Surf Process Landforms, **18**, 383–398

Jahn, A (1985) Experimental observations of periglacial processes in the Arctic Field and Theory, Lectures in Geocryology, ed by M Church and O Slaymaker Vancouver, University of British Columbia Press, 17–34

Jahn, A (1991) Slow soil movement in Tarfala Valley, Kebnekaise Mountains, Swedish Lapland Geogr Ann, **73A**, 93–107

Lewkowicz, A G (1988) Slope processes Advances in Periglacial Geomorphology, ed by M J Clark Chichester, Wiley, 325–368

Lewkowicz, A G (1992) Factors affecting the distribution and initiation of active-layer detachment slides on Ellesmere Island, Arctic Canada Periglacial Geomorphology, ed by J C Dixon and A D Abrahams Chichester, Wiley, 223-250

Lewkowicz, A G and Clarke, S (1998) Late-summer solifluction and active layer depths, Fosheim Peninsula, Ellesmere Island, Canada Proc 6th Int Conf Permafrost, ed by A G Lewkowicz and M Allard Sainte-Foy, Centre d'ētudes nordiques, Université Laval, 641-666

Mackay, J R (1981) Active layer slope movement in a continuous permafrost environment, Garry Island, Northwest Territories, Canada Can J Earth Sci, **18**, 1666-1680

Mackay, J R (1984) The frost heave of stones in the active layer above permafrost with downward and upward freezing Arct Alp Res, **16**, 439-446

Matsuoka, N (1994) Continuous recording of frost heave and creep on a Japanese alpine slope Arct Alp Res, **26**, 245-254

Matsuoka, N (1998) Modelling frost creep rates in an alpine environment Permafrost Periglac Process, **9**, 397-409

Matsuoka, N (1999) Monitoring of thermal contraction cracking at an ice wedge site, central Spitsbergen Polar Geosci, **12**, 258-271

Matsuoka, N and Hirakawa, K (1993) Critical polygon size for ice-wedge formation in Svalbard and Antarctica Proc 6th Internatl Conf Permafrost, 1 Wushan, South China University of Technology Press, 449-454

Pērez, F L (1987) Downslope stone transport by needle ice in a High Andean area (Venezuela) Rev Gēomorphol Dyn, **36**, 33-51

Price, L W (1991) Subsurface movement on solifluction slopes in the Ruby Range, Yukon Territory, Canada a 20-year study Arct Alp Res, **23**, 200-205

Rein, R G, Jr and Burrous, C M (1980) Laboratory measurements of subsurface displacements during thaw of low-angle slopes of a frost susceptible soil Arct Alp Res, **12**, 349-358

Repelewska-Pękalowa, J and Pękala, K (1993) The influence of local factors on solifluction rates, Spitsbergen, Svalbard Solifluction and Climatic Variation in the Holocene, ed by B Frenzel Stuttgart, Gustav Fisher Verlag, 251-266

Sawaguchi, S (1995) Rates and processes of mass movement on periglacial rubble slopes in Spitsbergen Chigaku Zasshi (J Geogr), **104**, 874-894 (in Japanese with English abstract)

Williams, P J (1966) Downslope soil movement at a Sub-Arctic location with regard to variations with depth Can Geotech J, **3**, 191-203

Williams, P J and Smith, M W (1989) The Frozen Earth Fundamentals of Geocryology Cambridge, Cambridge University Press, 306 p

Yamada, S and Kurashige, Y (1996) Improvement of strain probe method for soil creep measurement Chikei (Trans Jap Geomorph Uni), **17**, 29-38

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