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A PRELIMINARY INVESTIGATION OF SOLIFLUCTION MACROFABRICS

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SUMMARY

Statistical analysis of clast orientation in various parts of solifluction lobes demonstrates large departures from uniformity. Although concentration is not homogeneous, the clasts of all samples are strongly oriented parallel to the direction faced by the slope, and dip upslope. This pattern probably reflects operation of both flow and creep processes. Samples are coplanar after rotation of data into the plane of their respective local slopes, and this transformation is suggested as a precursor to statistical analysis in future studies. Three-dimensional fabric analysis is a useful tool for establishing the direction in which movement occurred within fossil solifluction deposits, but should be accompanied by other lines of evidence for establishing the origin of such deposits.

1. INTRODUCTION

Elongate rock fragments within solifluction features have long been thought to create a characteristic orientation pattern that is diagnostic of processes operative within the forms. Some workers have used the orientation of clasts within a soil mass as a basis for paleoclimatic inference, suggesting that it provides a clue for identification of fossil solifluction deposits associated with former periglacial environments. In view of such applications, it is surprising that three-dimensional statistical analyses of fabrics from presently active features and comparisons with fabrics from other mass-movement features have not been published. This paper takes an initial step toward standardizing data-analytic techniques through examination of solifluction fabrics by the "eigenvalue method" widely used in studies of till fabric, and by suggesting a standard plane of reference for analysis of solifluction-deposit fabric data.

2. PREVIOUS INVESTIGATIONS

LUNDQVIST (1949) was among the first to measure the two-dimensional orientation of clasts within solifluction forms. In turf-banked terraces, which correspond to the lobes investigated in this paper, he found that the major axes of elongate stones conform closely to the direction of movement in the features. This situation has been confirmed by most subsequent measurements of particle orientation in solifluction features. RUDBERG (1958) extended observations to solifluction forms developed in glacial till; he showed that clasts in near-surface layers subjected to contemporary movement processes are strongly oriented in the direction of the local slope, while those of the underlying till diverge markedly from it. This finding demonstrated that solifluction is capable of creating preferred stone orientations, and that the depth to which movement extends can be estimated through fabric

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analysis under certain circumstances. Two-dimensional orientation data have subsequently been collected by many workers (e.g. BROCHU 1978, KOTARBA 1981, MOTTERSHEAD 1976, SCHWAN et al. 1982). However, two-dimensional treatments provide little information other than demonstrating that clast orientation is in close coincidence with the direction faced by the local slope.

Although three-dimensional representations of particle orientation in solifluction features are not uncommon, relatively little effort has been invested in statistical description or analysis. Again, most fabric presentations were incidental to work on other aspects of solifluction. Among such works are those of HARRIS & WRIGHT (1980), KÄLLANDER (1967), RAGG & BIBBY (1966), and SMITH (1956). The three-dimensional observations which have been plotted on hemispherical projections all used the horizontal plane as a reference. Most of these representations depict bipolar fabrics in which the azimuthal modes coincide with a horizontal projection of the maximum gradient of the slope. Other workers (BENEDICT 1970, FURRER & BACHMANN 1968, SÖDERMAN 1980) collected three-dimensional data but displayed and/or analyzed azimuth and dip measurements separately.

Many investigators (e.g. BENEDICT 1976, WILLIAMS 1957) have noted that clasts within solifluction features lie parallel with or dip into a slope viewed in profile. HARRIS & ELLIS (1980) reported that microfabrics form a similar pattern. These observations suggest that horizontal may be an inappropriate plane of reference for analysis of solifluction fabrics, a problem recognized by WATSON (1969, 105). In some deposits an upslope-facing dip is apparent even when horizontal is used as the projective plane (BENEDICT 1976, HARRIS 1981, Fig. 75, p.135).

3. METHODS

3.1. DATA COLLECTION

Orientation data were collected from clasts within eight solifluction lobes on the north-facing sideslope of a cryoplanation terrace near Eagle Summit, Alaska (65°30′ N., 145°25′ W.). The lobes lie at elevations between 1100 and 1200 m; late-lying snowbanks upslope provide moisture for mass movement. Except for small Pleistocene cirque glaciers, the area has not been glaciated (PÉWÉ et al. 1967). The lobes are composed predominantly of silt, but contain numerous angular cobbles and blocks derived from the underlying schist (REGER 1975, 73).

Each of the eight samples was comprised of 50 observations on the long (A) axis azimuth and dip of tabular clasts within a near-surface (10-40 cm) layer of a lobe. Only elongate rock fragments with A–B axial ratios greater than 2.0 were used. Clast lengths were in the approximate range 10-35 cm. The field procedure consisted of sinking a shallow pit on each lobe and carefully excavating particles within it; a short nonmagnetic rod was inserted in the resulting voids and measurements of long-axis orientation were obtained from this with a Brunton compass. Some characteristics of each site are listed in Table 1.

3.2. STATISTICAL ANALYSIS

Orientation measurements were analyzed by the eigenvalue method (MARDIA 1972,

Tab. 1: SITE CHARACTERISTICS

site	slope azimuth	slope angle	microtopographic position
1	041°	13°	center of tread near lobe front
2	040°	13°	lobe riser
3	052°	26°	extreme rear of lobe
4	068°	12°	center of tread near lobe front
5	025°	20°	center of tread
6	020°	08°	center of tread
7	017°	18°	near lateral margin of tread
8	013°	12°	center of tread

1975). The eigenvalues and eigenvectors are extracted from a symmetric 3 x 3 matrix formed by the sums of squares and products of direction cosines from the individual measurements. The eigenvectors t_i, $i = 1,2,3$ of this matrix represent the mutually orthogonal axes of minimum, intermediate, and maximum clustering of the observations, respectively, and the corresponding normalized eigenvalues $\overline{\tau_i}$ ($\overline{\tau_1} \leqslant \overline{\tau_2} \leqslant \overline{\tau_3}$) provide a measure of the relative length of these axes. Fabric shape and departures from uniformity can also be assessed from the eigenvalues (MARDIA 1972, 225-226, MARDIA 1975, 358).

Table 2 provides the values obtained by applying these procedures to the data obtained at Eagle Summit. All samples can be regarded as having been drawn from nonuniform distri-

Tab. 2: EIGENVALUE AND BINGHAM STATISTICS (INVARIANT UNDER ROTATION) AND PRINCIPAL AXES (t_3) FOR DATA OF FIGURE 1b. MEAN RESULTANT LENGTHS ARE GIVEN FOR DATA SHOWN IN FIGURES 1a, 1b, and 1c, RESPECTIVELY; VALUES FOR THE ROTATION OF 1d ARE IDENTICAL TO THOSE OF 1c.

sample	$\overline{\tau_1}$	$\overline{\tau_3}$	U	A	D	$\overline{R}$
1	0.025	0.930	4.00^S	179.2°	10.0°	0.37, 0.86, 0.96
2	0.064	0.811	2.59^S	181.6°	12.5°	0.33, 0.68, 0.88
3	0.036	0.833	2.84^S	179.7°	11.2°	0.84, 0.64, 0.90
4	0.017	0.891	3.52^S	181.3°	9.8°	0.40, 0.85, 0.94
5	0.027	0.925	3.94^S	180.2°	15.2°	0.34, 0.82, 0.96
6	0.027	0.932	4.04^S	179.9°	6.0°	0.15, 0.48, 0.96
7	0.017	0.945	4.21^S	180.0°	8.5°	0.75, 0.63, 0.97
8	0.011	0.971	4.58^S	179.9°	9.1°	0.29, 0.79, 0.98

$\overline{\tau_3}$ = largest normalized eigenvalue.

$$\sum_{i=1}^{3} \overline{\tau_i} = 1.0$$

$\overline{\tau_1}$ = smallest normalized eigenvalue.

U = Bingham's uniformity test statistic.

$$U = \frac{15}{2} \sum_{i=1}^{3} (\overline{\tau_i} - 1/3)^2$$

A = "azimuth" of t_3 at intersection with lower hemisphere.

D = dip of t_3

$\overline{R}$ = mean resultant length.

S = statistically significant (0.05 level).

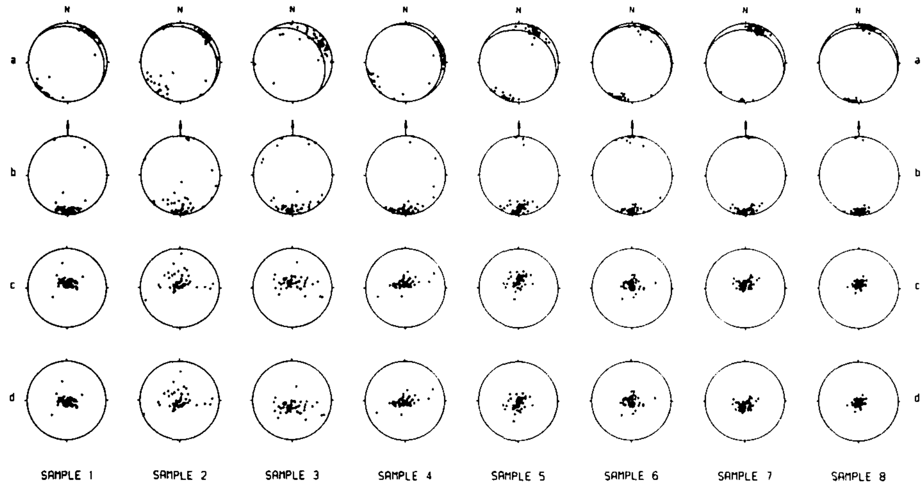

Fig. 1a: Raw orientation data. Plane of local slope is shown in each diagram.
b) Azimuthal values have been modified so that the "north" pole (indicated by arrow) of the diagrams represents the downslope direction. The dip of each data point has been rotated by an amount equal to the angle of the slope at the measurement site.
c) Dip data of Figure 1b have been rotated an additional 90°. Total transformation is thus $90° + \theta$ where θ is the local slope inclination.
d) Dip data of Figure 1a have been rotated 90°. Note that the clusters appear less coincident between samples than in 1c, suggesting that the latter is a better standardization. Azimuthal vaues have been modified in these diagrams by the same amount as in 1b and 1c. All diagrams in Figure 1 are equal-area lower-hemisphere projections.

butions in which the modes conform closely with a horizontal projection of the maximum slope gradient. With the exception of samples 3 and 7, the raw data appear bipolar when the horizontal plane is used for reference (Figure 1a). Axial data forming such patterns may actually represent only one cluster (SCHUENEMEYER et al. 1972, 180), and rotation of the points can result in a unimodal pattern which greatly strengthens the resultant vector. However, results obtained by the eigenvalue method remain unchanged.

Each sample was rotated into the plane of its local slope and replotted on Schmidt nets (Figure 1b); the data in most cases emerge as unimodal distributions inclined in the upslope direction. However, the few points remaining opposite the main clusters present problems for comparative statistical procedures based on the Fisher distribution. Such tests can be used to compare strong unimodal axial distributions (KOCH & LINK 1971, 148), although Fisherian single-sample tests for statistical significance should not be applied to axial data.

Following MCFADDEN (1980), χ^2 tests were employed to assess the fit of the Fisher distribution to the points shown in Figure 1c, which represent a rotation of the raw data by $90° + \theta$, where θ is the slope angle at the measurement site. Note the very high values of the mean resultant length $\overline{R}$ that result from this transformation (Table 2). Some divergence from the Fisher model was found in Samples 2, 3 and 4, which lack strict circular symmetry about the mean direction. However, WATSON (1966, 793) indicated that multisample tests are fairly robust against such minor departures from the Fisher distribution, and comparative procedures (MARDIA 1972, 267-271) were applied to the points shown in Figure 1c.

Results from MARDIA's multisample tests for equality of concentration and mean

Tab. 3: RESULTS OF MULTISAMPLE COMPARISONS FOR EQUALITY OF CONCENTRATION PARAMETERS AND MEAN DIRECTIONS. TESTS WERE APPLIED TO ROTATED DATA SHOWN IN FIGURE 1c.

MULTISAMPLE COMPARISONS
($\alpha = 0.05$)

Test for equality of concentration: $U_3 = 154.4$ $\chi^2_{14} = 23.68$

Test for equality of mean directions: $F_0 = 1.15$ $F_{14,784} = 2.31$

ANALYSIS OF VARIANCE TABLE

SOURCE	D.O.F.	SUMS OF SQUARES	MEAN SQUARES	F
BETWEEN SAMPLES	14	0.45	0.0321	1.15
WITHIN SAMPLES	784	21.95	0.0280	
TOTAL	798	22.40		

directions are given in Table 3. The large value of U_3 (computed using a corrected version of MARDIA's eq. 9.5.11) demonstrates that the concentrations of at least two of the samples are significantly different. The observed mean-direction test statistic F_0 indicates that the null hypothesis of no significant difference between samples should be retained. However, when applied to the simple 90° rotation (Figure 1d), the mean-direction test results in rejection of the null hypothesis.

The fact that unimodal distributions with relatively strong concentrations and similar mean directions result from rotating samples into the plane of the slope from which they were obtained suggests that the local slope is indeed the correct reference plane. This assertion was examined by means of a test for coplanarity developed by WATSON (1960) and discussed by MARDIA (1972, 271-275). Despite differences in the inclination and aspect of the various slopes from which the data were obtained, the samples should be coplanar after rotation if the local slope is the correct reference plane.

WATSON's coplanarity tests include procedures for detecting deviations from a prescribed normal, or, as in the present case, for testing the null hypothesis of coplanarity when the plane containing the means is unknown. Because the concentrations of the various samples are unequal, the coplanarity test for the nonhomogeneous case was applied to the points shown in Figure 1c. The observed value of the test statistic w_1 is 1.71, considerably below the critical value, $\chi^2_{6,0.05}$ (12.59). Despite the fairly wide range of slope angles, the various samples can therefore be regarded as coplanar when each is rotated into the plane of the slope from which it was obtained.

The small (1.46°) semivertical angle of the 95% confidence cone for the true mean direction, obtained using FISHER & LEWIS' (1983) method for weighting samples according to their strength, also supports use of this rotation (Figure 2). Taken together, these results suggest that the horizontal plane is a less appropriate reference for the solifluction data than is the plane of the local slope. The relations of the principal eigenvectors t_3 to the slope after the rotation of Figure 1b are also shown in Figure 2; a pronounced tilt away from the direction of inferred motion is apparent. Diagrams presented by other workers (e.g. BENEDICT 1970, Fig. 51, 210, RAGG & BIBBY 1966, Fig. 5, 18) indicate that this upslope dip is a common characteristic of rock particles embedded in solifluction deposits. Conversely, block slopes

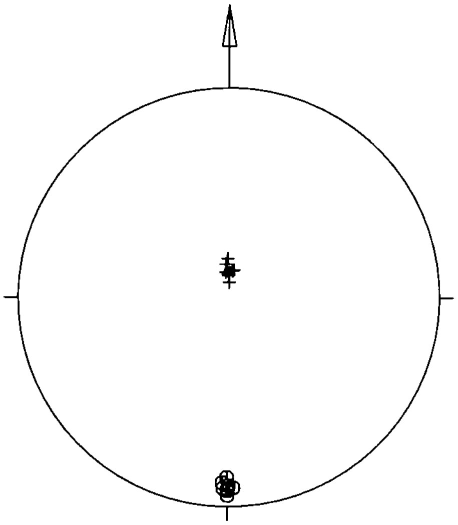

Fig. 2: Small circle near center of net outlines 95% confidence cone centered on combined-sample mean direction under rotation of Figure 1c. Sample weighting is proportional to strength, following method of FISHER & LEWIS (1983). Crosses indicate mean directions of individual samples. Circles near primitive are eigenvectors t_3 of samples under rotation of Figure 1b. Arrow indicates downslope direction. Plotted on Schmidt net, lower hemisphere.

lacking an interstitial matrix of fines have bipolar fabrics when rotated into the plane of the slope (NELSON, unpublished data). These findings indicate that rotation of fabric data into the plane of the local slope should be a routine data standardization.

4. INTERPRETATION

4.1. FABRIC ORIGIN

The coincidence and coplanarity of the sample means after rotation suggests that clasts from the various samples have been affected by the same orienting processes; the fabrics are similar to those formed in a viscous fluid under simple shear (e.g., REES 1979). An ellipsoidal particle immersed in a velocity gradient in such a medium is rapidly rotated to a position parallel to flow, where, because its angular velocity is decreased, it remains longer than in other positions (GLEN et al. 1957). In any given sample, a majority of particles is therefore more likely to lie parallel to flow than in other positions, producing a statistically significant preferred orientation.

Although lobes such as those at Eagle Summit have long been thought to move by slow flow of the materials contained in them, determination of the relative importance of flow and seasonal creep is difficult. Velocity profiles in solifluction lobes have been determined by several workers (summarized by HARRIS 1981, Fig. 60, 110); some profiles agree well with theoretical profiles (CARSON 1976, Fig. 4.3, 107) for viscous flow, or combinations of flow and seasonal creep. Even in cases in which the profiles agree primarily with those for seasonal creep, the displacement was greater than that which could be produced by creep alone

(CARSON 1976, 108), implying that flow processes are operative.

The solifluction fabrics also exhibit upslope-dipping modes which are inconsistent with an origin attributable only to viscous flow. A similar pattern of upslope dips was noted by MILLS (1983) in deposits affected by seasonal soil creep in the near-surface ($\leqslant 20$ cm) layer of hillslope colluvium in southwestern Virginia. In a laboratory experiment on solifluction, HIGASHI & CORTE (1971, Fig. 3, 482) showed that slight rotation of particles occurs as a result of frost creep. Although spherical particles were used, the direction of rotation was such that if elongated particles were similarly affected, an upslope tilt would evolve. This observation suggests that frost creep may be responsible for the upslope dip in the Eagle Summit solifluction fabrics. Although "emergent" flow patterns (HUTCHINSON 1970, Fig. 21, 431, JAHN 1975, Fig. 102B, 150) could be responsible for upslope-dipping clasts, this is considered unlikely for the data under consideration here because the various samples were obtained from diverse parts of solifluction lobes.

Movement mechanisms other than viscous flow and seasonal creep may also be active in many solifluction lobes. HUTCHINSON (1974) considered solifluction as a type of slip phenomenon acting on surfaces parallel to the slope, or slightly emergent in a downslope direction. This interpretation is supported by the laboratory experiments of REIN & BURROUS (1980), in which displacement was induced by high porewater pressures associated with thawing ice-rich layers. MACKAY (1980) demonstrated "plug-like" active-layer movement in the continuous permafrost zone of arctic Canada. Such movement may not produce internal deformation and strong fabrics except in the immediate vicinity of the layer in which shear takes place. If "slip" has been operative at a site, it may be detectable by a stratum in which fabric strength is appreciably greater than in bounding layers. This may be a common phenomenon in permafrost areas experiencing two-sided freezing, where ice-rich zones form annually at the base of the active layer (MACKAY 1980).

The transverse orientation reported by BENEDICT (1970), BOULTON (1971), KOTARBA (1981), and LUNDQVIST (1949) from the downslope toe of lobate features is not present in Sample 2, which was collected from the near-surface 40 cm of a lobe riser. Although the scatter of points is greater than in the other samples, the dominant orientation is still aligned with the direction faced by the slope. A few transverse particles are present; these were found immediately below the turf cover, suggesting that perpendicularity is not achieved until contact is made with the turf mat at the front of the lobe. A somewhat more pronounced dip may develop prior to significant azimuthal reorientation, as reflected in the weaker concentration caused by several steeply inclined clasts in this sample (Figure 1b, Sample 2).

4.2. RECOGNITION OF SOLIFLUCTION DEPOSITS

Several recent papers have used the eigenvalue technique to examine the fabrics of various types of colluvial and glacial deposits; comparison of the solifluction data with those from other types of deposits may indicate whether fabric analysis can be useful for identification of fossil solifluction deposits.

LAWSON (1979) and MAY et al. (1980) constructed scattergrams in which the eigenvalues of samples from sediment flows and ice-slope colluvium are well separated from those of basal-zone ice and meltout tills, indicating that fabric shape can be used to distinguish between deposits emplaced by different processes. WOODCOCK (1977, 1231-1232) described a logarithmic two-axis ratio plot adapted from structural geology, in which deformations (progressions from strongly clustered distributions to great-circle girdles) plot as straight lines. Fabric strength is reflected by distance from the origin, where uniform or random distributions fall. This graphical method has some advantages over triangular or rectangular diagrams due to its simple geometrical relations, and because it contains no areas in which values cannot be obtained. Because the fabrics of different broad categories of deposits may be expected to have different shapes and strengths, ratio plots of their eigenvalues may help to distinguish between various types of deposits.

When plotted on a logarithmic ratio graph (Figure 3), the solifluction fabrics fall in the zone occupied by LAWSON's (1979, 633) basal-zone ice and meltout-till fabrics, which are strongly developed (high $\overline{\tau}_3$ / $\overline{\tau}_1$ ratios) and tightly clustered.

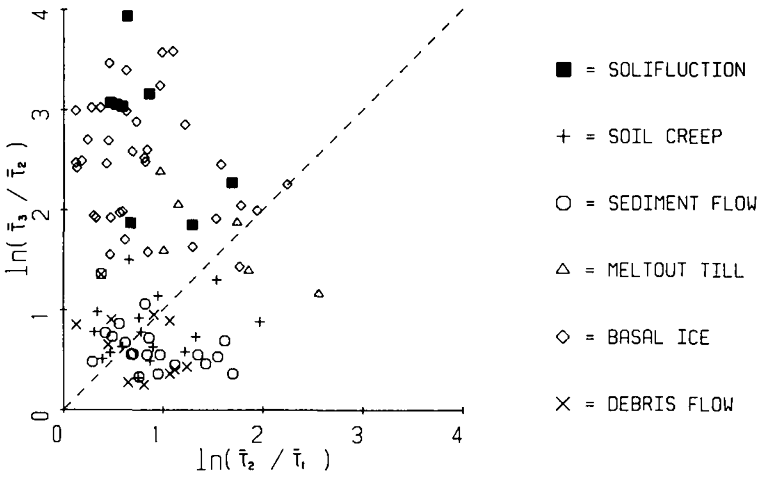

Fig. 3: Logarithmic ratio plot of eigenvalues from various types of deposits reported in the literature. Dashed diagonal line indicates position of the cluster-girdle transition "zone" where the ratio of values along the ordinate to those on the abscissa is unity. Values greater than unity represent clustered distributions, while smaller values indicate girdle tendencies. Distance from the origin gives an indication of fabric strength. For further details, see WOODCOCK (1977). Data sources: soil creep, MILLS (1983); debris flows, MILLS (1984); sediment flow, meltout till, and basal ice, LAWSON (1979).

Meltout tills form by slow ablation of debris-rich ice overlain by supraglacial sediments (BOULTON 1971). The overburden inhibits downslope creep or flow of the former englacial materials, in effect preserving the englacial fabric in a slightly weakened form. Meltout tills therefore possess strongly oriented fabrics which reflect flow patterns, often simple shear, in the former glacier. The similarities in shape and strength between the solifluction and glacial-deposit fabrics tend to support the interpretation that the former are indicative of simple shear.

In contrast, fabrics from soils affected by seasonal creep (MILLS 1983), lahar-type debris flows (MILLS 1984), and small sediment flows (LAWSON 1979) are evenly distributed between the cluster and girdle sectors, and are much weaker than those from solifluction lobes, meltout till, and basal ice. These results suggest that solifluction deposits may possess a fairly distinctive fabric pattern which, by considering fabric shape, strength, and dip, could be distinguished from those of many other types of deposit. However, the fact that LAWSON (1979) found that fabric strength in some colluvial deposits increases with water content, while MILLS (1983) found a similar relation with slope angle suggests that the relationships between controlling variables may be complex, and that positive identification requires more information than can be obtained from simple scattergrams or strain-ratio plots. BENEDICT's (1976) assertion that solifluction deposits can be positively identified only through examination of a variety of criteria must, therefore, be maintained.

5. CONCLUSIONS

The macrofabrics of solifluction deposits have strong modes aligned with the direction faced by the local slope, and dip into the slope. The fabrics are similar to those found in basal-zone glacier ice and meltout tills, and suggest viscous flow. The shape of solifluction fabrics is probably reflective of both flow and creep; fabric strength is presumably a function of time, water content, and slope angle, and is affected by impediments to movement.

Use of the plane of the local slope as a reference is recommended for future studies. This rotation is justified because the reference plane is brought into coincidence with that in which movement occurs. An additional advantage is that fabrics are "standardized" by this procedure, making them more amenable to three-dimensional comparative analyses.

Fabric analysis appears to be an excellent method for establishing the direction of movement in fossil solifluction deposits. However, to identify such deposits, as many supporting lines of evidence as possible should be utilized. Fabric is not acceptable as a sole criterion, but can be a useful part of identification procedures.

Much more work is required before a good understanding of solifluction-fabric development is achieved. Better knowledge of solifluction mechanics is crucial, and might be studied most profitably in the laboratory, where fabric development could be monitored. Field studies are important, and should be carried out using a spatially based sampling scheme, with attention given to variations with depth and in different parts of the landforms. Meso- and microfabric investigations are also desirable, as are more macrofabrics such as those reported in this study.

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