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Processes dominating macro-fabric generation in periglacial colluvium

Susan W.S. Millar *

Department of Geography, Syracuse University, Syracuse, NY 13244, USA

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Abstract

Mass wasting processes in a periglacial environment are considered to result from a combination of frost creep and gelifluction. The relative importance of these processes is often difficult to determine, but appears to be related to factors such as slope angle, soil moisture content, soil texture, and vegetation cover. Further, the importance of any one of these factors can vary from year to year, thereby making long term predictions of slope stability or reconstructions of behaviour history difficult. This study uses two-dimensional macro-fabric analysis as a recorder of the dominant mode of mass-wasting on a slope.

Clast trend and plunge data were collected from 68 sites at Eagle Summit, Alaska, and examined in two separate dimensions: the plane of the slope to represent the stress-field driven by gravity; and in a vertical plane trending down the slope to represent the stress-field created by frost heaving pressures. Circular correlation tests indicate the importance of the downslope stress-field on clast position in the plane of the slope. In the vertical plane clast plunge varies according to slope. On gentle slopes, clasts tend to be steeply dipping, on moderate slopes they are parallel to the plane of the slope, and on steep slopes they are imbricated. These observations correspond to modeled experiments of slope deformation under periglacial conditions, and suggest that at the scale of the slope, mass-wasting processes are influenced by varying intensities of frost heave and gravity transfer that are conditioned by slope angle.

Keywords: Gelifluction; Frost heave; Slope stability; Fabric analysis

1. Introduction

Slope processes in a periglacial environment involve several mechanisms that lead to sediment deformation and movement. In general, soil movement can be attributed to frost creep due to ice segregation, commonly referred to as frost heaving because of its distinct difference from rheological creep; and loss of strength due to increases of pore-water pressure upon thawing, often referred to as gelifluction (Washburn, 1980; Williams and Smith, 1989). In various combinations, these processes produce sorted ground phenomena, solifluction lobes and terraces, and stone stripes (Washburn, 1980; Williams and Smith, 1989; Matsuoka, 2001; Kessler and Werner, 2003). Most resulting landforms are therefore polygenetic, thereby requiring caution when making basic assumptions of landform-process relations in the periglacial context (Hugenholtz and Lewkowicz, 2002; Millar, 2005).

Fabric analysis, or the orientation of clasts within a soil matrix, has been used extensively to understand glacial and periglacial processes of deformation and deposition. The rationale for its application is based on mathematical descriptions of how an elongated particle moves within a shearing mass (Jeffery, 1922). Since Jeffery's calculations, most work indicates that glacial fabrics do provide some indication of the form and history of the stress-field experienced by a sediment mass (e.g., Lindsay, 1970; Carr and Rose, 2003). Fabric analysis does not, however, appear sensitive enough to distinguish landform units across a periglacial slope (Millar, 2005). This lack of uniqueness raises questions for the validity of its use for paleoenvironmental reconstructions of periglacial mass-

* Tel.: +1 315 443 5635; fax: +1 315 443 4227.
E-mail address: swmillar@maxwell.syr.edu.

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wasting; however, it does not necessarily invalidate its use as an indicator of the dominant processes acting on a periglacial slope.

In this study, I have focused on two-dimensional fabrics on the assumption that they can provide information on the two separate, but related, stress-fields operating on the slope materials. Frost creep is dominated by the stress-field perpendicular to the plane of the slope due to the predominance of frost heave; whereas gelifluction is dominated by gravity in the downslope direction. Since fabric measurements consider both the trend and plunge of individual stones, these two stress-fields can be analysed independently by examining the plunge of clasts relative to slope angle, and the trend of the stones relative to slope direction. The results presented here suggest that slope angle plays an important role in determining the relative importance of frost heave versus gelifluction, and therefore that clast dip and slope angle relations may provide a tool to identify dominant modes of deformation of a periglacial slope.

2. Methods

2.1. Study area

Eagle Summit, Alaska, is located about 110 miles NE of Fairbanks, and was selected for study due to its relative ease of accessibility and the presence of large solifluction lobes indicative of active mass-wasting (Fig. 1). Climate statistics from Central, Alaska (280.4 m a.s.l.) show a mean annual air temperature of −5.1 °C. Assuming a lapse rate between 5–6.5 °C/km, mean annual air temperature at the study area (800–1200 m a.s.l.) is between −7.7 and −11.04 °C. Permafrost active layer thicknesses of approximately 1 m were measured in the field using a metal probe in August during the field season. Quartz-muscovite schists provide a high silt and mica content in soils, both of which create conditions conducive for solifluction (Harris, 1987). Vegetation varies according to moisture; wet sites are dominated by *Carex* and *Eriophorum* species, and dry sites by *Carex* and *Dryas* (Hanson, 1950). Vegetation mat thickness varies from

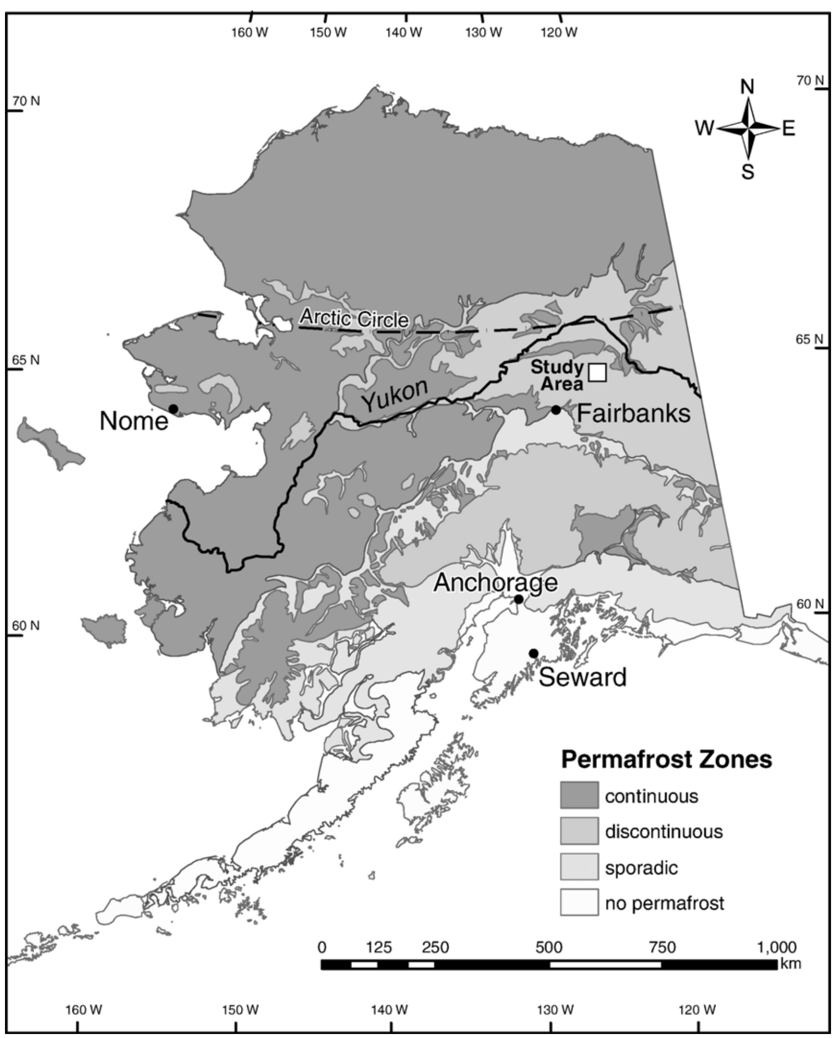

Fig. 1. Location of study area.

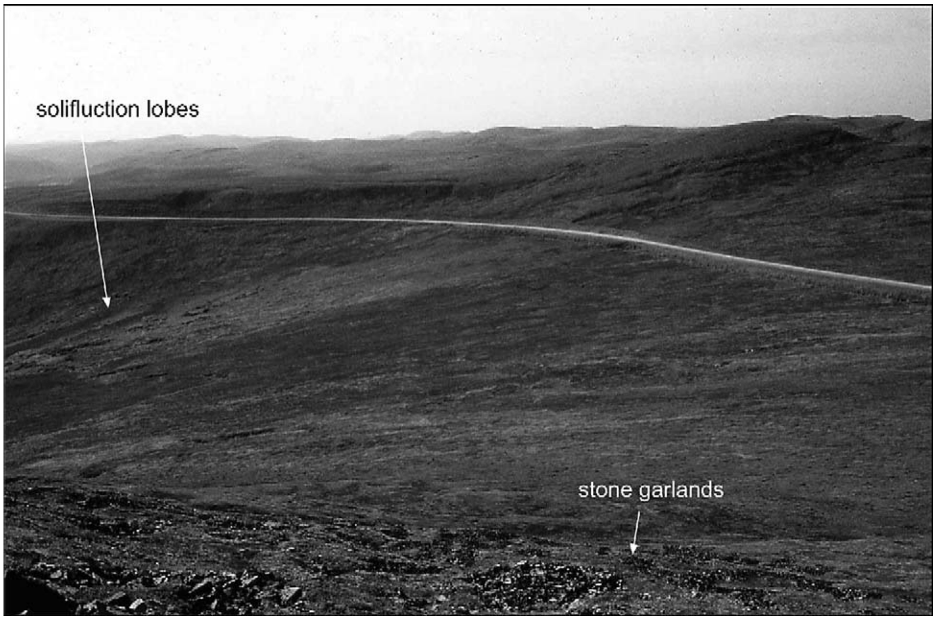

Fig. 2. Typical landscape at study area. The road is approximately 0.5 km distant at the center of image.

0 cm on block slopes, to 15 cm on wetter and lower sites. Evidence of periglacial activity includes stone stripes on steeper slopes, solifluction lobes with risers of approximately 1 m in height, and sorted circles on terrace treads (Fig. 2).

2.2. Data collection

Data were collected during August, towards the end of the thaw season, at Eagle Summit. A stratified systematic unaligned method was used to select 68 sites to collect fabric data across a range of micro-environments (Iachan, 1985). This strategy avoided selective sampling of specific geomorphic features, and therefore provided a dataset representative of the range of slope processes and forms. Standard techniques were used to measure the plunge, plunge azimuth and a-, b-, and c-axial lengths of 50 elongated clasts at each site (Andrews, 1971). The local slope azimuth and dip, distance to the nearest divide, sampling depth, thickness of vegetation mat, and stone concentration assessed using comparative charts (Compton, 1985) were also recorded. Soil moisture was evaluated at each sample location using a five-category descriptive scale, ranging from very wet to very dry. Nineteen soil samples were taken for textural analysis. Standard preparation and analysis procedures were conducted at the Institute of Arctic and Alpine Research in Boulder, Colorado.

3. Analysis of results

3.1. Two-dimensional fabric data

Most recent fabric studies examine the three-dimensional position of stones, usually presented in the form of a lower hemisphere equal area plot (Nelson, 1985; Mills, 1991; Bertran et al., 1997; Millar and Nelson, 2001). However, three-dimensional fabric patterns in periglacial sediments result from a suite of independent processes, including the rate of deformation, characteristics of clasts entrained in the deforming sediment, the mode of deposition, and the post-depositional modification (Glen et al., 1957). It is unlikely that, when examined in three dimensions, macrofabrics are sensitive enough to allow isolation of the dominant mode of sediment deformation, whether through frost creep or gelifluction.

Frost creep and gelifluction are dominated by stress-fields represented by planes oriented orthogonally to each other. This suggests that it may be possible to identify their operation by examining the fabric data separately in these two planes. First, stress is generated by gravity in the downslope direction, reflected in the relation between the trend of the stone and slope azimuth. Theoretical, simulation and laboratory modeling, and field observations show a strong tendency for slope-parallel and subparallel stone orientation due to shear (e.g., Jeffery, 1922; Lindsay, 1970; Mills, 1983). Second, a stress-field is associated with the direction of the freezing front, perpendicular to the plane of the slope, reflected in the relation between the local slope angle and its comparison with clast plunge. Field and laboratory observations of the frost heave process on stones indicate not only a vertical movement under freezing and thawing conditions, but also a tilting of stones into more upright positions (Johnson et al., 1977; Washburn, 1980). The fabric data, therefore, were separated into a horizontal plane that encompasses the trend of the long axis of the stones, and a vertical plane that examines the plunge of the stones relative to the dip of the local slope. This division of the three-dimensional position into two separate two-dimensional planes is typical of microscopic studies of fabric where only two dimensions can be viewed at any one time (Fitzpatrick, 1993). It is also typical for fabric studies of metamorphic rocks in thin section used to understand deformation processes (Borradaile et al., 1982). For macro-fabrics in slope deposits, this division into two planes can be justified by the fact that there are two separate stress-fields operating on the slope materials.

3.2. Analytic procedures

The importance of the downslope stress-field on the orientation of fabrics on a periglacial slope has been shown in numerous studies (e.g., Benedict, 1976; Nelson, 1985; Bertran et al., 1997). In this study, I calculated the circular correlation co-efficient using the procedures presented in Zar (1998). The circular correlation co-efficient corresponds to Spearman's r, such that the paired ranks of the slope azimuth and mean clast direction are compared. The test statistic is compared to the theoretical distribution to determine the level of significance of the association. The slope azimuth was compared to three different forms of the sample ($n=50$) mean clast direction (Fig. 3). The three forms were used because the clast data are axial but are being treated as vectors to allow comparison with the slope direction vector. The first assessment is based on the mean direction of the resultant vector (Table 1; Davis, 1986; Fisher, 1993). The second involved a rotation of the three-dimensional axial data into the plane of the slope (Table 1; Nelson, 1985). Third, the relation between the slope azimuth and each sample's principal eigenvector was tested (Table 1; Millar, 2005). The test statistic indicates that the null of no relation can be rejected in all three forms of the data (Table 1). The most significant relation is with the sample rotated into the plane of the slope. That all three methods of assessing mean clast direction indicate a significant relation with downslope direction demonstrates the overall importance on fabric orientation of shear driven by the downslope stress-field (Jeffery, 1922; Benedict, 1970; Mills, 1983; Nelson, 1985; Bertran et al., 1995).

For the stress-field generated by freezing and thawing, the relation between a sample's average clast plunge and

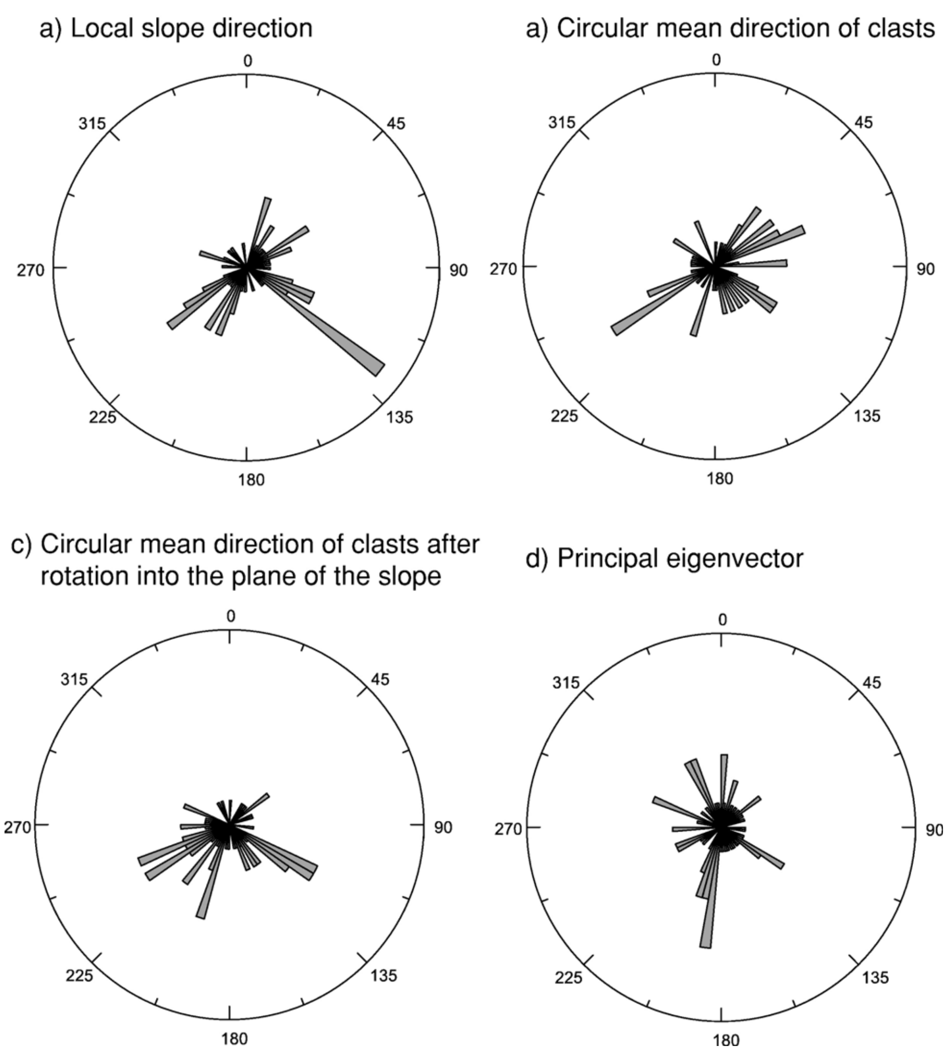

Fig. 3. Rose diagrams of slope and clast directions ($n=68$).

Table 1
Circulation correlation analyses

Variables in test	Circular correlation coefficient[a]	Critical values ($n=68$)
Slope direction and circular mean direction[b]	7.03	4.62; $p=0.01$
Slope direction and circular mean direction rotated into the plane of the slope[c]	10.67	4.62; $p=0.01$
Slope direction and the principal eigenvector[d]	2.85	2.03; $p=0.1$

[a] Correlation coefficient=r($n-1$) where, $r=r_d+r_s$, and

$$r_d = \frac{\left\{\sum_{i=1}^{n}\cos\left[\frac{360}{n}(\text{rank } x_i - \text{rank } y_i)\right]\right\}^2 + \left\{\sum_{i=1}^{n}\sin\left[\frac{360}{n}(\text{rank } x_i - \text{rank } y_i)\right]\right\}^2}{n^2}$$

$$r_s = \frac{\left\{\sum_{i=1}^{n}\cos\left[\frac{360}{n}(\text{rank } x_i + \text{rank } y_i)\right]\right\}^2 + \left\{\sum_{i=1}^{n}\sin\left[\frac{360}{n}(\text{rank } x_i + \text{rank } y_i)\right]\right\}^2}{n^2}$$

where, x = slope azimuth; y = mean clast direction.

[b] Circular mean (Fisher, 1993; equ. 2.7 and 2.8, p 31.)

$$C = \sum_{i=1}^{n}\cos\theta_i;\ S = \sum_{i=1}^{n}\sin\theta_i;\ R^2 = C^2 + S^2$$

$$\cos\bar{\theta} = \frac{C}{R};\ \sin\bar{\theta} = \frac{S}{R}.$$

[c] Rotation of axial data so that the primitive represents the plane of the slope. Data were rotated by the slope dip angle, about the axis represented by the strike of the slope (Nelson, 1985).

[d] Principal eigenvector is the principal axis of the orientation matrix calculated from the sums of squares of the cross-products of the direction cosines of the sample axes (Fisher et al., 1987, §3.2.4, p. 33).

the local slope gradient was evaluated. The Pearson correlation coefficient of -0.805 ($p=0.99$) suggests that there is a strong and systematic relation between these variables (Fig. 3).

3.3. Analysis of environmental data

Rates and modes of mass wasting in a periglacial environment are dependent on a suite of site-specific environmental constraints (Benedict, 1976; Harris, 1987; Smith, 1987; Matsuoka, 2001; Hugenholtz and Lewkowicz, 2002). The biophysical data in this study were examined in relation to average clast dip to determine the extent to which site factors were responsible for producing the observed relation between slope dip and clast dip. A Spearman's rank was applied because soil moisture and stone concentration were assessed on a rank scale. Although this reduces the robustness of the test, it is preferred over Pearson's r, because it allows for direct comparison of all the biophysical data. The correlation matrix indicates a negative relation between the clast plunge and the sample's distance downslope from the divide ($r=-0.311$), but no systematic relation between clast plunge and any of the other environmental variables (Table 2).

4. Discussion

Mass-wasting processes under periglacial conditions are commonly considered a combination of frost creep and gelifluction. Frost creep is the net result of volumetric strain of the sediments due to expansion and contraction over the freeze–thaw cycle. The stress-field is generated by frost heave in the vertical direction; a component of downslope transfer may be present and related to the slope gradient (Washburn, 1980). If frost heave dominates, then the slope materials are most strongly affected by the stress-field perpendicular to the plane of the slope. Gelifluction is considered a flow process, resulting from elevated pore water pressures upon thaw, and is therefore influenced by

Table 2
Spearman rank matrix of clast dip and local environmental factors

	Clast dip–slope angle	Moisture	Stone concentration	Slope angle	Vegetation mat thickness	% silt	% clay
Moisture ($n=68$)	−0.198	1.000					
Stone concentration ($n=68$)	0.007	0.257	1.000				
Slope angle ($n=68$)	−0.762	0.114	0.059	1.000			
Vegetation mat thickness ($n=68$)	0.037	−0.107	−0.159	−0.107	1.000		
% silt ($n=19$)	−0.009	0.006	−0.419	−0.059	−0.337		
% clay ($n=19$)	0.281	0.301	−0.541	−0.300	−0.061	0.719	
Downslope distance ($n=68$)	−0.311	0.07	0.062	0.229	0.082	0.001	−0.047

the stress-field in the downslope direction. Methods of separating gelifluction and frost creep to understand the contribution of each to downslope transport have engaged geomorphologists for some time (Matsuoka, 2001). On the basis of the significant correlation between slope direction and mean clast direction, the importance of the stress-field in the downslope direction is quite apparent from the Eagle Summit data. The most significant variable in the circular correlation analysis is the mean clast direction when rotated into the plane of the local slope (Table 1; Fig. 3). The rotated data generate the strongest relation because, in the process of rotating the clast data, the order is changed, therefore within the correlation test structure there is a more direct one-to-one mapping of equivalent ranks (Table 1). This tendency for a downslope orientation of a-axes has been observed in numerous environments, and is a primary rationale for the use of fabrics for identifying sediment depositional history (e.g., Holmes, 1941; Mills, 1983; Nelson, 1985; Abrahams et al., 1990; Bertran et al., 1995). The changing relation between average clast dip and local slope gradient suggests that slope gradient influences the predominance of either the downslope stress-field or the stress-field perpendicular to the plane of the slope (Fig. 4).

The lack of association between the clast–slope relation and the biophysical factors is surprising in light of previous research. Hugenholtz and Lewkowicz (2002) for example, suggest that a large concentration of clasts tends to form on solifluction lobe risers, thereby increasing the shear strength of the materials. Continued mass-wasting of material from upslope builds up on the lobe tread, possibly eventually leading to lobe collapse (Hugenholtz and Lewkowicz, 2002, p. 311). Areas with higher concentrations of large clasts therefore, may be expected to exhibit more steeply dipping clasts that are thrust upwards by the compressional forces generated by the riser's braking effect on the continued

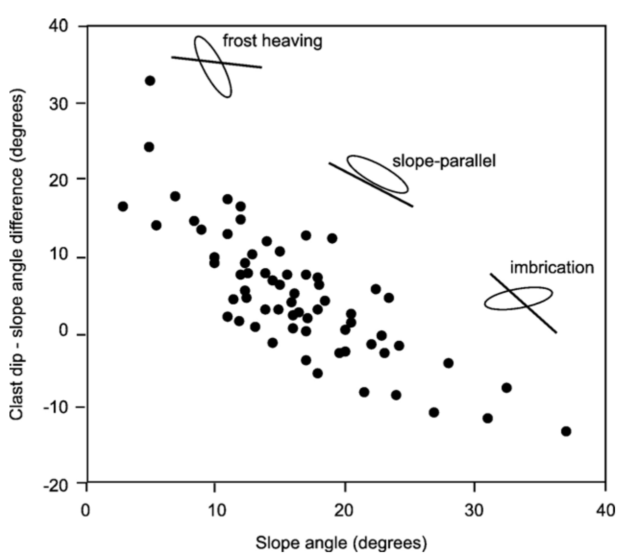

Fig. 4. Relation between the slope and the difference between slope and average clast plunge.

sediment input from upslope (Benedict, 1970). Only fifteen samples were collected specifically from lobe risers; however, they show no greater than average clast plunge. It is likely that stone concentration is not the only factor at work in the formation of fabrics in lobe risers. Bertran et al., (1995), Benedict (1976), and Nelson (1985), all noted an increase in transversely oriented fabrics due to either compressional forces or interaction with the vegetation mat. An increase in the frequency of planar clasts would reduce the overall mean direction of the sample. The lack of association is therefore most likely due to an interaction of factors.

Other important site characteristics also do not show any systematic relation with the position of clasts relative to the slope. Soil texture influences frost susceptibility; therefore it might be expected to influence the nature of deformation by frost heaving and gelifluction (Harris, 1987). Matsuoka (2001) showed that rates of downslope movement vary substantially across a periglacial slope, in large part due to variations in soil texture. Although only 20% of the sites were sampled for soil texture, there is no strong relation according to whether embedded clasts are steeply dipping, parallel or imbricate. This may be in part due to soil textures across the study area being generally limited to silty-sands.

The presence of vegetation and its thickness are frequently considered important controls on the rate of movement due to their influence on moisture content and the shear strength of slope materials (Benedict, 1970; Hugenholtz and Lewkowicz, 2002). In this study, no relation is observed in the data. Finally, soil moisture can influence the degree of soil freezing, frost heave, and slope stability (Williams and Smith, 1989). The Spearman's r of moisture and clast dip–slope difference does not show a significant relation in this data set ($r = -0.198$). This may be due to the fact that soil moisture was assessed only once at each site at the end of the thaw season when slope materials were undergoing little activity. A more detailed monitoring of soil moisture throughout freezing and thawing would provide a more rigorous test of moisture and clast relations.

4.1. Is the dominant mode of periglacial deformation conditioned by slope angle?

These results suggest that the average clast plunge relative to the local slope dip may provide a broad-scale instrument to assess the most recent processes active at Eagle Summit, when considered in light of the relative slope position (Fig. 5). The lack of association with other biophysical data indicates that slope gradient exerts a dominant influence on the clast position observed.

A possible explanation for the strong relation between the clast dip and slope angle may be associated with the resultant stress-field operating on the sediments. On low gradient slopes which, in the study area, are generally

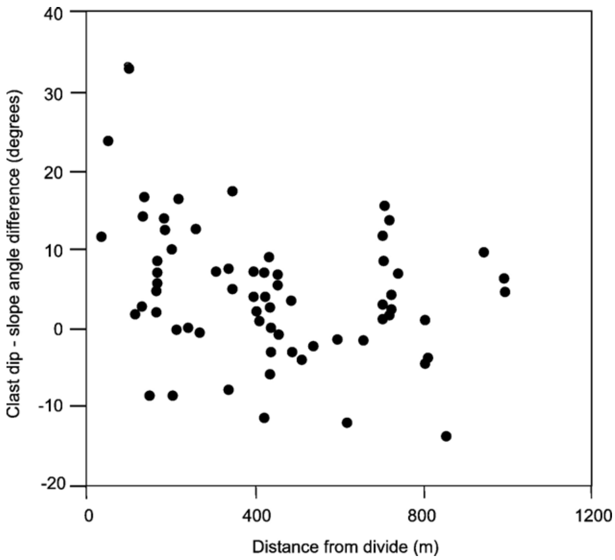

Fig. 5. Relation between clast and slope difference and relative slope location as indicated by the distance from the slope divide.

located near the divide, and are planar or convex, clasts tend to plunge more steeply than the slope angle. In these locations, sorted forms are abundant suggesting that frost heaving is a dominant effect reorienting clasts into an upright position by frost-push or frost-pull mechanisms (Washburn, 1980). In the absence of a significant downslope stress-field, the primary process operating is heave generated by soil freezing and thawing. Both field (Millar and Nelson, 2001) and laboratory experiments (Johnson et al., 1977) have indicated that clasts embedded in materials undergoing freeze–thaw action rotate to a position where the long axis is perpendicular to the direction of the freezing front. This repositioning and increase in clast dip appears to be independent of the original clast position, and increases over time with subsequent freeze–thaw episodes (Johnson et al., 1977; Washburn, 1980).

Strongly imbricate patterns of stone position are associated with the steepest slopes. Imbrication can result under several situations. Bed load in stream flow can exhibit imbrication of the intermediate axis when individual stones are sequentially deposited as material comes to rest following the flow (Collinson and Thompson, 1989; Jo et al., 1997). In experimental debris flows, Major (1998) has proposed that flow parallel upslope imbrication results from incrementally deposited waves of sediment undergoing flow. Such fabrics are typical of alluvial and debris flow deposits (Collinson and Thompson, 1989; Major, 1998). Large clast concentrations have also been shown to result in imbricate fabrics (Rees, 1979; Ildefonse et al., 1992; Bertran et al., 1997). Ildefonse et al. (1992), for example, showed that higher concentrations of clasts tend to produce a tiling effect that stabilizes the material during further deformation. No morphological evidence suggests that a highly fluid, rapid slope failure has occurred at Eagle Summit; however, gelifluction is often considered to behave as a viscous fluid (Harris, 1981; Matsuoka, 2001), in which case it may be possible for any of these mechanisms to produce the imbricated clasts observed, depending on local conditions of soil moisture, texture, and stone concentration. The probability that the slope materials will behave as a viscous fluid will depend primarily on the steepness of the slope (Harris et al., 2001). At Eagle Summit, the mid-slope position of imbrication is typical of stone stripes and small lobes (c.f. Hugenholtz and Lewkowicz, 2002). In the stone stripes, stone collisions may be partly responsible for imbrication, whereas in small lobes, either vegetation or braking effects might be more likely. The multiple influences can help to explain the lack of association in the biophysical variables.

Clasts tend to lie in a slope-parallel position on moderate slopes. The parallel position may simply represent a balance between downslope and vertical forces. So, although frost heaving is likely occurring, on moderate gradients the greater downslope stress-field produces a resultant fabric parallel with the slope. The relative position of these sites is both upslope and downslope of the steepest slopes, also suggesting a transitional location relative to the stress-fields. On the other hand, the slope-parallel fabric could be a result of simple shear operating under conditions of laminar flow reorienting clasts preferentially parallel to the downslope direction in the manner illustrated by Bertran (1993) and Jeffery (1922). Harris et al. (2003) have interpreted observations from scaled-modeling experiments on gelifluction as evidence of elasto-plastic deformation operating as the primary mode of transport, rather than the frequently assumed flow, controlled by viscosity. If this is the case, when sediments reach their critical state, continued stress application will result in shear deformation that tends to exhibit properties of laminar flow (Maltman, 1994 p. 10). Thaw consolidation will then allow for the preservation of fabric orientations in the plane of the slope (Mitchell, 1993 p.340; Cetin, 2004). Whether one or more of these mechanisms is responsible for the slope-parallel fabrics cannot be determined. Modes of deformation are closely dependent upon soil and moisture properties, neither of which shows a significant relation with the clast positions reported here. There is a need for further field and laboratory analyses of the links between processes of deformation and clast fabric.

The data suggest that slope angle relates to the dominant stress-field operating on slope materials. Although other factors, such as soil texture (Matsuoka, 1998), vegetation braking effects (Hugenholtz and Lewkowicz, 2002), and stone concentration (Ildefonse et al., 1992) have been shown to be important at the local scale, the results here suggest that at the landscape scale, the relation between frost heave and gelifluction as shown through clast plunge and slope angle relations, is determinant, particularly when considered in relation to slope position. Specific slope angle thresholds between the dominant processes influencing clast dip at Eagle Summit require further detailed field examination of their relation to soil texture and moisture and material strength. Whether these relations hold for other periglacial areas will likely depend on local biophysical conditions.

5. Conclusion

Processes operating on slope materials under periglacial conditions are highly varied and complex, as evident in the volume of research that has been conducted to date. The results presented here indicate the importance of examining the entire slope as a continuum. Observations of the two-dimensional clast fabrics which examine independently the stress-fields generated by the slope gradient and frost heave suggest that it is likely the dominant, and most recent process, affecting stone orientation. Further, if that is indeed the case, the relation between clast dip and slope angle, in the context of its relative slope position, allows us to consider the periglacial slope as a continuum of interaction between two stress-fields. Slope gradient determines the relative importance and intensity of each stress-field thereby conditioning the dominant style of deformation. Two-dimensional fabrics, therefore, may provide useful evidence on which to base a more general understanding of the relative importance of frost heaving or gelifluction on modes of sediments transfer during mass-wasting on periglacial slopes.

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