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Geomorphology 72 (2005) 222–237

GEOMORPHOLOGY

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Fabric variability associated with periglacial mass-wasting at Eagle Summit, Alaska

Susan W.S. Millar *

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

Received 25 January 2005; received in revised form 10 May 2005; accepted 11 May 2005

Abstract

Fabric analysis is a frequently applied technique and, when used in concert with other tools, aids the interpretation of glacigenic and colluvial depositional environments. The research presented here focuses on its application to periglacial colluvium, using a stratified systematic unaligned sampling framework in order to assess the variation of fabrics generated. The range of possible variation in fabric is necessary information for its application to periglacial paleoenvironmental interpretation. Fabric strength and shape from 68 samples, of 50 stones each on a range of microgeomorphic settings across terrain influenced by periglacial mass-wasting in central Alaska, were analyzed in relation to local slope orientation, clast characteristics, organic mat thickness, stone density, distance downslope from the divide, soil texture and soil moisture. Principal components analysis (PCA) was used to reduce stone characteristics to three factors. Multiple regression analyses of the three factors and environmental variables, with the fabric strength parameters as dependent variables, indicate that stone characteristics, particularly size and platyness, are the most significant factors determining fabric strength. No distinct fabric strength or shape was associated with specific landforms. These results raise serious doubts as to the time-cost effectiveness of the application of fabric analysis as a paleoenvironmental tool to identify periglacial landforms from their deposits.

Keywords: Sediment fabric; Periglacial mass-wasting; Solifluction; Spatial variability; Alaska

1. Introduction

The orientation of elongated stones within soil and sediments has been extensively used to help understand the geomorphic history of a sediment mass. This technique, often referred to as fabric analysis, has been employed frequently for differentiating glacial tills and colluvium, including that on arid and periglacial slopes. The results of such studies are often applied in a paleoenvironmental context as one in a suite of many criteria. The physics of particle motion, physical modeling of rotating particles, and computer simulations of fabric generation, all confirm a tendency for distinct arrangements of particles entrained in moving masses of sediment to develop (Glen et al., 1957; Lindsay, 1968; Bertran, 1993). However, this assumes that, when the sedi-

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

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doi:10.1016/j.geomorph.2005.05.012

ment mass comes to rest, the style of dynamic deformation is retained in the fabric pattern, ignoring the possibility that mode of deposition will also exert a different stress field. Results of field studies, particularly those in paleo-settings, are therefore often equivocal. Instead of providing corroborative evi-

Table 1
Factors in functional equation defining resultant fabric and their use in laboratory and field experiments

Factor	Effect on fabric development	Selected references	This study
Mechanism of movement (P)	The assumption in almost all studies is that this factor will be directly reflected in the resultant fabric. The expected fabrics in solifluction are further discussed in the text.		Can be discerned in terms of stress field orientation and magnitude.
Clast properties (C)			
• Clast axial ratio	Increasing downslope-parallel orientation with increasing axial ratio.	(Holmes, 1941; Lundqvist, 1949; Yamamoto, 1989; Bertran, 1993; Kjær and Krüger, 1998; Millar and Nelson, 2003)	Combined clast properties of size, prolateness and within sample a:b variation explain up to 16% of fabric strength; 13% of fabric shape.
• Clast shape	Angular clasts more frequently oriented downslope-parallel. Blade and rod shaped clasts develop stronger fabrics.	(Lundqvist, 1949; Glen et al., 1957; Krüger, 1970; Drake, 1974; Yamamoto, 1989)	
• Clast size	Longer clasts more reflective of direction of movement.	(Krüger, 1970; Kjær and Krüger, 1998)	
• Within sample variation	Clasts differentially respond to stress field whereby smaller clasts more likely to become transverse to flow. Overall, greater variation weakens composite fabric.	(May et al., 1980; Carr and Rose, 2003)	
Stone concentration (D)	Laboratory experiments indicate a weakening of fabric with increased concentration	(Ildefonse et al., 1992)	No systematic relation observed.
	Collisions between stones restrict full rotation of clast, resulting in a preferred parallel orientation.	(Glen et al., 1957)	
	Collisions in a dense stone network weaken fabric.	(Rappol, 1985)	
	Interaction of grains in moving debris flow mass with now-stationary deposits creates imbricate and lobe-parallel fabrics.	(Major, 1998)	
Post-depositional modification (M)	Seasonal freezing rotates clasts into an upright position.	(Millar and Nelson, 2001)	NA
	Re-orientation most significant for small clasts.	(Lindsay, 1970)	
Local slope angle (α)	Fabric strength shows positive relation with slope angle in colluvial deposits in VA, suggesting that fabric is related to creep rate.	(Mills, 1983)	Parallel to transverse progression of stone orientation weakly observable with increasing slope.
Rate of movement (v)	Usually considered unknown in fabric studies and inferred from resultant fabric.	(Harris et al., 2001)	Not directly measured, but slope angle assumed to provide relative approximation.
	Experimental models indicate a relation between rate of gelifluction and slope angle.		
Distance downslope (m)	Unimpeded flow upslope results in parallel. Obstructed flow at terminus re-orients into transverse position.	(Caine, 1968)	Fabric strength increases away from divide.
Depth in deposit (h)	Seasonal frost re-orients surface fabrics, destroying original fabrics.	(Millar and Nelson, 2001)	Sample depth kept constant.
	Rate of fabric development and degeneration dependent on velocity gradient, therefore fabric varies with depth in any one deposit.	(Lindsay, 1968)	

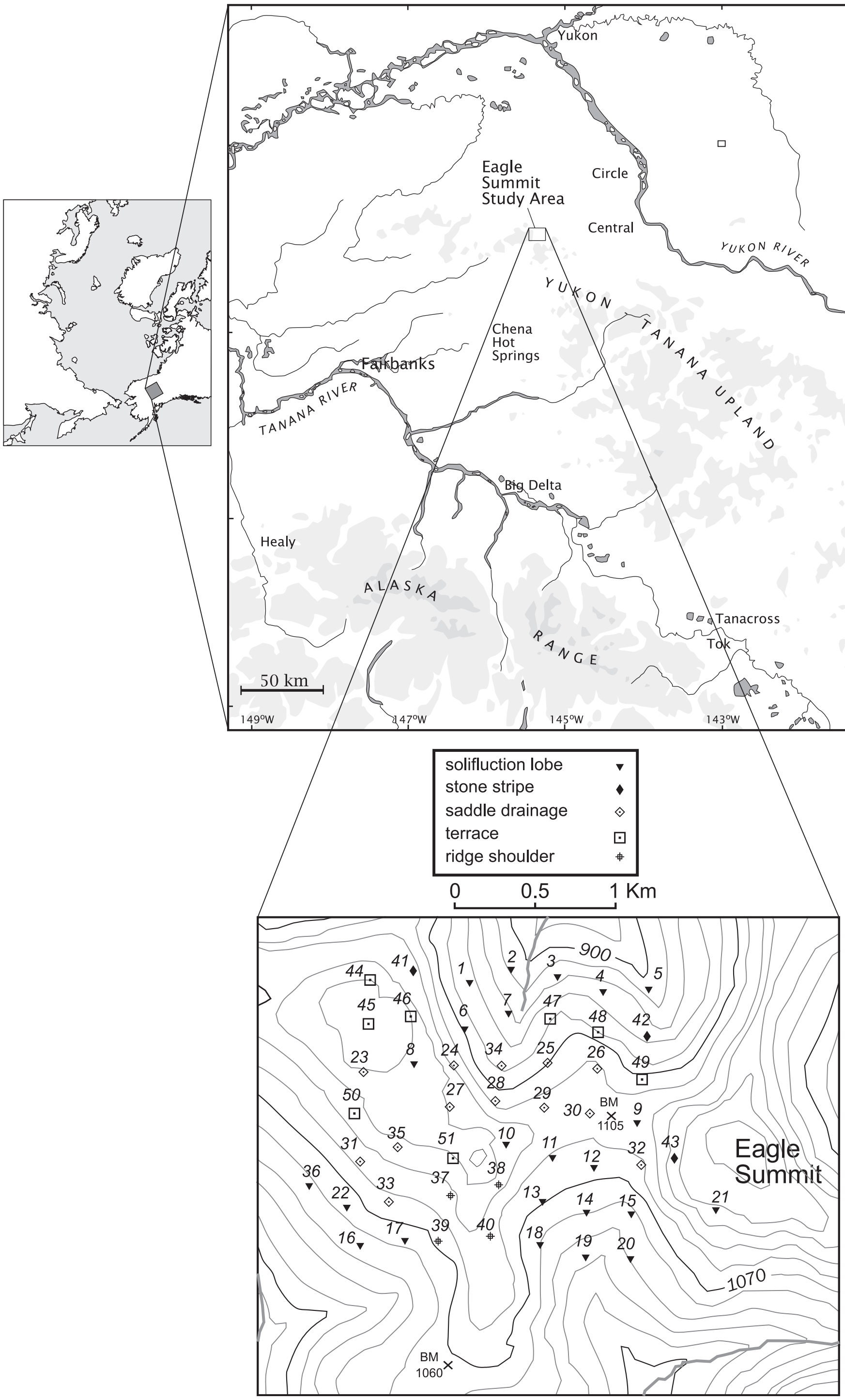

Fig. 1. Location of Eagle Summit and sample collection sites.

dence, fabric data are simply accounted for by marshalling other types of evidence. In a periglacial environment, all stages of fabric development must be considered before realistic interpretations of fabrics in relict slope deposits can be made.

Glen et al. (1957), in reference to glacial fabrics, provide a useful summary of four sets of processes that can occur before the final fabric is generated: (1) those intrinsic to the flow of material entraining the stone, including the thickness of the moving mass and its rate of flow; (2) those associated with the individual behavior of stones, based on their size, shape and axial ratio; (3) those involved in deposition, when a moving mass comes to rest; and (4) any post-depositional processes. In practice, most research has focused attention on one or a few of these influences and how they affect the resultant fabric (Table 1).

An expansion of these four suggests a functional relation for describing influences on fabrics in mass wasting deposits (F):

$$F = f(P, C, D, M, \alpha, v, m, h) \tag{1}$$

where P is the mechanism of deformation or process; C is clast properties of size, shape and axial ratio; D is stone concentration; M is post-depositional modification or form relaxation; α is the local slope angle; v is the rate of movement; m is the distance downslope; and h is the depth or position in the deposit. The value of fabric analysis as a paleoenvironmental tool must rest on its ability to tease out relations between these factors so that the genetic identity of the deposit can emerge.

Mills' (1991) compilation of fabrics in glacial and mass-movement sediments represents a broad attempt to determine the utility of fabrics for distinguishing between depositional environments. He concluded that fabric strength rather than pattern was a better diagnostic criterion, and that fabric in relict periglacial colluvium, often interpreted as the product of solifluction, was distinctly different from that measured in active solifluction lobes. Although Mills (1991) did examine the data in light of matrix content and slope angle, comprehensive data on microenvironmental and clast characteristics were not available. In a similar comparative analysis of non-glacial slope deposits incorporating additional fabric data from solifluction lobes, Bertran et al. (1997) illustrated a greater overlap between relict and active solifluction; however, the data were collected from distinct lobes, albeit from different positions on the lobe. In general, solifluction fabric studies tend to focus on the lobe form itself (Benedict, 1970; Nelson, 1985).

In a paleoenvironnmental context, the luxury of selecting the appropriate location to get directly comparable fabrics is frequently not available. A more realistic control data set, therefore, should incorporate the range of variation. The objectives in this study are therefore (1) to examine the variation in measured fabrics across a 4 km^2 area showing evidence of active periglacial slope processes and, therefore, whether specific periglacial landforms on a slope exhibit consistent fabrics; and (2) to collect corresponding microenvironmental and clast data to assess the degree to which site and stone characteristics, rather than processes, might influence fabric. By addressing these objectives, the potential utility of fabric analysis, as a paleoenvironmental tool to identify periglacial landforms from their deposits, is evaluated.

2. Methods

2.1. Data collection

Data were collected from a variety of microenvironments and geomorphic features at Eagle Summit,

Table 2
Eagle Summit site and sample descriptions

Location:	65°30′N, 145°30′W
Elevation:	800–1200 m a.s.l.
Temperature:	Normal July max, January min, annual mean air T (°C): 18.02, −37.48, −11.07. [Climate data approximated by applying 6.5 °C/km lapse rate to records from Central, Alaska (65°34′N, 144°46′W, 280.4 m)]
Bedrock:	Quartz-muscovite schist and carbonaceous quart-muscovite schist and intercalated micaceous quartzites (Reger, 1975)
Soil:	Histic pergelic cryaquepts
Vegetation:	Wet sites: Alpine Sedge—Carex and Eriophorum dominant Dry sites: Alpine-Dryas Sedge—Carex and Dryas dominant (Hanson, 1950)
Sampling depth:	0.2–0.6 m
Number of samples:	38 lobes, 14 saddle drainage slopes, 8 small terraces, 4 ridge shoulders, 4 stone stripes.

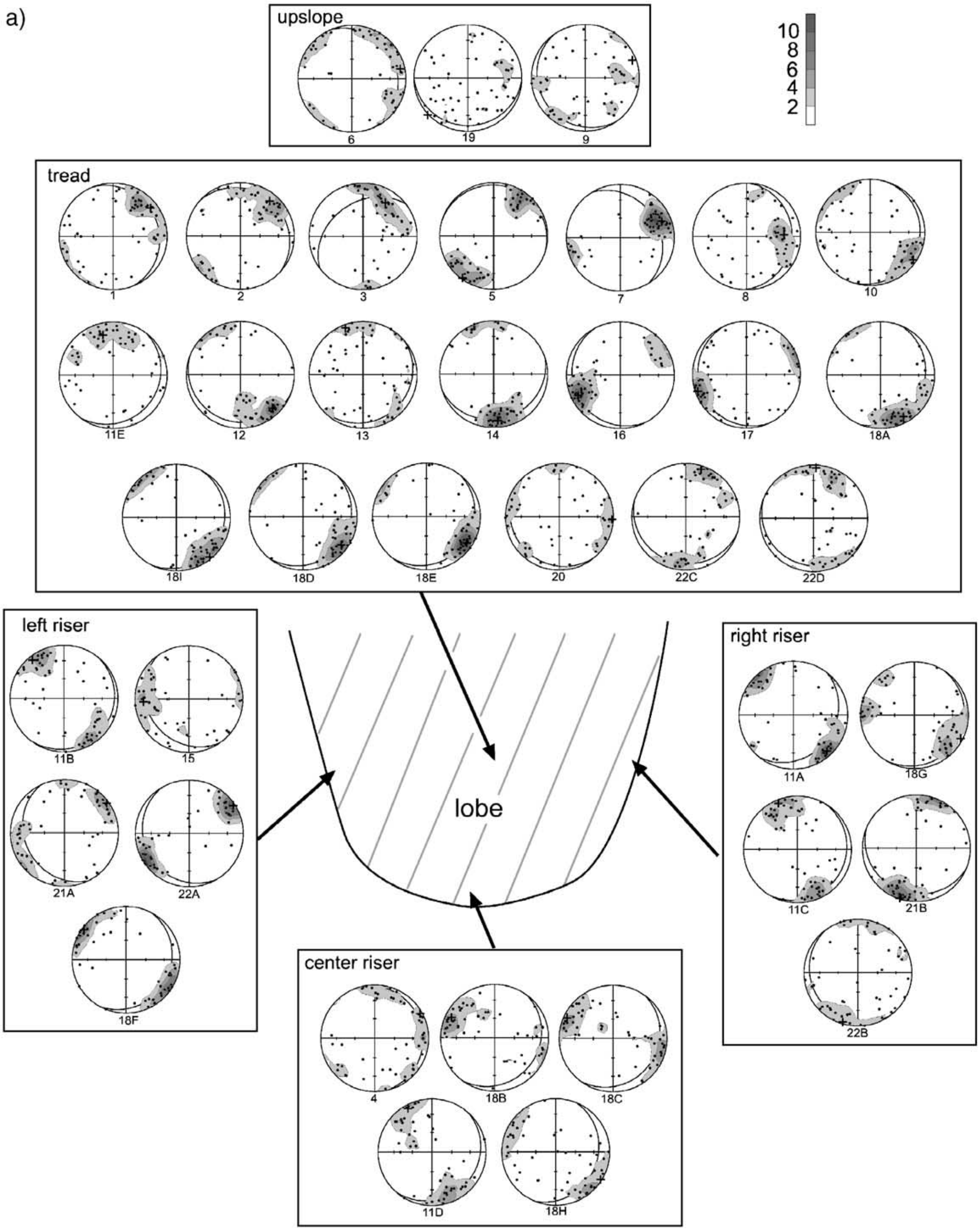

Fig. 2. Equal area, lower hemisphere plots of, (a) solifluction lobes, and (b) terrace, saddle drainage, stone stripe and shoulders sites, at Eagle Summit. The black cross represents the position of the principal eigenvector; the arc represents the plane of the local slope. North is at the top. Contours represent two point count intervals using Starkey's (1977) method.

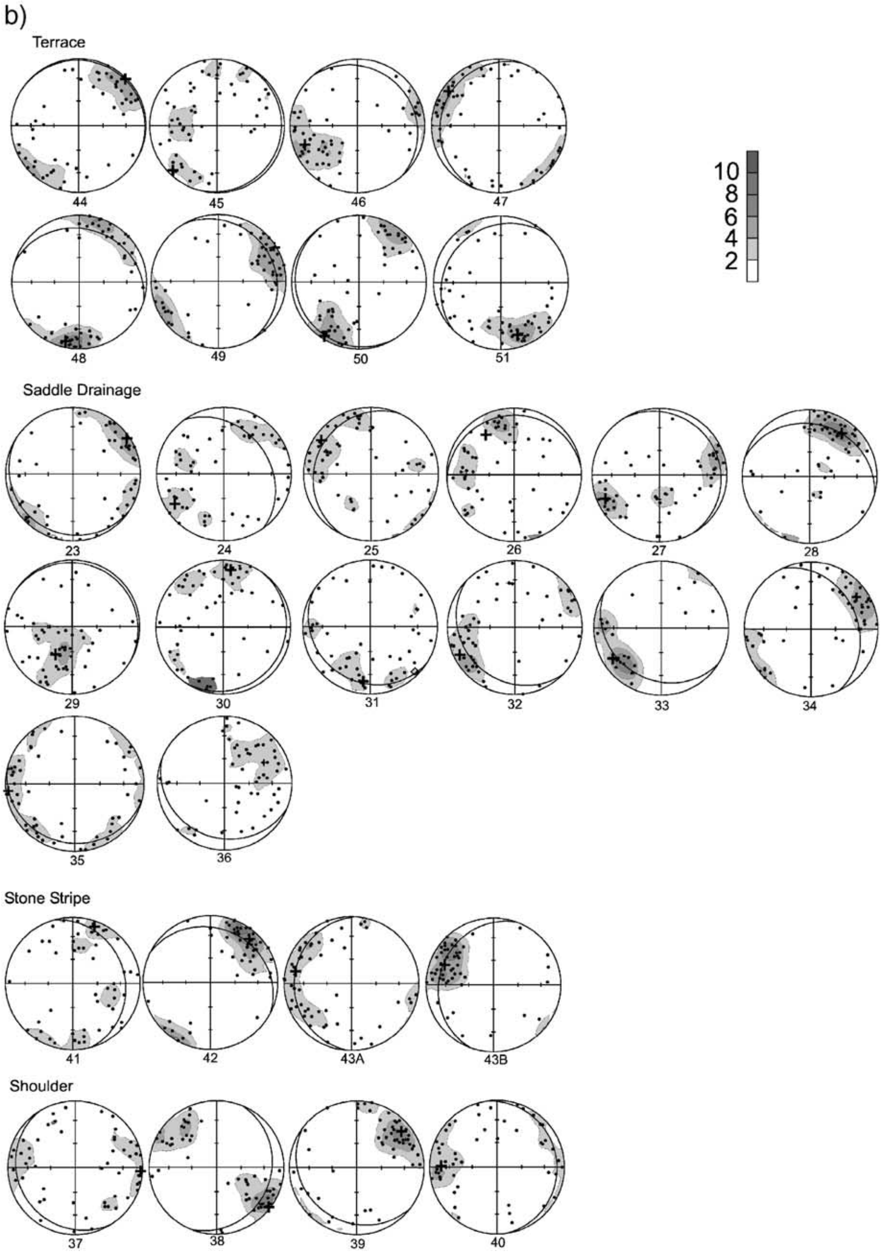

Fig. 2 (*continued*).

Alaska (Fig. 1). Evidence of active periglacial slope processes at Eagle Summit includes many turf-banked solifluction lobes, often with small shrubs undergoing burial from upslope materials. Stone garlands, circles and stripes occur at higher elevations; however, there is some question as to their present-day activity. Details of site characteristics are provided in Table 2.

To define variation in fabrics across the slope, I collected a systematic stratified unaligned sample on a 275 m grid, centered over a 4 km^2 area. Two USGS benchmarks provided spatial reference for the sample grid to ensure correct field identification of sites. This sampling strategy has been shown to produce a representative coverage (Berry and Baker, 1968; Iachan, 1985), and to eliminate systematic bias due to inherent geomorphic self-organization or regularity, a phenomenon that has been observed in other periglacial environments (Gleason et al., 1986; Krantz, 1990; Kessler and Werner, 2003).

Clast samples were collected by two operators in the field, using methods outlined by Andrews (1971). This involved the extraction of 50 elongated clasts from the matrix and their replacement by a nonmetallic rod to allow measurement of plunge and plunge azimuth by Brunton compass. Stone size and shape properties were measured on the basis of *a*-, *b*-, and *c*-axial lengths measured to ± 1 mm using calipers. Although most fabric data are collected within a range of specified but varying axial ratios (Mills, 1983; Nelson, 1985; Giardino and Vitek, 1988; Perez, 1989; Major, 1998), this study was concerned with how clast properties, including axial ratio, influence fabric; therefore no axial ratio limit was imposed. Other factors in the functional relation that were collected at each sample location were local slope azimuth and gradient, distance to the nearest divide, and the visual estimate of stone concentration (Compton, 1985, p. 366). Matrix samples were also collected from 19 sites for particle size analysis. These samples were oven dried and treated with H_2O_2 to remove organics before analysis by dry sieving and pipette of the <2 mm fraction.

No measures of the rate of movement of the material are available, despite its apparent importance in influencing the strength of the fabric (Table 1; Benedict, 1976; Mills, 1983). Rates of movement may also be an important concern in understanding how the material finally comes to rest, and therefore provide clues about the mode of deposition as well as transport. Here, slope angle was used as a proxy for mass wasting rate. Empirical field data (Carson and Kirkby, 1972; Harris, 1987), and scaled modeling experiments (Harris et al., 2001), suggest that such an assumption is valid. Sample depth was consistent across all samples and within the range of minimal variation in fabrics generated (Hill, 1968; Benedict, 1970); and post-depositional modification was considered part of the process suite responsible for the resultant fabric, although it is assumed minimal in the context of the active mass-wasting at Eagle Summit.

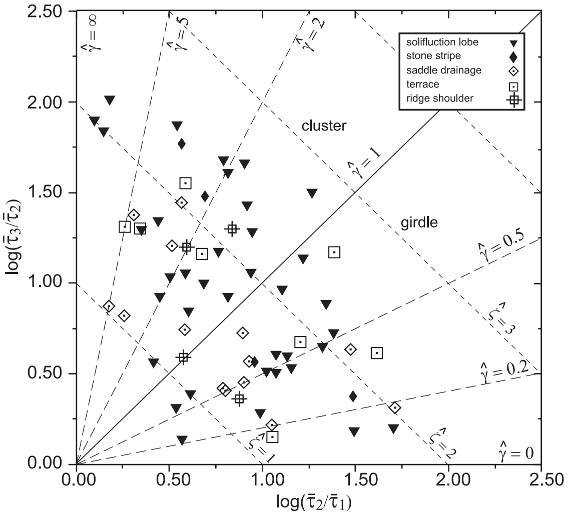

Fig. 3. Eagle Summit data plotted in Woodcock (1977) log ratio eigenspace.

2.2. Exploratory analysis using eigenvalues

Individual sample fabric patterns were plotted on equal area plots, showing the local slope angle and azimuth (Nelson, 1985), and contoured using Starkey's (1977) point counting method (Fig. 2).

Clast orientation data were subjected to eigen analysis following the methods outlined by Mark (1971), Mardia (1972), and Fisher et al. (1987). An orientation matrix of the sum of squares and cross products of the axes direction cosines was constructed. The eigenvectors of this matrix represent the three principal directions of the distribution and the eigenvalues ($\tau_3>\tau_2>\tau_1$) represent their relative magnitudes. The eigenvalues are normalized by dividing each by the sample size ($\bar{\tau}_1=\bar{\tau}_1/n$, where $i=1$, 2, 3, and $\bar{\tau}_1+\bar{\tau}_2+\bar{\tau}_3=1$). Results are plotted on a Woodcock (1977) log ratio diagram where the abscissa represents log $\bar{\tau}_2/\bar{\tau}_1$ and the ordinate log $\bar{\tau}_3/\bar{\tau}_2$ (Fig. 3). Fabric shape and strength can be visualized and compared through examination of a sample's position in the Woodcock eigenspace, and quantified as strength ($\hat{\zeta}$) and shape ($\hat{\gamma}$) parameters (Woodcock, 1977; Fisher et al., 1987), where

$$\zeta = \log(\bar{\tau}_3/\bar{\tau}_1) \tag{2}$$

Table 3
Fabric data for all samples

Sample	Landform[a]	$\bar{\tau}_1$	$\bar{\tau}_2$	$\bar{\tau}_3$	t_3[b]	γ[c]	ζ[d]	S_u[e]	Slope azimuth, dip	Mean *a*-axis (mm)	Mean *a*:*b* ratio
1	L	0.112	0.253	0.634	51, 13	1.130	1.731	54.69	068, 16	120.28	1.67
2	L	0.126	0.227	0.647	39, 16	1.767	1.639	57.32	042, 14.5	97.95	1.67
3	L	0.084	0.316	0.600	30, 24	0.484	1.962	49.97	323, 37	96.51	1.57
4	L	0.094	0.412	0.494	161, 5	0.121	1.658	33.45	080, 11.5	86.56	1.69
5	L	0.067	0.148	0.786	199, 7	2.101	2.468	116.37	018, 5.5	118.7	1.93
6	L	0.076	0.417	0.507	188, 8	0.116	1.892	38.65	058, 28	125.06	1.90
7	L	0.072	0.124	0.804	189, 9	3.443	2.410	124.96	093, 17	64.4	1.66
8	L	0.193	0.293	0.513	353, 14	1.344	0.977	20.12	235, 14	89.68	1.64
9	L	0.199	0.339	0.462	195, 18	0.587	0.842	12.99	108, 10	80.77	1.67
10	L	0.142	0.259	0.599	123, 5	1.391	1.441	42.31	128, 24	103.54	1.75
11A	L	0.092	0.235	0.674	133, 5	1.123	1.994	68.99	128, 9	129.14	1.87
11B	L	0.148	0.197	0.655	322, 3	4.152	1.489	58.67	120, 11	121.34	1.76
11C	L	0.099	0.213	0.688	338, 3	1.539	1.933	72.98	132, 15	123.3	1.84
11D	L	0.120	0.238	0.642	331, 1	1.443	1.676	56.09	127, 16	118.76	2.02
11E	L	0.114	0.334	0.551	347, 19	0.467	1.573	35.80	200, 12.5	78.82	1.67
12	L	0.118	0.184	0.699	154, 13	3.003	1.781	75.90	140, 14	96.54	1.74
13	L	0.180	0.333	0.488	338, 3	0.619	0.999	17.80	162, 17	104.88	1.68
14	L	0.090	0.108	0.802	169, 13	10.963	2.186	123.50	235, 23	88.18	1.66
15	L	0.108	0.316	0.576	269, 16	0.557	1.678	41.36	242, 13	100.32	1.90
16	L	0.049	0.174	0.778	246, 15	1.176	2.774	114.08	246, 12	93.76	1.80
17	L	0.071	0.272	0.658	246, 6	0.657	2.232	66.81	112, 19.5	89.96	1.79
18D	L	0.069	0.156	0.775	122, 14	1.976	2.415	111.08	126, 18	94.08	1.92
18A	L	0.067	0.227	0.706	148, 16	0.931	2.355	82.97	126, 18	55.14	1.80
18B	L	0.137	0.227	0.636	295, 8	2.047	1.534	53.04	129, 15	75.86	1.79
18C	L	0.084	0.254	0.662	295, 2	0.860	2.069	66.24	129, 15	79.04	1.76
18D	L	0.078	0.201	0.721	126, 15	1.357	2.219	87.22	118, 18	100.22	1.72
18F	L	0.072	0.180	0.748	307, 0	1.555	2.339	98.83	122, 10	90.46	1.72
18G	L	0.132	0.188	0.680	116, 8	3.615	1.640	68.14	112, 23	96.1	1.76
18H	L	0.154	0.241	0.605	122, 5	2.040	1.369	42.90	117, 12.5	89.48	1.93
18I	L	0.106	0.117	0.777	139, 10	20.373	1.989	110.72	181, 12	81.06	1.62
19	L	0.209	0.369	0.422	229, 4	0.236	0.703	9.22	229, 12.5	83.82	1.77
20	L	0.138	0.371	0.490	91, 1	0.282	1.265	24.02	244, 27	110.44	1.73
21A	L	0.103	0.320	0.577	53, 0	0.52	1.723	42.13	202, 17	80.2	1.80
21B	L	0.106	0.123	0.771	200, 6	12.34	1.984	107.67	240, 16.5	103.32	1.82
22A	L	0.061	0.151	0.788	58, 2	1.803	2.566	117.89	233, 14	80.04	1.77
22B	L	0.119	0.331	0.550	199, 7	0.498	1.526	34.69	198, 14	95.66	1.71
22C	L	0.076	0.303	0.621	18, 0	0.521	2.098	56.20	202, 12.5	109.18	1.81
22D	L	0.105	0.333	0.562	1, 5	0.456	1.678	39.24	212, 11	114.35	1.81
23	SD	0.073	0.318	0.608	205, 13	0.11	2.120	53.81	54, 32.5	102.93	1.57
24	SD	0.153	0.333	0.513	186, 44	0.556	1.210	24.31	295, 17	105.84	1.70
25	SD	0.192	0.245	0.563	188, 3	3.413	1.076	30.16	354, 12	60.764	1.51
26	SD	0.152	0.337	0.511	332, 15	0.523	1.212	24.09	060, 11	85.68	1.81
27	SD	0.126	0.315	0.559	189, 14	0.626	1.490	35.23	016, 22.5	110.4	1.75
28	SD	0.130	0.175	0.694	16, 2	4.635	1.675	73.60	032, 5	102.42	1.66
29	SD	0.199	0.234	0.567	180, 55	5.463	1.047	30.83	125, 8.5	96.71	1.71
30	SD	0.137	0.333	0.530	241, 19	0.523	1.353	28.98	213, 18.5	78.88	1.67
31	SD	0.135	0.381	0.483	336, 4	0.229	1.275	24.00	234, 22	89.04	1.81
32	SD	0.117	0.285	0.598	243, 11	0.832	1.631	44.63	212, 24	85.75	1.78
33	SD	0.099	0.172	0.729	237,16	2.614	1.997	88.94	065, 31	61.79	1.62
34	SD	0.122	0.202	0.675	173, 19	2.393	1.711	66.94	193, 13	80.09	1.88
35	SD	0.070	0.389	0.541	75, 1	0.192	2.045	43.36	202, 19	80.43	1.89
36	SD	0.154	0.272	0.574	61, 34	1.313	1.316	35.24	238, 15	79.07	1.66

(continued on next page)

Table 3 *continued*

Sample	Landform[a]	$\bar{\tau}_1$	$\bar{\tau}_2$	$\bar{\tau}_3$	t_3[b]	γ[c]	ζ[d]	S_u[e]	Slope azimuth, dip	Mean a-axis (mm)	Mean a:b ratio
37	SH	0.166	0.295	0.540	96, 1	1.051	1.180	27.07	112, 20.5	76.92	1.66
38	SH	0.084	0.194	0.722	127, 3	1.57	2.151	87.17	217, 20	69.86	1.76
39	SH	0.112	0.203	0.685	47, 14	2.045	1.811	70.99	074, 23.5	85.09	1.59
40	SH	0.121	0.317	0.562	270, 10	0.595	1.536	36.52	027, 20	88.22	1.66
41	SS	0.145	0.348	0.506	5, 5	0.428	1.250	24.52	082, 12	93.38	1.82
42	SS	0.076	0.133	0.791	192, 5	3.186	2.343	118.50	273, 16	118.74	1.83
43A	SS	0.084	0.371	0.545	282, 16	0.259	1.870	40.66	290, 20.5	151.3	2.01
43B	SS	0.085	0.168	0.748	292, 21	2.192	2.175	97.90	033, 3	120.37	1.65
44	T	0.139	0.186	0.675	43, 2	4.985	1.580	66.27	106, 5	85.09	1.59
45	T	0.139	0.399	0.463	115, 10	0.141	1.203	22.10	049, 15.5	62.68	1.57
46	T	0.132	0.185	0.682	203, 30	3.865	1.642	69.08	067, 17	54.93	1.71
47	T	0.066	0.328	0.607	195, 7	0.387	2.219	54.95	290, 14.5	62.16	1.64
48	T	0.056	0.222	0.722	181, 22	0.856	2.557	90.23	017, 21.5	140.15	1.78
49	T	0.088	0.158	0.753	2, 8	2.663	2.147	100.20	060, 16	87.32	1.78
50	T	0.108	0.212	0.681	335, 0	1.73	1.841	69.85	238, 7	95.94	1.65
51	T	0.092	0.306	0.602	210, 34	0.563	1.878	49.33	315, 18	96.28	1.81

All samples consist of 50 replications of plunge and plunge azimuth.

[a] L—lobe; SD—saddle drainage; SH—ridge shoulder; SS—stone stripe; T—terrace.

[b] Azimuth and plunge of principal eigenvector t_3.

[c] Shape parameter: $\gamma=\log(\bar{\tau}_3/\bar{\tau}_2)/\log(\bar{\tau}_2/\bar{\tau}_1)$.

[d] Strength parameter: $\zeta=\log(\bar{\tau}_3/\bar{\tau}_1)$.

[e] Mardia's (1972, p. 276) uniformity statistic (critical value at 0.05 is 11.07).

and

$$\hat{\gamma} = \log(\bar{\tau}_3/\bar{\tau}_2)/\log(\bar{\tau}_2/\bar{\tau}_1) \tag{3}$$

The origin represents a uniform shape distribution with zero strength. Positions along the x-axis represent increasing strength or tightness of a girdle distribution, and positions along the y-axis represent increasing strength of a uniaxial clustered distribution. The strength parameter is, in effect, a measure of the within sample variance of stone orientation. The diagonal, with a slope of 1 (i.e. $\gamma=1$), represents the transition between cluster and girdle distributions (Woodcock, 1977). Mardia's (1972, p. 272) test statistic was calculated for each sample to test for uniformity (Table 3).

2.3. Statistical treatment

A circular correlation procedure was run on the slope azimuth and azimuth of the principal eigenvector generated for the aggregated clast sample at each site. The T-monotone association described by Fisher (1993) provides an estimate of the correlation coefficient $\hat{\Pi}_n$. The steps in the procedure and the results are outlined in Table 4.

To assess which variables exert the greatest influence on resultant fabric, the functional equation was tested using a backward stepwise multiple regression which provided the fewest number of factors with the best explanatory power (SYSTAT, 1998). Multi-colli-

Table 4
Procedure and results for circular correlation

Procedure		
1. Circular data sets	Slope direction (γ)	Azimuth of principal eigenvector (ε)
2. Circular ranks (a) r_i=ordered rank, 1 is the smallest (b) circular ranks	$\gamma_i=2\pi r_i/n$	$\varepsilon_i=2\pi r_i/n$
3. $\hat{\Pi}=(4/n^2)$ $(AB-CD)$	$A=\sum_{i=1}^{n}\cos\gamma_i\cos\varepsilon_i$	$B=\sum_{i=1}^{n}\sin\gamma_i\sin\varepsilon_i$
	$C=\sum_{i=1}^{n}\cos\gamma_i\sin\varepsilon_i$	$D=\sum_{i=1}^{n}\sin\gamma_i\cos\varepsilon_i$
Results		
$\hat{\Pi}_n=-0.045$	$\lvert(n-1)\hat{\Pi}_n\rvert=3.00$	Critical value=2.31, $\alpha=0.05$.

nearity between variables representing clast characteristics was addressed by running a principal components analysis (PCA). This was used to define a set of factors describing the key elements of the clasts that could be used as variables in the regression model. The fabric shape parameter was transformed to log shape to normalize the model inputs. Residuals were compared to the grouped data for soil textural class, soil moisture, landform, and operator.

On the assumption that landform expression may indicate the intensity of slope processes, a comparison of fabric parameters across landform types was conducted using the Kruskal–Wallis non-parametric form of ANOVA (Zar, 1998). The 5% loss in power compared to the parametric form of the test was preferred to the breaking of the ANOVA assumption of even class sample size.

3. Results

3.1. Variation of fabrics across landform units

The first objective of this study was to examine the range of variation in fabric on a meso-scale periglacial slope. The Woodcock log ratio plot of all data from Eagle Summit illustrates considerable variation in both strength and shape (Fig. 3). Mardia's test (Table 2) shows that in all but one case (sample 19) the null hypothesis of uniformity must be rejected. The Woodcock plot (Fig. 3) was constructed to indicate samples stratified by landform class. Systematic characteristics of fabric strength and shape were tested across landform types on the basis of the Kruskal–Wallis test, but show no significant differentiation (Table 5). Fabric patterns, therefore, appear not to be diagnostic of the landforms units studied at Eagle Summit.

Table 5
Kruskal–Wallis test between landform type and fabric parameters

Landform	Shape (rank sum)	Strength (rank sum)
Lobe	1267	1346
Saddle drainage	340	224
Shoulder	142	115
Stone stripe	121	159
Terrace	275	301
Test statistic	0.344	6.727
Probability (4*df*)	0.987	0.151

3.2. Influence of clast and microenvironmental variables

The second objective was to assess the degree to which clast and microenvironmental characteristics, rather than processes, might influence observed fabrics. The PCA analysis defined a reduced set of factors describing the key elements of the clasts that could then be used in multiple regression analysis while maintaining independence between variables. Three factors were defined that explained 91.8% of the variance. Variables with high loadings for each factor are detailed in Table 6, and suggest that factor 1 represents average clast size, factor 2 is a measure of clast 'platyness', and factor 3 is clast 'prolateness'.

The three factors were then used in a backwards stepwise regression (variables removed at $\alpha > 0.05$) with the variables slope angle, slope azimuth (using cosine azimuth and sine azimuth) used as a proxy for microenvironmental conditions (Hugenholtz and Lewkowicz, 2002), distance downslope, stone concentration and depth of organic mat, to test their explanatory power on fabric strength and shape. Only the variables with a significant relation ($\alpha = 0.05$) were used in the general model. The results suggest that there is minimal explanatory power in the variables commonly applied to fabric analysis (Table 7). Only 15.8% of the relation between the variables and fabric strength can be explained, and 13.5% of that between shape and the independent variables. Further, the variables with the greatest explanatory power include factors 1 and 2, which are those associated with the size and shape of the clasts being measured at any one site, and the distance from the nearest divide.

Moisture conditions, landform types and operator differences could not be included within the linear regression model owing to their measurement as categorical variables. Residual analysis was used to determine the form of the unexplained component in relation to these variables. The studentized residuals were plotted against fabric strength and log of fabric shape and grouped into categories by geomorphic form, operator, soil moisture class, and soil textural class (Fig. 4a–h). The plots show a significant linear correlation between the variables with a correlation

Table 6
Component loadings for first three factors in PCA

Factor	Variable[a]	Component loadings	Variance explained	% Total variance
1			3.781	47.257
	Mean volume	0.944		
	Mean a-axis	0.921		
	Mean c-axis	0.867		
	Mean b-axis	0.804		
2			2.153	26.908
	c/a[b]	−0.906		
	$(a-b)/(a-c)$[b]	−0.779		
3			1.408	17.602
	s^2a/b	−0.785		
	a/b	−0.710		

[a] Only variables with component loadings ≥0.700 included in table.

[b] Spherical indices from Benn and Ballantyne (1993).

coefficient at $\alpha=0.001$, of 0.891 for strength, and 0.922 for log shape ($n=68$). In the case of the 19 soil samples, the corresponding statistics are $r=0.955$ at $\alpha=0.001$ for strength, and $r=0.869$ at $\alpha=0.001$ for log shape. The linear form of the residuals is an indication that a linear variable is missing in the model; however, none of the categorical variables shows a distinct pattern that might suggest that they explain the systematic nature of the residuals.

3.3. Process–fabric relations

A basic assumption in the use of fabrics is that they indicate the orientation of the stress field (Carr and Rose, 2003). For a periglacial slope, this suggests that a strong signal in fabric should be the downslope direction. This assumption was tested by applying a circular correlation model to slope aspect, and the azimuth of the principal eigenvalue (Fisher, 1993). The correlation coefficient between the two circular variables is significant, supporting the conclusion that the aggregate tendency for clasts is to be oriented in the downslope direction (Tables 3 and 4).

4. Discussion

The results from Eagle Summit indicate a wide range of fabric patterns ranging from strong girdles to strong clusters, with no consistent form to the fabric that might be indicative of a common set of processes.

Table 7
Linear regression models for fabric strength and log of fabric shape

(a) Regression model for fabric strength parameter ($R=0.397$; $R^2=0.158$; $n=68$)

Effect	Coefficient	Standard error	Standard coefficient	Tol	t	P
Constant	1.558	0.102	0.000		15.348	0.000
Factor (1)	0.133	0.052	0.291	0.998	2.553	0.013
Distance	0.0001	0.000	0.257	0.998	2.258	0.027

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio	P
Regression	2.195	2	1.098	6.078	0.004
Residual	11.739	65	0.181		

(b) Regression model for log shape parameter ($R=0.368$; $R^2=0.135$; $n=68$)

Effect	Coefficient	Standard error	Standard coefficient	Tol	t	P
Constant	0.088	0.128	0.000		0.689	0.493
Factor (1)	0.295	0.129	0.264	1.00	2.287	0.025
Factor (2)	−0.279	0.129	−0.250	1.00	−2.168	0.034

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio	P
Regression	11.040	2	5.520	4.965	0.010
Residual	72.266	65	1.112		

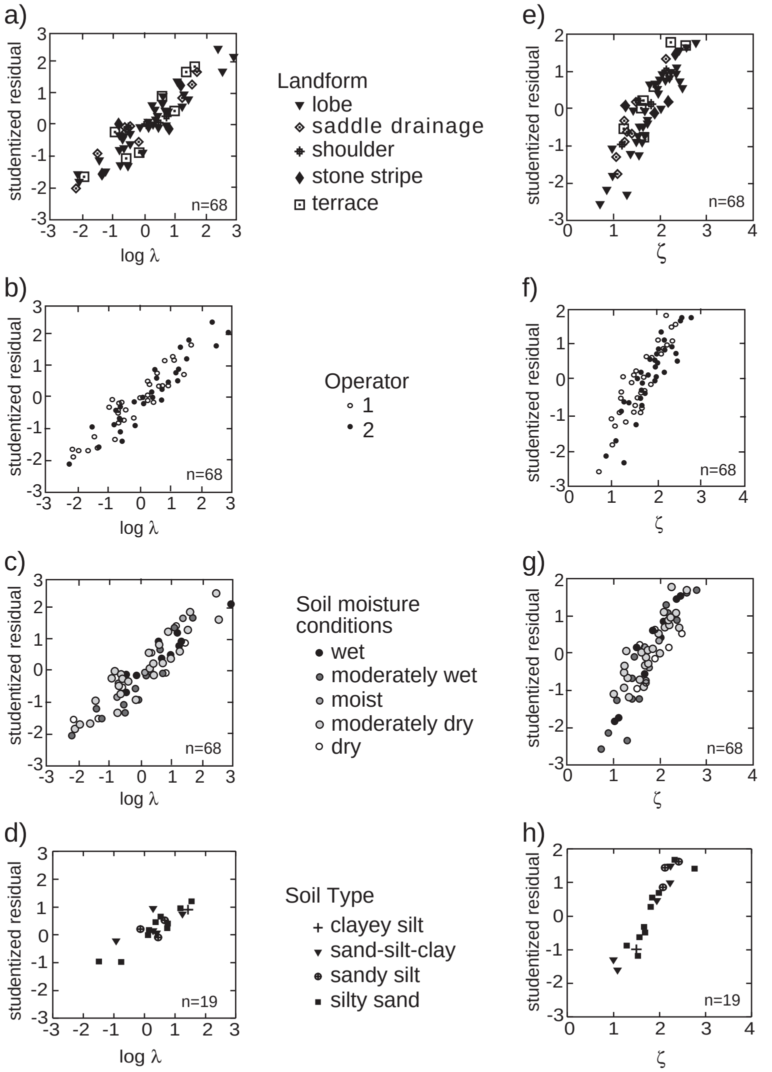

Fig. 4. Studentized residual plots of the log of the fabric shape parameter with (a) landform type, (b) operator, (c) soil moisture conditions, and (d) soil texture; and the strength parameter with (e) landform type, (f) operator, (g) soil moisture conditions, and (h) soil texture.

The single most important factor for determining fabric strength and shape is related to the clast size. These findings are of concern for the utility of fabrics for paleoenvironmental interpretations. Three potential sources contributing to fabric variability are addressed.

4.1. Variation of fabric on a periglacial slope

First, an assumption made in this study was the presumed relation between slope angle and rate of movement (Carson and Kirkby, 1972; Harris, 1973; Mills, 1983). Due to varying soil texture, across a single 7 m periglacial slope transect, Matsuoka (1998) measured as much as a 78% variation in volumetric transport. So, although slope angle creates the primary stress exerted on slope materials, fabrics are generated by deformation or strain which is differently expressed depending on the characteristics of the sediments (Harris, 1987; Williams and Smith, 1989; Harris et al., 1995; Harris and Davies, 1996). The lack of a strong association between slope angle and fabric strength in this study is perhaps reflective of the high degree of variability in microenvironmental characteristics across the sample grid generating varying styles of deformation and resultant fabric.

4.2. Non-process influences on fabric generation

Second, the importance of clast characteristics has been addressed by others and is frequently shown to influence resultant fabrics (see Table 1). Krüger (1970) and Kjær and Krüger (1998) discussed the relation between clast size and fabric strength, wherein longer clasts in glacial till showed a stronger preferred parallel orientation. Yamamoto (1989) and Millar and Nelson (2003) have illustrated a strong relation between the average clast axial ratio and fabric strength in periglacial colluvium. The factors with the greatest explanatory power in this study are those associated with average clast size (factor 1), and clast platyness (factor 2), which correspond to those discussed by other workers (see Table 1).

4.3. Variation in mass-wasting processes

Third, as pointed out by Glen et al. (1957), there is no single process being measured by fabrics. Fabrics in periglacial colluvium are a composite of a complex history of transportation, deposition and post-depositional modification. The intensity of processes may indeed vary, but at any one point in time, when fabric samples are being measured, each location will reflect one of several time steps in fabric generation. Fabric analysis across a slope is therefore comparing all of these processes at once.

4.4. Implications for paleoenvironmental reconstruction

This study highlights the degree of variation in fabrics generated across a slope currently undergoing a variety of periglacial mass-wasting processes. The results from the suite of statistical analyses indicate that no systematic quantitative descriptor of fabric can be detected from a broad sampling of fabrics across a periglacial terrain. Fabric generation appears to be partially due to clast properties; however, no single or combination of environmental variables is strongly associated with fabric shape, and only downslope distance has a weak association with fabric strength. For comparative purposes then, only a very limited range of clast size and shape can be used. In reality, this restriction severely constrains the use of fabric analogs for periglacial slope processes. Grouped residual analysis of fabric parameters indicates that operator error, landform categories, and soil moisture conditions have no significant effect. From the Kruskal–Wallis tests, none of the geomorphic environments sampled exhibit a distinct and consistent fabric that would support the use of fabric as a diagnostic criterion. These results cast serious doubt on the utility of fabric analysis for identifying periglacial slope conditions. At best, on the basis of the strong relation between the downslope orientation and fabric, it is possible to suggest that material has undergone some form of downslope transport.

A number of questions and concerns surrounding the validity of fabrics for identifying periglacial slope deposits have been raised. A majority of research using stone orientation as a measure of process, and as a tool to identify particular depositional environments, has alluded to the need for applying a suite of techniques to corroborate hypotheses (Hicock et al., 1996; Catto, 1998). Although a common part of that toolbox, there is a misunderstanding of exactly what fabric analysis is showing, and therefore, the fabric that is measured is frequently used to corroborate any conclusion that is made using other techniques after significant construction of explanations and caveats. Such ambiguous results from clast measurement experiments suggest that a critical examination of some important geomorphic tenets is required that highlights the inherent problems with the use of fabric analysis for paleoperiglacial interpretation.

“Geomorphology” encapsulates our interest in the shape of the land surface rather than the processes that formed it. This disciplinary historical preoccupation with form detracts from our understanding of underlying processes (Thorn and Welford, 1994) and, to a large extent, precludes the use of geomorphic evidence as a paleoenvironmental tool. A periglacial slope is subject to a wide array of influences that operate at varying degrees across space and time, so simple classification cannot be made on the basis of form alone, but must involve rates and modes of process (Leopold et al., 1964). Recent work on such questions is beginning to shed light on just how complex those patterns of process on periglacial slopes are (Matsuoka, 2001;

Hugenholtz and Lewkowicz, 2002). The possibility that fabric analysis can be used to classify an already little understood regime represents a leap of faith that we are not sufficiently equipped to make.

Fabric analysis represents a mismatch between the scale of the periglacial process and scale of evidence. The position of large clasts in a sediment matrix represents an aggregate of processes, including transportation, deposition and post-depositional modification; therefore, it provides little detail as to the individual processes that are occurring in the movement and emplacement of periglacial colluvium (cf. Rose, 1974). Carr and Rose (2003) highlight how, in glacial till, clast size influences their behavior in response to strain, leading to their varying orientations. A much clearer link between clast size, patterns and rates of fabric development must be established. The hierarchical type of clast size sampling conducted by Carr and Rose (2003) might provide insight into not only the continuum of process intensity on a periglacial slope, but also how the sediment and clast fabrics themselves influence the nature of the continuum. Periglacial slope deposits most likely reflect combinations of varying intensities of several processes and microenvironments rather than a complex of distinct processes with unique identifying characteristics. Modeling experiments on self-organization of periglacial deposits suggest that this may be the case (Kessler and Werner, 2003). Similarly, the variation in downslope movement across a periglacial slope has been shown to be quite significant over a very short distance (Matsuoka, 2001), again indicative of intensity rather than distinctly different processes.

The geomorphology of a periglacial slope therefore reflects a complex suite of interacting biophysical factors that have varying degrees of influence on the behavior of sediment deformation and presumably on resultant fabrics. Superimposed on this are the nuances of fabric generation itself; the behavior of particles according to size and shape; the possible cyclical development and degeneration of fabrics; and the degree to which prior effects on fabric are preserved when changes in external factors occur. Teasing out what particular factors predominate at any one point in time, by definition precludes the application of discriminating fabric characteristics for the purposes of paleoenvironmental reconstruction. The inherent level of complexity in both fabric generation and across any one slope also raises serious doubts as to the utility of fabrics in process and genetic studies of periglacial colluvium.

5. Conclusion

The objectives of this study were to determine the range of fabrics generated across a slope experiencing periglacial conditions, and what factors most strongly influence fabric development. Results indicate that the range of fabrics in this small area is as extensive as those from all the mass-wasting deposits examined by Mills (1991). Further, there is no relation between fabric and microenvironment, although there is a relation with clast characteristics. Because landform type does not necessarily indicate what processes are occurring, and processes vary at small scales, the scale at which fabric analysis is applied is inappropriate. Such a conclusion tends to support similar criticisms for glacial fabrics (Bennett et al., 1999). It indicates that certainly within our current understanding of periglacial slope processes, fabrics are not a good indicator of former slope processes: fabrics cannot be used to distinguish any particular process, nor identify any particular microenvironmental slope position. No single signature emerged that represented a specific landform type across the slope. Further, the variables that can be measured and are typically used to explain the "noise" in fabric results, such as clast characteristics, do have minor explanatory power. The regression model suggests that at least one linear factor is unaccounted for, which may be associated with the rate of sediment movement, a factor that has been shown to vary considerably across a periglacial slope. There is a need, however, for more detailed scaled-modeling and field-based research to understand what single process might result in a particular fabric behavior and for paleoenvironmental questions the extent to which transportation or depositional signatures are preserved following post-depositional modification and burial.

Acknowledgements

This work was supported by National Science Foundation grant SBR-9305029. Field assistance was provided by Sherry Fuchs, and lab facilities and help by Rolf Kihl and Institute of Arctic and Alpine Research in Boulder, Colorado. I also thank Nel Caine, Norm Catto and Fritz Nelson for valuable comments on earlier versions of the manuscript.

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