INFLUENCE OF CLAST AXIAL RATIO ON MACROFABRIC STRENGTH IN PERIGLACIAL COLLUVIUM

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ABSTRACT: **Samples of fabric data collected from periglacial solifluction lobes in central Alaska show a systematic, positive relation between clast axial ratio and fabric strength. Samples composed of clasts with low *a*:*b* axial ratios have relatively low fabric strength. Restricting sampling to clasts with axial ratios of 1.5:1 or higher increases fabric strength and decreases its variability. To enhance comparability between fabric studies and the utility of fabric interpretation, sampling should be restricted to clasts with relatively large (≥ 1.5:1) axial ratios.**

INTRODUCTION

Reconstruction of Quaternary paleoenvironments relies on a convergence-of-evidence approach requiring data from many diverse sources. Analysis of clast orientation in a sediment or soil matrix (macrofabric analysis) is a common field-based technique that provides information about depositional environment, flow regime, and slope processes (e.g., Lundqvist 1949; Lindsay 1968; Mills 1983, 1987; Nelson 1985; Major 1998).

Although technological and interpretive advances in fabric analysis (e.g., Fisher et al. 1987; Benn 1994) have provided progressively more detailed information about the nature of processes on hillslopes, their relative intensity, and the deformation of colluvial masses, development of general theory and a comprehensive database have been hampered by the fact that sampling procedures vary considerably between investigators (Mills 1991; Bertran et al. 1997).

The utility of macrofabric analysis has been questioned on several grounds. Criticisms include inconsistency in field measurement techniques (Hill 1968), inability to differentiate between depositional environments (Bennett et al. 1999), and the influence of sampling procedures and criteria (Kjær and Krüger 1998; Major 1998; Millar and Nelson 2001a,b). Such concerns should be considered carefully, and confounding factors that could affect resultant fabrics addressed.

Using Zingg's categories of disc, sphere, blade, and rod, Drake (1974) illustrated that pebble shape can influence macrofabrics developed in glacial till. In a study of solifluction in the Japanese Alps using the same categories, Yamamoto (1989) found a statistically significant relation between clast shape and fabric characteristics. Rod-shaped particles, which have the greatest degree of elongation in this classification, were most likely to be oriented parallel to the direction of flow. Yamamoto concluded that axial ratio exerts an appreciable effect on fabric strength, a finding with important implications for sampling design in subsequent studies of colluvial macrofabrics.

Multi-scale approaches to geomorphic problems have gained wide acceptance (e.g., Schumm 1991, p. 48; Bauer et al. 1999). To be effective, well-designed sampling programs must be implemented at each scale of investigation, or cumulative errors of substantial magnitude may develop. To assess the influence of sampling decisions at different scales in macrofabric studies, Millar and Nelson (2001b) classified sampling considerations along a continuum of spatial scale: *microscale* decisions involve such factors as the size and geometry of clasts selected for measurement; *mesoscale* considerations include selection of topographic position and orientation of the sampling surface; and *macroscale* decisions involve the spacing and geographic interrelations between sampling locations. This note is concerned primarily with the first class by demonstrating the systematic effect of clast axial ratio on the strength of macrofabrics in sediments affected by periglacial solifluction. The implications may extend beyond studies of periglacial colluvium to sampling considerations during examination of genetic and depositional processes in glacial, fluvial, and other colluvial environments.

METHODS

Field Procedures

Data were collected from a series of periglacial solifluction (''gelifluction'') lobes and terraces (Fig. 1) near Eagle Summit (65.5° N, 145.5° W) in the Yukon–Tanana Upland physiographic province of interior Alaska (Wahrhaftig 1965). The features are active, as evidenced by small shrubs bent or partially buried by slope materials, and by displacement of markers installed in the early 1960s to monitor slope movements (Haugen and Miller 1963).

Samples examined in this study are a subset of a larger collection of fabric data from sites selected across the terrain at Eagle Summit using a stratified systematic unaligned sampling design (Berry and Baker 1968; Iachan 1985). The sampling program was formulated to assess the variability of fabrics on heterogeneous slopes, many of which were mantled with well-developed solifluction lobes, an important consideration in a paleoenvironmental context (Millar and Nelson 2001a). To enable standardized comparisons for this study, analysis was restricted to data obtained from 38 sites that displayed well-defined lobate solifluction forms. Sampling locations included a variety of micro-environmental settings, including lobe-front riser, lateral margins, and upslope position on the tread (Table 1).

Fifty observations of plunge and plunge azimuth of the *a* axes of elongate clasts were made at each sampling location (Fig. 2). Samples were obtained from the floor of 1 m × 1 m × 1 m excavations, between 25 and 50 cm depth, as detailed in Millar and Nelson (2001b). The *a, b,* and *c* axes of each clast were identified and measured following the method detailed by Andrews (1971, p. 13). Clasts were selected on the basis of the existence of a well-defined major axis.

Eight samples from an earlier study by Nelson (1985) are included in

FIG. 1.—View of representative lobes on sampled slopes at Eagle Summit, Alaska. Distance indicated by bar scale is approximate. View is from the north-center of map shown in Figure 2.

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TABLE 1.—*Statistical summary of Eagle Summit macrofabric data.*

Site	Lobe Position	Mean *a*:*b* ratio	Unfiltered Data			*n*	Mean *a*:*b* ratio	Filtered Data		
			$\bar{\tau}_1$	$\bar{\tau}_3$	ζ			$\bar{\tau}_1$	$\bar{\tau}_3$	ζ
1	left side tread surface	1.67	0.112	0.634	1.734	38	1.99	0.121	0.607	1.615
2	lobe	1.67	0.126	0.647	1.636	36	1.89	0.113	0.657	1.759
3	on small lobe	1.57	0.084	0.600	1.966	28	2.02	0.061	0.626	2.325
4	center riser on small lobe	1.69	0.093	0.494	1.670	35	1.98	0.082	0.535	1.876
5	right tread of lobe	1.93	0.670	0.786	2.462	40	2.28	0.063	0.821	2.565
6	upslope of small lobe	1.71	0.076	0.507	1.898	35	2.02	0.034	0.586	2.861
7	upslope of tread	1.91	0.072	0.804	2.413	40	2.29	0.071	0.818	2.450
8	on small lobe	1.65	0.193	0.513	0.978	34	2.10	0.149	0.544	1.292
9	left back tread of small lobe	1.64	0.199	0.462	0.842	32	1.97	0.199	0.506	0.936
10	right side tread	1.67	0.142	0.599	1.439	30	2.26	0.101	0.673	1.897
11A	lobe riser	1.74	0.092	0.674	1.991	34	2.18	0.067	0.734	2.392
11B	left riser	1.87	0.148	0.655	1.487	38	2.19	0.119	0.700	1.775
11C	right riser	1.76	0.099	0.688	1.939	36	2.05	0.076	0.728	2.265
11D	nose center	1.84	0.120	0.642	1.677	38	2.29	0.118	0.652	1.710
11E	tread center	1.87	0.114	0.551	1.576	39	2.51	0.108	0.530	1.587
12	slightly right of tread central axis	1.67	0.118	0.699	1.779	36	1.95	0.118	0.694	1.774
13	slightly left of center on tread	1.73	0.180	0.488	0.997	39	2.10	0.192	0.467	0.892
14	center of small flat lobe	1.68	0.090	0.802	2.187	38	2.05	0.094	0.799	2.135
15	lobe riser left side	1.66	0.108	0.576	1.674	33	2.01	0.073	0.582	2.075
16	center of mid tread	1.90	0.049	0.778	2.765	42	1.91	0.045	0.806	2.883
17	right center tread	1.80	0.071	0.658	2.227	40	2.20	0.071	0.701	2.293
18A	near center of small flat lobe	1.79	0.067	0.706	2.355	39	2.21	0.065	0.755	2.456
18B	tread center riser 20 cm depth below duff	1.92	0.137	0.636	1.535	42	2.20	0.151	0.595	1.373
18C	tread center riser 50–70 cm depth below duff	1.80	0.084	0.662	2.064	40	2.15	0.081	0.680	2.133
18D	back center tread 20 cm depth below duff	1.78	0.078	0.721	2.224	42	2.02	0.058	0.758	2.569
18E	back center tread 50–70 cm depth below duff	1.76	0.069	0.775	2.419	37	2.07	0.072	0.767	2.364
18F	left riser	1.72	0.072	0.748	2.341	37	2.10	0.056	0.774	2.623
18G	right riser	1.71	0.132	0.680	1.639	36	2.06	0.121	0.693	1.747
18H	nose center	1.76	0.154	0.605	1.368	37	1.97	0.169	0.606	1.277
18I	tread center	1.93	0.106	0.777	1.992	41	2.01	0.099	0.770	2.052
19	upslope of tread	1.62	0.209	0.422	0.703	35	2.10	0.225	0.423	0.631
20	break in slope on riser-tread of lobe	1.77	0.138	0.490	1.267	38	2.36	0.161	0.479	1.087
21A	left riser	1.72	0.103	0.577	1.723	36	2.07	0.083	0.565	1.922
21B	right tread of lobe	1.80	0.106	0.771	1.984	39	2.07	0.116	0.751	1.865
22A	left riser	1.82	0.061	0.788	2.559	38	2.20	0.040	0.777	2.957
22B	right riser	1.77	0.119	0.550	1.534	38	2.12	0.119	0.617	1.650
22C	nose center	1.71	0.076	0.621	2.101	36	2.01	0.076	0.618	2.090
22D	tread center	1.81	0.105	0.562	1.678	39	2.11	0.115	0.591	1.636

Sample locations are indicated in Figure 2. Letters appended to sample numbers indicate sites from which multiple samples were obtained. Symbol definitions are provided in text.

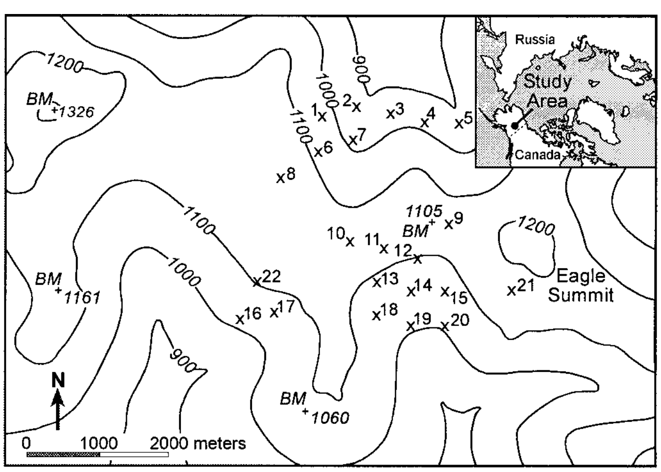

FIG. 2.—Generalized contour map of Eagle Summit study area, showing sampling locations relative to U.S. Geological Survey benchmarks. Symbol on inset shows location of study area in Alaska and circum-Arctic region.

the analysis. These samples were collected from the semivertical, upslope faces of shallow pits dug in solifluction lobes located in the same general area. Details are provided in Nelson (1985, p. 24). Only clasts with *a*:*b* axial ratios greater than 2:1 were sampled. Clast dimensions were not recorded.

Data Analysis

Following procedures and notation developed in Mardia (1972, Chapter 8) and Fisher et al. (1987, Chapter 3), eigenvalues and eigenvectors were extracted from the symmetric 3×3 ''orientation matrix'' T formed by the sums of squares and products of direction cosines from the measurements of plunge and plunge azimuth. The eigenvectors t_i, where $i = 1, 2, 3$ of T represent the mutually orthogonal axes of minimum, intermediate, and maximum clustering of the observations, respectively. The corresponding normalized eigenvalues $\bar{\tau}_i$, such that $\bar{\tau}_3 \geq \bar{\tau}_2 \geq \bar{\tau}_1$, provide a measure of the relative length of these axes. The data are represented graphically in Figure 3, a statistical summary is provided in Table 1, and sample position in Woodcock's (1977) eigenspace is shown in Figure 4.

Figure 5A shows the relation between clast axial ratio and Woodcock's (1977) strength parameter ζ, given by $\zeta = \log(\bar{\tau}_3/\ \bar{\tau}_1)$, a measure of the degree of fabric clustering or tightness, for the Eagle Summit samples. The

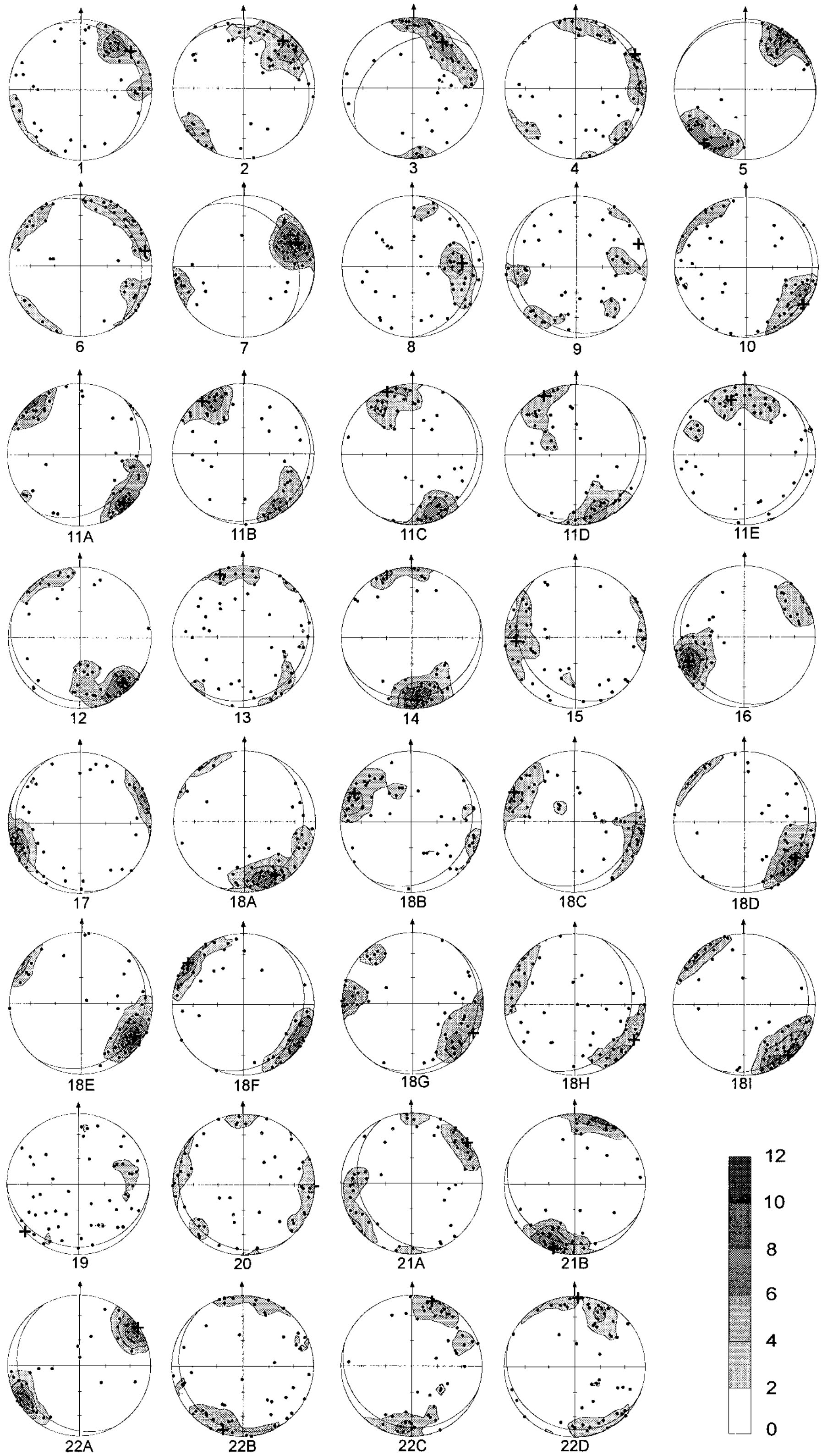

FIG. 3.—Eagle Summit macrofabric data, plotted on lower hemisphere, Lambert equal-area projections. Data were rotated into the plane of the local slope (Nelson 1985) and contoured using Starkey's (1977) point-counting method. Each counting circle occupied 2% of the projective net (Stesky 1998). Shading density is standardized between nets; isolines represent 2, 4, 6, 8, 10, and 12 points per counting circle. Position of principal eigenvector is indicated.

plot includes data from the mean of the eight sites sampled by Nelson (1985) in the same locality. Although there is considerable scatter, Pearson correlation coefficients indicate a statistically significant relation ($r = 0.541$, $\alpha = 0.001$) between fabric strength and clast axial ratio (Table 2). The reduced major axis (RMA) line (Till 1974) in Figure 5A indicates the positive, linear form of the relation between axial ratio and fabric strength.

To examine the effect of clast axial ratio on fabric more closely, each of the Eagle Summit samples was filtered to remove all clasts with axial

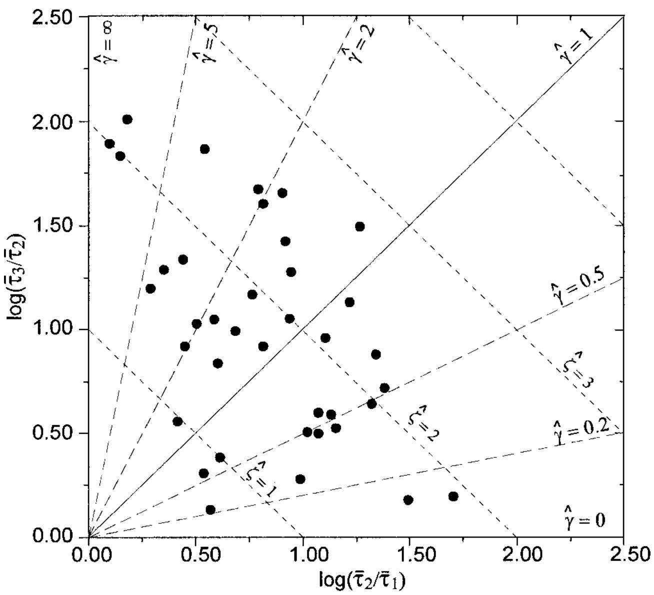

FIG. 4.—Eigenspace, following Woodcock (1977), of Eagle Summit lobe fabric data.

ratios less than 1.5:1 (Fig. 5B). This ratio was selected because it is frequently used (Table 3) and to ensure adequate sample size for statistical analysis. Correlation results are given in Table 2. There is no apparent relation between clast axial ratio and fabric strength in the filtered data set.

INTERPRETATION

The relation between clast elongation and fabric characteristics has been addressed only indirectly in studies of colluvial macrofabrics. Although in many cases researchers have limited axial ratios to some preset range, there is no consensus about a preferred *a*:*b* ratio for sampled clasts. An *a*:*b* ratio of 1.5:1 is frequently used as a threshold value for inclusion in a sample. Choice of this value enables the operator to identify elongate clasts readily, although the characteristics of the deposit and its source material may dictate what the axial ratio can be. The range of *a*:*b* limits in macrofabric studies is extensive: examples are listed in Table 3.

TABLE 2.—*Pearson's correlation of axial ratio and fabric strength.*

	n	Pearson *r*	Student's t	Probability
All lobe samples collected in present study	38	0.429	2.748	0.007
Lobes in this study, plus average of Nelson's data (1985) from 8 lobe sites	39	0.541	3.790	0.001
Samples with only clast *a*:*b* $\geq$ 1.5	38	0.095	0.902	0.428

Theoretical considerations indicate that restricting the range of axial ratios is desirable. According to Jeffery's (1922) consideration of the angular velocity of prolate objects in a viscous flow, the degree of clast elongation affects the rate of its rotation. Simulations by Lindsay (1968) showed considerable agreement between Jeffery's formulation and observed fabrics in mudflow deposits. At the microscopic level, Bertran (1993) elaborated this further, suggesting that fabrics show stronger preferred orientation when composed of more elongated clasts. Prolate clasts rotate more slowly when oriented normal to the velocity gradient than when at some angle to it, whereas equant clasts show little variation in angular velocity as they rotate. With increasing elongation, stones begin to behave as passive markers, spending most of the time normal to the velocity gradient (Bertran 1993).

Field evidence from Eagle Summit supports the theoretical considerations outlined above and indicates the existence of a direct relation between average clast axial ratio and fabric strength in materials affected by periglacial solifluction. The absence of such a relation in the Eagle Summit filtered data indicates the possible existence of thresholds involving clast geometry in generating tightly clustered fabrics.

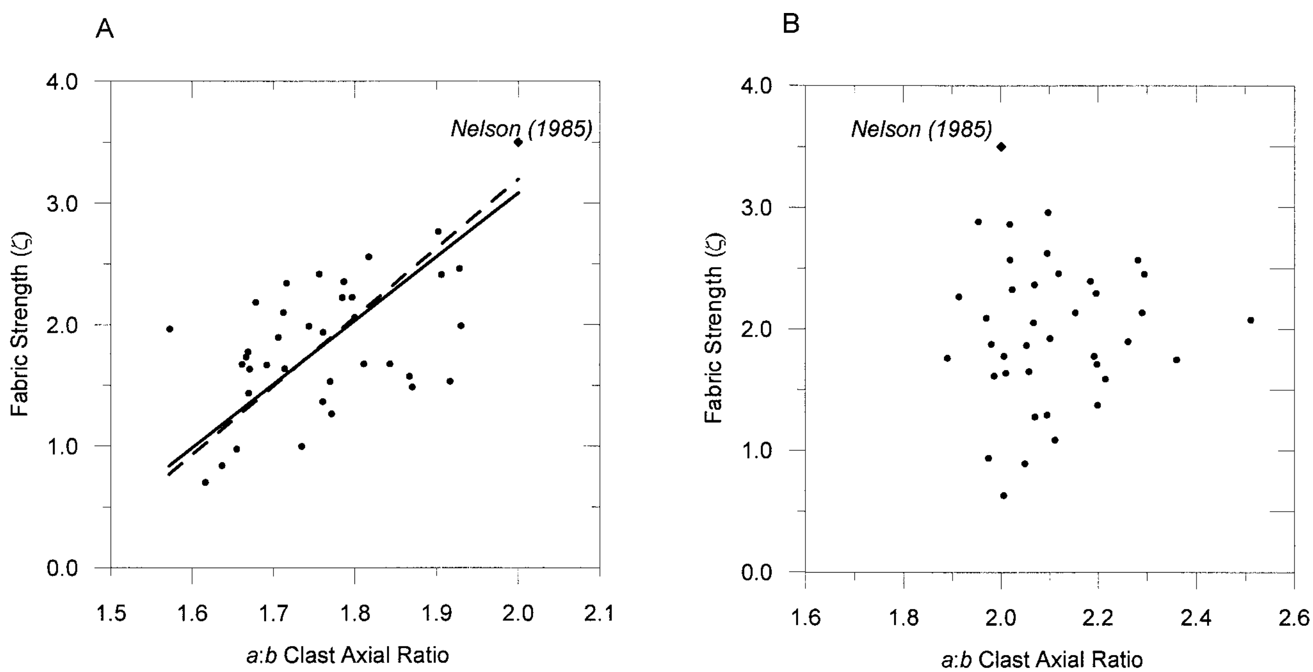

FIG. 5.—Plots showing relation between *a*:*b* clast axial ratio and fabric strength. **A)** Solid line is RMA for lobe sites with equation $y = 5.239x - 7.399$. The dashed line is the RMA for lobes and the mean value of Nelson's (1985) aggregated data with equation $y = 5.663x - 8.133$; **B)** Relation for filtered samples that include only clasts with *a*:*b* ratio greater than or equal to 1.5:1. Nelson's (1985) aggregated sample includes all clasts.

TABLE 3.—*Examples of* a:b *clast axial ratios used in studies of periglacial colluvium and documented in the literature.*

Author	Environment	Clast Axial Ratio (*a*:*b*)
Giardino and Vitek (1988)	Rock glaciers	>2:1
Nelson (1985)	Periglacial solifluction	≥2:1
Perez (1989)	Talus	1.502:1–1.922:1
Curry and Ballantyne (1999)	Paraglacial debris flows	>1.5:1
Mills (1983)	Colluvium	≥1.5:1
Rappol (1985)	Glacial tills and debris flows	>1.4:1
Major (1998)	Debris flows	1.33:1

CONCLUSION

Multiscale analysis and careful application of formal sampling procedures at each level can enhance both the value of macrofabric data and inter-study comparisons. Clast axial ratio appears to be an important microscale consideration in research designs involving fabrics from colluvial deposits. Our results indicate that the range of clast axial ratios used in fabric work should be restricted to a small interval, and that the ratios should be large (> 1.5:1). Further work is necessary to establish an optimal range and to ascertain possible relations between fabric strength, axial ratio, clast size and shape, and variations in velocity gradients. Because a large number of variables have the potential to affect fabric characteristics, future research should involve a variety of approaches, including deterministic modeling (Lindsay 1968), laboratory investigations (Harris et al. 1996), statistical simulation (Fisher et al. 1987), and critical field experiments (Millar and Nelson 2001b).

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