CLAST-FABRIC STRENGTH IN HILLSLOPE COLLUVIUM AS A FUNCTION OF SLOPE ANGLE

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ABSTRACT. Clast fabric was measured in the upper 20 cm of soil at 16 sites on forested hillslopes in Giles County, Virginia, U.S.A. Slope angles ranged from 9° to 42°. Despite an abundance of roots in the soil, most sites displayed a significant fabric, with long axes parallel to slope and imbricated uphill. There was a significant correlation (r=0.771) between slope angle and fabric strength as measured by the eigenvalue technique. Elevation, slope aspect, and soil texture appeared to have little effect on fabric strength. Soil creep probably produces the fabric.

Introduction

Investigations of stone orientation in colluvial mantles on hillslopes have for the most part been confined to deposits in periglacial environments or to deposits presumed to be relics of such environments. However, if stone fabrics are to be used to identify relict gelifluction deposits, for example, then it is important to have a knowledge of the pattern and strength of fabrics from nonperiglacial deposits. The present study takes a small step in this direction by examining fabrics of modern origin in soils on forested hillslopes.

While engaged in a study of possible gelifluction deposits in Virginia, USA, out of curiosity I measured the fabric in the uppermost 20 cm of soil on a steep hillslope. That a preferred orientation would exist in such a situation seemed unlikely, for penetrating this layer was a plexus of tree roots. I was surprised to find a fairly strong fabric. The measurement of several more fabrics at similar sites suggested a relationship between hillslope angle and fabric strength. Subsequently, additional fabrics were measured to bring the total number of sites to 16, and the results are presented herein.

Physical setting

The area of study is located in the Valley and Ridge province of southwest Virginia, USA, in the vicinity of latitude 37° 23′ N, longitude 80° 33′ W. The relief in the area is over 600 m, with the highest peak having an elevation of 1326 m. The mountains are strike ridges capped by resistant Silurian sandstones, and mountain flanks slope generally at right angles to the strike of the cap rocks. The local slope direction at a given point on a mountainside, however, may be somewhat different from the general slope direction, for numbers of first-order valleys, oriented approximately at right angles to the ridge crests, corrugate the mountain flanks. These first-order valleys, or hollows, are separated by first-order ridges, or noses.

The major bedrock formations underlying the fabric sites are as follows. The main cap rocks are the Silurian Rose Hill Formation and the underlying Silurian Tuscarora Sandstone. The former is a hematite-cemented sandstone with shale layers and the latter is a silica-cemented orthoquartzite. Below the Tuscarora is the much less resistant Ordovician Juniata Formation, consisting of sandstone, siltstone, and shale. Underlying the Juniata is the still less resistant Martinsburg Formation, the upper two thirds of which consist of siltstone and fissile shale (the lower one third, composed of limestone, underlies no site in this study). Because of its great thickness (425–490 m) this formation underlies the greater part of the mountain slopes and most of the study sites. Hillslope angles depend to a large extent upon the underlying bedrock. High-angle cliffs, rarely as much as 30 m high, occur mainly on the Tuscarora Sandstone. However, hillslope angles are rarely greater than 30°, declining to less than 10° on the Martinsburg Formation shale at the mountain foot. Angles much greater than 30° occur mainly on undercut side slopes.

Surficial sediments vary somewhat in both cross-slope and downslope direction. Concerning the former, the surface layer in hollows generally is much more bouldery than that on noses. However, as fabrics in hollows were not measured in this study, downslope variation is the chief concern here. The nature of the sediment at a given point on a hillslope depends not only on the bedrock type underlying that point, but upon the types that crop out upslope, for weathered debris from the outcrops moves downslope. Sandstone units supply mainly clasts and sand, whereas shale units supply silt and clay. The potential thus exists for great variability, but in actuality the observed colluvium varies less than might be expected. Although the number and size of boulders vary greatly, the character of the finer fraction varies much less. For example, at the 16 study sites the percentage of silt + clay in the less-than-2-mm fraction varied only from 40 to 68 %. The fabric sites occur on one of four soil series. These are the Ungers, Nolichucky, Clymer, and Monongahela Series. The first three are classified as Typic Hapludults, the fourth as a Typic Fragiudult (John Vann, U. S. Forest Service, unpublished data).

All hillslopes studied are covered by dense hardwood forests, with most trees at least 50 years in age. Oaks and hickories are the most common trees on noses, whereas red and sugar maples and basswoods are more common on sideslopes. Yellow birches are common in bouldery hollows.

Eight years of weather records at the Mountain Lake Biology Station (elevation 1180 m), located in the study area, show a mean annual temperature of 8.1°C and a mean annual precipitation of 1436 mm. Precipitation is distributed relatively uniformly throughout the year. The mean January temperature is −3.3°C, but extended periods of much lower temperatures occur. For example, the average January temperature in 1977 was −10.4°C. The temperature regime is characterized by frequent freeze-thaw cycles during the winter.

Procedure

Study locations were selected so as to provide fairly uniform coverage of slope angles and aspects. All sites were on noses or sideslopes, with slope profiles either approximately straight or convex up. Sites were located away from tree trunks on surfaces which were relatively smooth and even. Bouldery areas were avoided. The *O* horizon was scraped away over an area of about 30 cm×30 cm. Then, beginning at the surface and excavating downward, the direction and dip of the long axes of all stones meeting the specified criteria were measured. The criteria were stone length between 2 and 10 cm, and long axis:intermediate axis ratio of at least 1.5:1. Upon reaching a depth of 20 cm below the top of the mineral soil (as measured normal to the surface), the excavation was enlarged laterally until the required number of stones (either 25 or 50) were measured. Stones were obtained from the A1, A2, and occasionally B1 horizons. All excavations contained large numbers of small tree roots. A total of 16 fabrics were measured. Slope angle was measured over a distance of 1 m, centered on the excavation.

The data for each fabric site were plotted on Schmidt equal-area nets and contoured by Kamb's (1959) method. In addition, fabrics were subjected to both two- and three-dimensional analyses. For the two-dimensional analysis (dips ignored), Krumbein's (1939) method was used. This method allows the resultant vector and the vector magnitude (L %) to be calculated. The latter can be tested against a random sample by means of a diagram provided by Curray (1956). For three-dimensional analysis, the eigenvalue method was used (Scheidegger 1965; Mark 1973). This method produces three eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3$ and their associated mutually perpendicular eigenvectors V_1, V_2, and V_3. V_1 represents the axis of maximum concentration of the long axes and V_3 the axis of minimum concentration (which is, in effect, the pole to the preferred plane of the long axes). The quantities S_1, S_2, and S_3 are defined by $S_i = \lambda_i/N$. A table provided by Anderson and Stephens (1971) allows S_1 and S_3 values to be tested to determine whether V_1 and V_3 are significantly different from the values expected for a random sample of axes drawn from a uniform population.

Results

Kamb diagrams for each fabric site are presented in Figure 1, and the results of fabric analysis are given in Table 1. The 16 fabric sites have been numbered according to their strengths as indicated by S_1 values, site 1 having the highest S_1 value and site 16 the lowest. Figure 1 shows that all fabrics can be characterized (at least approximately) as unimodal. Because all nets have been rotated so that the downhill direction is toward the bottom of the page, it can be seen that the preferred alignment of the long axes is

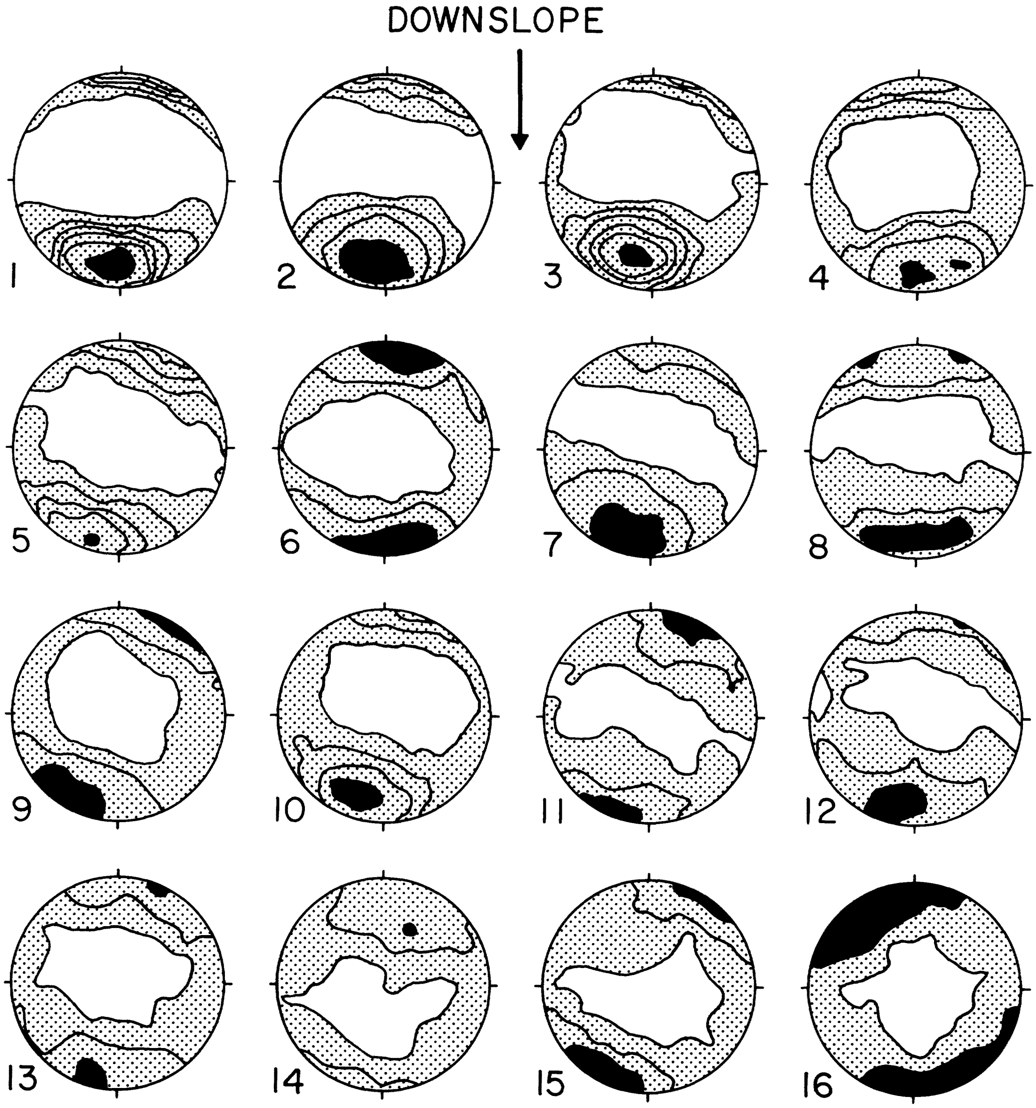

Fig. 1. Equal-area Schmidt net for all fabric sites. Nets have been rotated so that the downhill direction is toward the bottom of the page in all cases. Contouring was done by the method of Kamb (1959) at intervals of two standard deviations. The black areas are those of greatest density, the white areas are those of least density, and the stippled areas are those of intermediate density. The sites are arranged in order of fabric strength as indicated by the value of S_1.

approximately parallel to slope, dipping downhill. (The reason that many modes are offset to the right of the downhill direction is not known. The most likely explanation is bias in measurement, but study of my previous measurements of fabric in colluvium and till, using the same equipment and techniques as in the present study, reveals no such bias.) Table 1 shows that of the 15 sites with significant S_1 values, the V_1 orientation is downhill in 12 cases. Most of the fabrics can be said to have an upslope imbrication, however, for Table 1 also shows that in 11 of these 12 cases the dip of V_1 is less than the slope angle.

Note that some fabric samples consist of 25 stones, whereas others consist of 50. This differ-

TABLE 1. FABRIC MEASUREMENT RESULTS

Site No.	No. Clasts	Slope Angle	Slope Ort*	V_1 Ort	V_1 Dip	S_1	V_3 Ort	V_3 Dip	S_3	L %	% Silt	% Clay
01	50	30°	360°	014°	22°	.751	177°	67°	.044	53.9	33	22
02	25	42°	205°	213°	24°	.747	333°	47°	.086	63.7	44	23
03	50	33°	158°	180°	27°	.692	337°	60°	.086	49.8	36	13
04	25	30°	270°	263°	16°	.680	049°	71°	.039	35.7	35	10
05	50	25°	180°	208°	09°	.632	360°	79°	.117	42.1	31	15
06	25	15°	003°	007°	02°	.621	110°	79°	.079	36.7	45	20
07	25	35°	220°	239°	20°	.610	048°	70°	.162	45.2	47	18
08	25	30°	175°	178°	12°	.599	359°	78°	.126	34.5	44	15
09	25	21°	010°	039°	09°	.580	171°	77°	.096	24.4	44	15
10	50	27°	352°	014°	20°	.573	220°	68°	.123	30.5	31	33
11	25	11°	030°	229°	01°	.557	133°	80°	.187	35.7	40	14
12	25	25°	230°	241°	14°	.546	094°	73°	.162	24.5	48	20
13	25	21°	153°	167°	07°	.535	305°	80°	.137	23.4	40	20
14	25	09°	070°	263°	22°	.522	090°	68°	.184	23.5	30	10
15	50	15°	204°	047°	03°	.499	148°	76°	.202	34.3	42	21
16	25	10°	277°	075°	07°	.484	245°	82°	.166	12.4	44	09

*Ort is abbreviation for orientation.

The $p \leq 0.05$ significance level for S_1 is 0.512 (n = 25) or 0.460 (n = 50); for S_3 it is 0.169 (n = 25) or 0.216 (n = 50); for L % it is 34 (n = 25) or 24 (n = 50).

ence does not affect the values of S_1, S_3, and L %, although of course it does affect the corresponding significance levels.

Table 2 presents Pearson product-moment correlation coefficients between pairs of selected variables. Note that of the strength measures, S_1 and S_3 correlate fairly well ($R = -0.830$; the negative correlation results from the fact that whereas a *larger* value of S_1 indicates greater strength, a *smaller* value of S_3 indicates greater strength), as do S_1 and L % ($r = -0.873$). S_3 and L % do not show a significant correlation, however. Note that the percent silt + clay (of the less-than-2-mm fraction) shows no significant correlation with any variable.

The most interesting correlations in Table 2 are those involving slope angle, particularly those between slope angle and strength mea-

TABLE 2. INTERRELATIONSHIPS AMONG SELECTED FABRIC AND HILLSLOPE VARIABLES (PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS)

	Slope Angle	S_1	S_3	L %	V_1 Dip	V_3 Dip
S_1	.771**					
S_3	-.562*	-.830**				
L %	.735**	.873**	-.492			
V_1 Dip	.665**	.578*	-.368	.496		
V_3 Dip	-.685**	-.667**	-.360	-.713**	-.828**	
% Silt + Clay	.284	-.032	.095	.129	-.153	-.096

*$p \leq 0.05$

**$p \leq 0.01$

The significance levels indicated above assume normally distributed variables and the absence of closed number systems. As one or both of these assumptions are violated in some cases, the indicated levels should be considered only approximate.

sures. Slope angle correlates significantly with all three strength measures, the correlation with S_1 being the highest ($r = 0.771$). A plot of S_1 as a function of slope angle is presented in Figure 2. Correlation using the sine of the slope angle was slightly lower. Slope angle also correlates significantly with the dips of V_1 and V_3. That is, on steeper slopes both the axis of maximum concentration and the preferred plane of the long axes dip more steeply.

Concerning other environmental factors, elevation, bedrock type, and slope aspect had no influence on fabric strength. The fact that aspect had no effect, together with the absence of a particle-size effect, suggests that the mean soil-moisture condition likewise was unimportant. As clast size and shape were not measured, these variables cannot be eliminated as factors influencing the results. However, my impression was that differences in these variables were not systematically related to slope angle, so that I believe their effect to have been minimal. Two possible confounding hillslope variables not listed in Table 1 are hillslope length and shape. Generally, stronger fabrics tended to occur on side slopes, where slope profiles often are steep, convex, and short. Weaker fabrics tended to occur on noses, where slope profiles often are gentle, straight, and long. As a result of these associations, fabric strength showed a correlation with both slope length and shape, as well as with slope angle. However, the former correlations seemed to be somewhat weaker than the latter. For example, the correlation between slope length (as measured on maps) and S_1 was only -0.344, which is not significant. As slope profiles were not surveyed, no similar correlation coefficient between slope convexity and fabric strength could be computed. Therefore, profile convexity cannot be eliminated as a

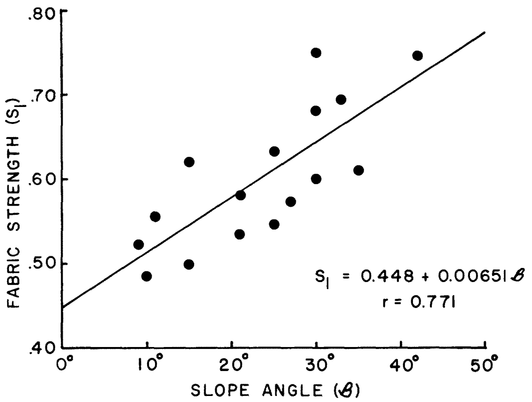

Fig. 2. Plot of fabric strength, as indicated by S_1, as a function of hillslope angle.

causal factor, although certainly this variable appeared to be inferior to local slope angle as a predictor of fabric strength

Discussion

The two most important findings of this study are that a preferred alignment of stones exists in the upper 20 cm of soil on forested hillslopes, and that the strength of this fabric increases as a function of slope angle. Concerning the first, most studies have shown that soil creep on hillslopes is active to at least a depth of 20 cm. Hence, it is reasonable to presume that the observed fabrics are produced by creep. The only reference I have seen to creep-induced fabric is in a study of melt-out till by Boulton (1971). He found that compact, relatively stable melt-out tills on the glacier surface underwent downslope creep at a rate of 1–5 cm per month. This creep produced fabric patterns similar to those described in this paper.

Creep is usually divided into two types. "Continuous creep" (Terzaghi 1950) is creep in the rheological sense, consisting of continuous deformation under the direct action of shear stress that is less than the upper yield strength of the material. However, many other processes can bring about the slow downhill movement of soil. These include expansion and contraction due to freezing and thawing or to wetting and drying, the action of plant roots, and the action of soil fauna. Terzaghi (1950) subsumed these processes under the category of "seasonal creep".

The manner in which continuous creep could produce clast fabric is fairly straightforward. Presumably the creep rate would decrease with depth, so that laminar shear would take place between layers of soil parallel to the slope surface. This situation is analogous to internal flow in glaciers. Boulton (1971) found that in the zone of extending glacier flow (which probably would correspond to creep on the straight and convex-up slope profiles of the present study), clast long axes tend to line up parallel to the direction of ice flow and to lie in the plane of shear. Analogous (though somewhat slower) flow in hillslope soil presumably would produce similar fabrics. One failure of this explanation is its inability to account for the consistent upslope imbrication of the colluvial fabrics.

Most downslope movement of soil probably results from seasonal rather than continuous creep, and envisaging how this type of creep may bring about stone alignment is more difficult. True, many studies have shown that seasonal creep decreases with depth, so that the net result in terms of velocity profile and mass transfer is similar to that produced by laminar shear. However, the actual motions of the particles are much more complex, and individual clasts travel downhill by very circuitous routes (as viewed in the vertical plane parallel to slope). Perhaps such "net shear", as M. J. Kirkby (1967, p. 360) has called it, can produce clast alignment in a manner analogous to laminar shear, but this remains to be demonstrated both theoretically and experimentally.

The second finding, that fabric strength increases as a function of hillslope angle, suggests that creep rate may influence fabric strength. Theoretical considerations suggest that soil creep should vary with the sine of the slope angle (e.g. Young 1972, p. 48), although it is true that the numerous other factors that affect creep rate tend to obscure this relationship in field studies. Some evidence has been provided, however, by Carson and Kirkby (1972, p. 289) and Harris (1973). (Actually, Harris found a better relationship to the logarithm of the sine of the slope angle. In light of the great amount of scatter in most studies, however, the question of which function best fits the data is secondary to that of whether creep rate shows a relationship to *any* function of slope angle.) Schumm (1967), in a related study, found that surficial rock creep varies as a function of the sine of the slope angle.

Assuming for the moment that fabric strength does vary as a function of creep rate, one may well inquire why such a relationship should exist. After all, since creep has been going on for a long time, even the slowest creep rate should by now have produced a strong fabric. The answer to this is that fabric strength must be seen as the result of a contest between processes in the soil tending to produce stone alignment and those tending to disrupt such alignment. The rates of the former processes probably increase more rapidly with increasing creep rate than do those of the latter, so that stronger fabrics are formed where creep is faster.

Just what are the processes promoting clast alignment whose rates increase with greater creep rates and thus (presumably) with greater slope angles? As with the problem of how fabrics are formed, there is no simple answer. If, as suggested earlier, fabric formation depends upon shear between adjacent soil layers, then shear velocity rather than actual downhill velocity should be the important factor, and it is not immediately obvious that the former as well as that of the latter should vary as a function of slope angle. However, on the slopes in question it is likely that both of these should increase with increasing slope. The reasoning is as follows. Unless the depth to which creep is active becomes greater on steeper slopes (which seems unlikely, because soil thickness decreases greatly on such slopes), then in order for the mean downhill movement to increase with increasing slope angle the overall velocity profiles must be steeper, whether they are linear or exponential in form. Such steeper profiles imply greater shear velocities (This reasoning would not apply, of course, if a large part of the movement was confined to a discrete shear surface, but this does not appear to be the case).

On the other hand, in seasonal creep it may be that the actual downhill velocity of a clast is an important factor in determining its alignment. The question of whether absolute or shear velocity is the more important must await resolution of the problem of how seasonal creep produces clast fabric.

A number of investigators have found that gelifluction deposits (or what are thought to be relict gelifluction deposits) have very strong fabrics (e.g., Källander 1967; Kirby 1967; Watson 1969; Watson and Watson 1970; King 1972; Ragg and Bibby 1966; Mottershead 1976; Brochu, 1978). Although the data of these authors have been presented in diverse fashions, thereby making comparison difficult, many of these fabrics do appear to be somewhat stronger than the ones observed in this study, even though the fabric patterns in general are similar. It is also known that movement rates associated with gelifluction are at least an order of magnitude greater than those associated with normal creep. Possibly this higher velocity is partly responsible for the greater fabric strength in the gelifluction deposits.

A final question is whether fabric strength could under some circumstances be used as an index of creep rate. Probably the relationship between the two variables is too weak to allow this. However, the possibility would seem to warrant the inclusion of fabric measurements in some future creep studies in order to see just how well fabric strength does correlate with creep rate, if indeed there is such a correlation. It would also be interesting to do a more detailed study of fabrics (perhaps microfabrics) at different depths and relate the findings to the creep velocity profile.

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