# SORTED-STRIPE MACROFABRICS (In Camp 29 Sector, Cathedral Massif, Atlin Wilderness Provincial Park, B.C.)

by

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ABSTRACT. Clast fabrics in the coarse borders of sorted patterned-ground features have been descriptively characterized in a variety of ways, but have rarely been measured or analyzed statistically. Three-dimensional analyses of rock fragments in the borders of a large sorted stripe reveal significant departures from uniformity. Most a-axes are oriented subparallel to the axis of the stripe and dip gently, but have no discernable tendency for up- or downslope imbrication. In contrast, b-axes are steeply inclined, indicating compression due to expansion of fine centers as autumn freezeback proceeds. Particle orientation at the stripe's downslope margin does not differ significantly from uniformity.

## Introduction

Although numerous and often contradictory casual observations have been made on the directional arrangement of elongate rock fragments in sorted patterned-ground features, very few reports of precise measurements have appeared in the literature. Several investigators made quantitative measurements of particle orientation, but observations were usually confined to two dimensions and not subjected to statistical analysis. Since rigorous treatments of clast fabric have yielded a great deal of valuable information in the study of tills, talus, blockfields and a wide range of sedimentary deposits, analysis of patterned-ground fabrics may provide new information about the origin and behavior of these features. This paper reports the findings of a preliminary study of clast fabrics in the coarse (stony) border of a large alpine sorted stripe.

## Previous Investigations

Several studies (Lundqvist, 1949; Schmertmann and Taylor, 1965; Furrer and Bachmann, 1968) have shown that a radial or centrifugal fabric is characteristic of sorted circle and polygon "centers". Particle long-axes tend to be oriented perpendicular to the nearest border, and are usually steeply dipping (Furrer and Bachmann 1968) or vertical (Corte 1962). The mechanism responsible for this pattern remains to be investigated, but may be due to mass displacement (Anketell *et al.* 1970) or to reorientation under the influence of repeated freezing and thawing (Washburn 1980, p. 89).

Sorted stripes are generally regarded as gradient-induced variants of circular or polygonal forms. Initial sorting produces concentrations of fines vulnerable to solifluction, with subsequent elongation of the patterns. This mechanism operates to destroy a radial fabric, replacing it with one characteristic of solifluction deposits. The latter fabric is well-known and is characterized by upslope-dipping long axes aligned parallel to the direction of movement (Benedict 1976, pp. 63–64).

Near the fronts of sorted steps and stripes, a transverse orientation becomes dominant. Lundqvist (1949, p. 342) presented a diagram suggesting a tangential orientation pattern near the fronts of "stone banked flow earth cones". Furrer and Bachman's (1968, p. 11) diagrams show that stones near lateral margins of the fines have long-axis orientations oblique to lines of flow, suggesting clast rotation during ejection or slower movement close to lobe margins.

The radial pattern is not translated into patterned-ground borders. Particles are instead often found in positions tangent to the outlines of the cells. The few quantitative characterizations of patterned-ground border fabrics which have been presented were confined to two dimensions, that is, to long-axis azimuthal observations. The first such study was performed by Lundqvist (1949), whose diagrams suggest a near-perfect agreement between the trend of the border and the blocky material within it. He did mention, however, that some fragments lie obliquely or normal to the border. Most subsequent work has substantiated Lundqvist's statements.

Studies in the Alps and in Svalbard by Furrer (1968) and Furrer and Bachmann (1968) convinced them that the fabric of patterned ground is "form typical", that is, diagnostic of the features. This conclusion enabled them to identify fossil forms through fabric analysis. Their work indicates that both recent and fossil patterned-ground forms have a maximum (50 %) number of clasts oriented parallel to the border, although a large minority (30 %) lies transverse to it. Long-axis dips were found to be much lower in the borders than in the central areas of fines.

Lundqvist (1962, p. 54) asserted that "the orientation of the boulders in the coarse stripes is directed strictly down the slopes, parallel to the stripes themselves", and presented diagrams to this effect. Brockie (1964, p. 98) who examined "stone streams" in New Zealand, found that "the orientation and dip of the major axis of individual rocks ... reveals a markedly preferential orientation and dip in the direction of the stream". King (1972, p. 162) detected no preferential orientation where rounded boulders formed "stone garlands", but where the garlands were composed of platy blocks, "circumferential orientation" was reported.

Many workers have made parenthetical reference to the inclination of blocks in patterned-ground borders, but again detailed measurements have rarely been made. Three-dimensional analysis has not been undertaken despite long-standing appeals for such information (Washburn 1973; Watson and Watson 1971). As noted by the latter authors, at least two contradictory lines of thought exist. The first regards long axes as predominantly vertical. Huxley and Odell (1924, p. 209) characterized the clasts of polygon borders as "upended", as did Ahlmann (1936, p. 11), and Richmond (1949, p. 145). Bunting and Jackson (1970, p. 201) described stones in the borders as "vertically oriented, but with no preferred directional orientation except in adjacent situations".

A second viewpoint was represented by Sharp (1942, p. 276), who found that "platy fragments lie flat in the central area and are set on edge in the borders" ("on edge" indicating steeply-dipping b-axes). Sharp's view was corraborated by Washburn (1956, p. 831) and by Benedict (1965, p. 24), who commented that "where tabular stones are present in the borders of polygons, they tend to stand on edge and to be oriented parallel to the sides of the polygons". French (1976, p. 189) suggested that in sorted stripes, "stones and boulders are commonly on edge with a long axis parallel to the line of movement of the stripe". According to Pinczés (1974, p. 39), however, stone stripes "consist of sharp rock in entirely unsystematic position".

**Site Characteristics and Data Analysis**

To reconcile some of the above contradictions, three samples of clast orientation were obtained from the coarse borders of a large sorted stripe and analyzed statistically. The study area is a patterned-ground field located on the tread of a small cryoplanation terrace at 1700 m in the Cathedral Massif of northwestern British Columbia (59° 20′ N, 134° 05′ W). Perennial snowbanks are present at the scarp-tread juncture, providing the moisture necessary for frost sorting and mass wasting. The patterned ground is rarely exposed by retreating snow before mid-July. Movement in the fine portions of the sorted stripes has been documented during the past decade, but rates are unknown (E. Kramer, personal communication, 1979). The patterned-ground field is largely unvegetated, and carries no significant lichen cover except in highly-localized areas of early snowmelt.

Orientation data were obtained from the surface of two representative sorted-stripe borders. In the area from which the samples were taken, fine and coarse stripes average 0.62 and 0.36 m in width, respectively. The slope is relatively uniform at 3–4°, and trends N55°E. A sample of 50 observations was taken from a small area in each of the stone stripes bordering a fine lobe, and from the "stone garland" at the unit's downslope margin. Measurements of a-axis azimuth and a- and b-axis dip were made with a Brunton compass. Only tabular blocks with axial ratios ⩾2:1 were measured. The a-axes of the blocks ranged between 15 and 35 cm in length. Figure 2 illustrates the a-axis orientation and dip observations on equal-area projections (Schmidt nets) positioned to indicate the approximate locations from which the samples were obtained. The data have been rotated so that inclination of the local slope corresponds with the projective plane, and slope direction with the north pole of the diagrams.

Statistical analysis of the data precludes use of a vectorial approach, since no sample is unimodal. The eigenvalue method advocated for till fabrics by Mark (1973), and detailed by Anderson and Stephens (1972) and Mardia (1972; 1975) was therefore utilized. Although this method has recently been criticized by Cornish (1979), the objections stem from a lack of appreciation of the three-dimensional nature of the procedure, and are invalid. The eigenvalue procedure was supplemented with Bingham's U test of uni-

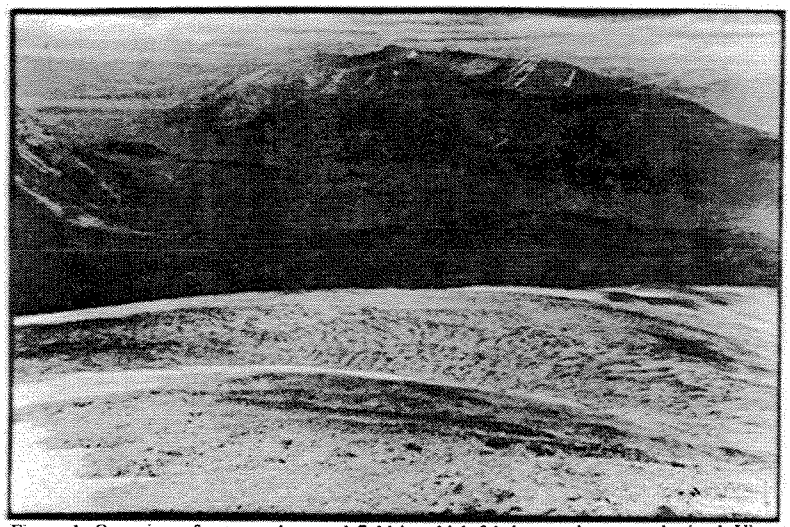

Figure 1. Overview of patterned-ground field in which fabric samples were obtained. View to northeast.

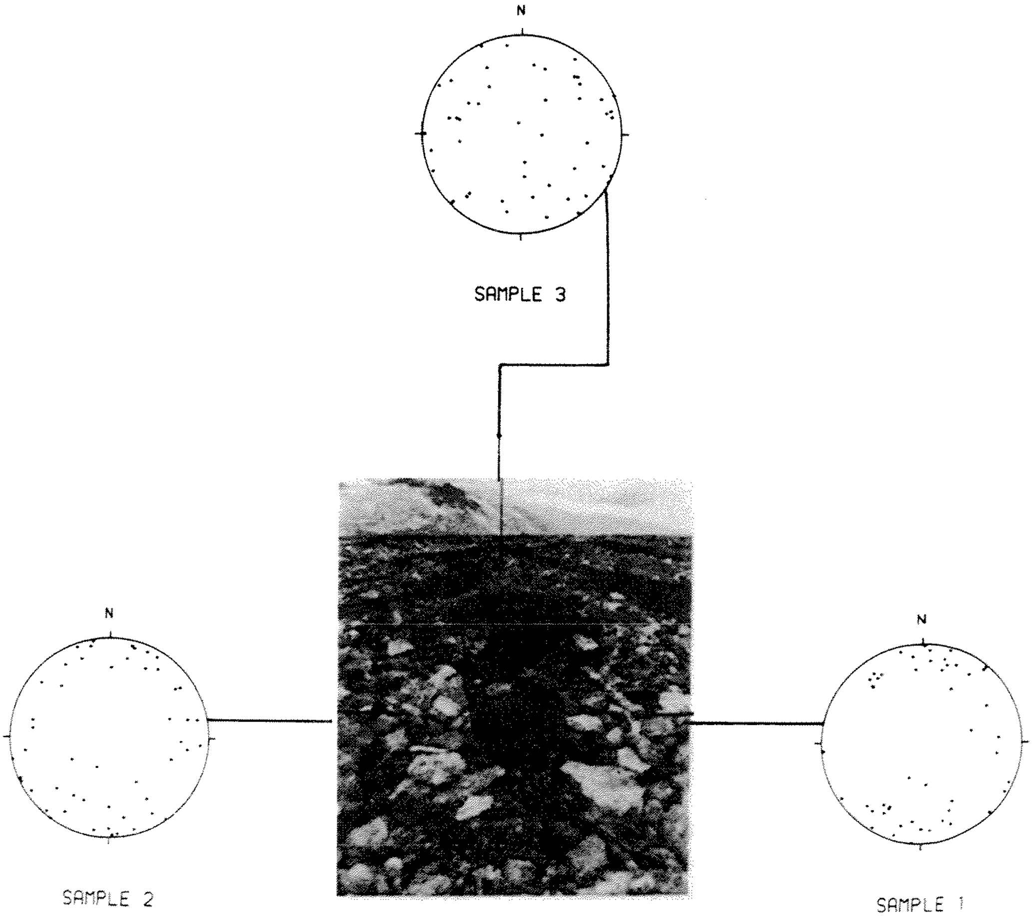


Figure 2. Stone-stripe macrofabrics, a-axes. Plotted on Schmidt net, lower hemisphere. View is directly downslope, approximately N55°E. Projective plane and orientation of diagrams correspond to plane of slope and downslope direction, respectively.

Table 1. Eigenvalue and Bingham statistics for a-axis data.

| Sample | $\bar{\tau}_1$ | $\bar{\tau}_3$ | U | $S_g$* | $S_b$* |
|---|---|---|---|---|---|
| 1 | $0.137^{S}$ | $0.618^{S}$ | $0.957^{S}$ | 17.92 | $4.96^{++}$ |
| 2 | $0.131^{S}$ | $0.532^{S}$ | $0.604^{S}$ | $4.79^{+}$ | 13.34 |
| 3 | $0.218^{NS}$ | $0.442^{NS}$ | $0.189^{NS}$ | – | – |

$\bar{\tau}_1$ = minimum normalized eigenvalue.
$\bar{\tau}_3$ = maximum normalized eigenvalue. $\Big\}\ \sum_{i=1}^{3} \bar{\tau}_i = 1.0$

U = Bingham's statistic = $15/2 \sum_{i=1}^{3} (\bar{\tau}_i - 1/3)^2$

$S_g$ = test statistic for rotational symmetry (girdle case)
$S_b$ = test statistic for rotational symmetry (hipolar case)
* $S_g$ $S_b$ are asymtotically distributed as $\chi^2_2$.

S = statistically significant
NS = not significant
\+ = accept girdle hypothesis
++ = accept bipolar hypothesis
(0.05 level)

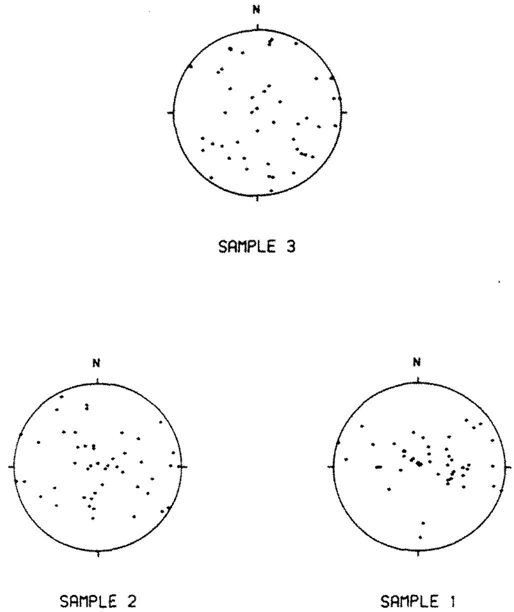


Figure 3. Stone-stripe macrofabrics, b-axes. Projection and rotation are identical to those of Figure 2.

formity (Mardia 1975, pp. 358–359). Information obtained from analysis of the a-axes is summarized in Table 1.

Both samples from the lateral stone stripes differ significantly from uniformity, while the frontal garland sample does not. Comparison of the normalized minimum and maximum eigenvalues of samples 1 and 2 with critical values in Anderson and Stephens (1972) yields ambiguous criteria for determining fabric shape. This problem was resolved by testing for bipolar and girdle rotational symmetry (Mardia 1972, pp. 277–278). These tests indicate that Sample 1 can be regarded as bipolar; its modes correspond with, but are loosely clustered about the direction and inclination of local slope and the stripe's axis. The stronger transverse element of sample 2 gives rise to a weak horizontal girdle, although as reported by Furrer and Bachmann (1968), the primary modes are oriented in the directions of the stripe axis. Sample 3 fails to achieve statistical significance by either Anderson and Stephens' or Bingham's criteria.

Since so many conflicting reports on the nature of b-axis dips are found in the literature, b-axis dip and dip direction were recorded for all clasts measured in the field. Analysis of b-axis data by the eigenvalue and Bingham methods confirms the nonuniformity of the lateral stripe samples, and the null hypothesis of uniformity is again retained for the frontal sample. From Figure 3 the b-axes of clasts in the lateral stripes can be characterized as dipping steeply in directions normal or subnormal to the trend of the stripes and the local slope. This pattern strongly suggests that the lateral stripes have been subjected to compressional stresses.

Unfortunately, most of these samples are not amenable to three-dimensional comparative procedures due to their nonunimodal configuration (Mardia 1972, p. 249). Although comparison of a-axis data would be most appropriate, it would require decomposition of the data into two dimensions and a further transformation (doubling of angles) to eliminate the effects of symmetric bimodality. Because this procedure would result in the loss of a large amount of information, only the b-axes of samples 1 and 2 were subjected to comparative analysis. These samples possess sufficient concentration for application of the Watson–Williams tests for equality of mean directions and concentration parameters (Mardia 1972, pp. 262–267). Results are contained in Table 2; note that vector quantities should be evaluated with respect to the projective plane of Figures 2 and 3. No evidence exists that samples 1 and 2 were drawn from different populations. Because the eigenvalue and Bingham tests failed to detect evidence of nonuniformity in sample 3, it can be regarded as fundamentally different from the others.

Table 2. Eigenvalue, Bingham, and comparative tests for b-axis data.

| sample | $\bar{\tau}_1$ | $\bar{\tau}_3$ | U | $\bar{R}$ | A | D | $\bar{R}'$ | $C_p$ |
|---|---|---|---|---|---|---|---|---|
| 1 | $0.098^{S}$ | $0.635^{S}$ | $1.131^{S}$ | 0.745 | 67.36° | 75.04° | | |
| 2 | $0.180^{S}$ | $0.519^{S}$ | $0.443^{S}$ | 0.645 | 58.74° | 86.48° | $0.695^{NS}$ | $1.393^{NS}$ |
| 3 | $0.288^{NS}$ | $0.399^{NS}$ | $0.051^{NS}$ | 0.531 | 108.62° | 76.67° | – | – |

$\bar{\tau}_1$ = minimum normalized eigenvalue
$\bar{\tau}_3$ = maximum normalized eigenvalue
U = Bingham's statistic
R = mean resultant length
A = resultant azimuth
D = resultant dip
R' = two-sample test statistic for mean directions
$C_p$ = two-sample test statistic for equality of concentration parameters
S = statistically significant (0.05 level)
NS = not significant

## Fabric Origin

Results of the foregoing analyses support the contentions of those earlier workers who reported edgewise blocks aligned parallel to stripe axes. The mechanisms responsible for this pattern are, however, still somewhat obscure.

King (1971, pp. 383–384) suggested that stone-stripe fabric is related to solifluction in adjacent fine stripes, which produces gentle inclinations in downslope-dipping border stones. According to this argument, upslope-dipping clasts should be steepened by such movement. Unfortunately, the data presented by King in support of this hypothesis, which show maxima at both low and high dip angles, were not distinguished by dip direction, making his supposition rather speculative. Several lines of evidence argue against King's hypothesis:

1) The blocks of sorted circles and polygons also lie tangent to the outlines of the fine cells. As Lundqvist (1949, p. 346) recognized, some process common to the various geometric forms of patterned ground must operate to produce analogous fabrics.

2) Forces exerted by differential downslope movement between coarse and fine stripes may be insufficient to produce concentrated particle orientation near the centers of large stone stripes.

3) If solifluction is the main control producing the orientation pattern, rates of movement would necessarily be greater in the fine lobes than in the stone stripes. Although movement survey was not a part of the present undertaking, various studies have established that movement may be greater in either the fines (Chambers 1966, pp. 29–30; 1970, p. 93; Mackay and Mathews, 1947) or the coarse stripes (Antevs 1932, pp. 57–58; Washburn, 1947, pp. 78–88; cf. also Washburn 1980, p. 154). Some investigators have found evidence for relative movement of both types within the same locality (Benedict 1970, p. 203 and 207; Washburn 1969, p. 187). This apparent discrepancy is explained by the predominance of solifluction in moist microenvironments, which results in higher rates of movement in the fine stripes. Where conditions are relatively dry, frost creep predominates and the coarse stripes move faster than the fines, due to the latter's cohesion on resettling (Benedict 1970). In both cases, however, similar two-dimensional fabrics apparently exist (compare Benedict 1970, p. 204, Fig. 44 with Benedict 1966, p. 26, Fig. 3).

King's assertion was tested using data available from samples 1 and 2. Since the long-axis dips of stones with azimuthal orientations normal or subnormal to the stripe axis were of little use in this analysis, b-axis dips were substituted in these instances. A sample of 100 clasts was therefore available, 49 dipping between south and west (upslope), and 51 between north and east (downslope). If the solifluction hypothesis is correct, the former group should display higher inclination angles, because the stripe's direction of slope is N55°E. The two sample Kolmogorov-Smirnov test was applied to the data; the null hypothesis of no significant difference could not be rejected, indicating that King's suggestion is

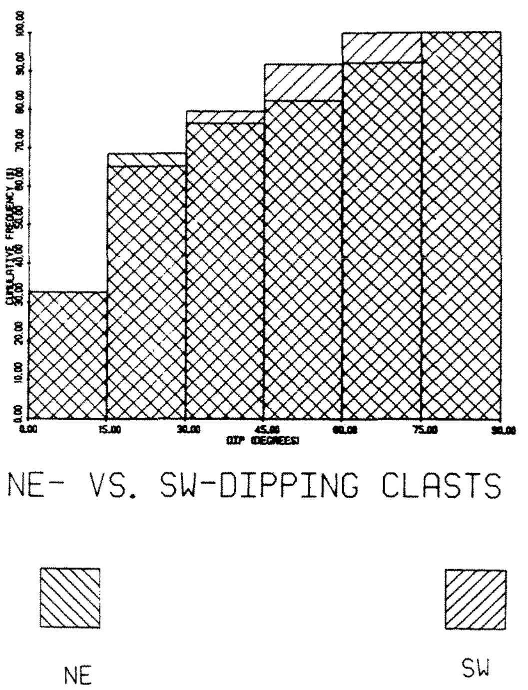


Figure 4. Pair chart of up- and downslope dips.

Results of one-tailed Kolmogorov-Smirnov test (0.05 level):

$\chi^2 = 0.899$

$\chi^2_{2,0.05} = 5.99$

Null hypothesis of no significant difference retained.

improbable, at least for large sorted stripes (Figure 4).

The major clue to the origin of patterned-ground fabrics lies not only in a-axis orientations, which could be produced by a variety of processes, but also in the dips, particularly of the b-axes. The b-axes of blocks within the stone stripes clearly are more steeply inclined than are the a-axes, supporting the observations of those workers who remarked on the large number of stones lying "on edge". In both samples drawn from the lateral stone stripes, more than 50 % of the b-axes are inclined ⩾45°. In contrast, the great majority of a-axis inclinations is less than 30° (Figure 5). There is no apparent preference for either axis to dip predominantly up- or downslope.

The pattern of inclinations described above suggests that stone stripes are subjected to compressive stresses exerted laterally by the central areas of fines. A mechanism which may account for both the tangential orientation pattern and the large proportion of edgewise blocks in all geometric forms of sorted patterned ground was suggested by Goldthwait (1976, p. 31). "Squeezing" of the coarse borders by lateral expansion of saturated fines during the autumn freeze could be expected to set stones on edge, and may also account for aligned a-axes in situations where adjacent centers exert compressive stresses. A reasonable analogy can be made between this hypothesis and the "March model" of grain rotation within a deforming rock body. Given an initial fabric parallel to the direction of shortening, the March model predicts rotation of fabric elements into a direction parallel with that of principal extension (Hobbs *et al.* 1976, p. 248, Fig. 5.27). The assumption of an initially transverse fabric is justified in patterned-ground borders because newly-ejected particles are oriented normal or subnormal to the outlines of the fine centers. Numerous examples of clasts undergoing ejection were noted in the Cathedral patterned-ground field, virtually all of which were oriented nearly perpendicular to stripe axes. Thus, although a majority of particles would not assume a transverse orientation at a single moment in time, most lie transverse during and immediately after ejection from the fines. As "shortening", that is, expansion of the fines proceeds, b-axes are steepened and transverse particles are rotated into positions parallel to the local trend of the coarse border (Figure 6a and 6b). The fact that a-axes lack consistent upslope imbrication, a common characteristic of mass-movement deposits, tends to support this explanation, as does the rather relaxed directional concentration about the stripe's axis. The strong similarity between b-axis orientation and poles to bedding in cylindrical folds should also be noted (Figure 3, especially sample 1).

Displacement of particles in the coarse borders by frost thrusting of the central fines has been documented by several workers. Jahn (1966, p. 144) reported thrust of at least 5 cm in the outer margin of a sorted circle's fine area, and remarked that it displaced stones in the borders. Benedict (1970, p. 201) used painted lines to detect movement of tightly-packed stones in polygon borders. In one "frost-

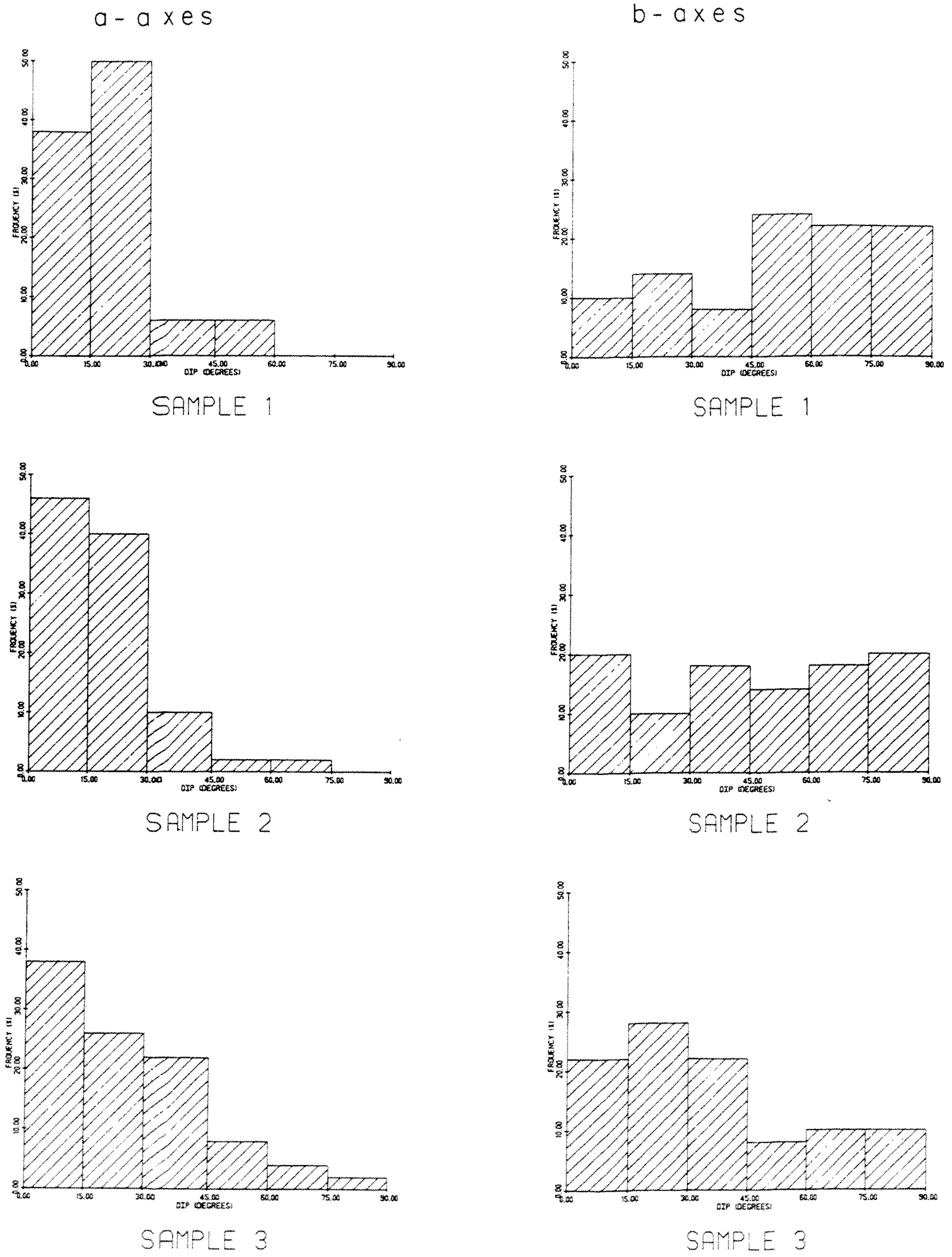


Figure 5. Histograms of a- and b-axis dips.

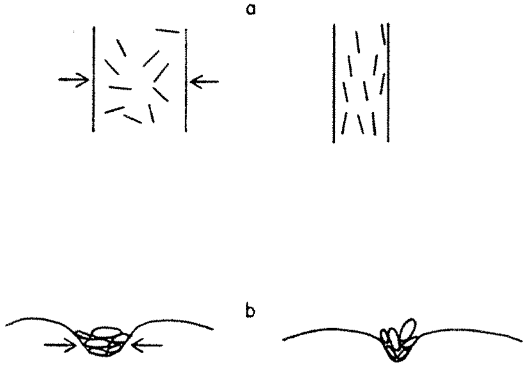


Figure 6. Inferred development of sorted-stripe macrofabric.
a) lateral stone stripe, plan view.
b) lateral stone stripe, cross-section view parallel to stripe axis.

disturbed area" he found that 15 of 20 marked stones were displaced during a single winter, apparently by "the influence of fine-textured centers."

Schmertmann and Taylor (1965, p. 27) also documented significant lateral thrust in the central portion of a sorted circle. Expansion of fine centers associated with autumn freezing thus appears to be a plausible explanation for the observed fabrics. A further indication of this lies in the apparently random nature of block orientation at the stripe unit's downslope margin (sample 3). Because the forces generated by mass movement and frost thrusting at this location are exerted from upslope with little compensating force or resistance offered from the opposing direction, blocks are more freely rotated, resulting in a random or "uniform" fabric.

## Conclusions

Clast fabrics in the coarse lateral components of sorted stripes differ significantly from uniformity, while those at the downslope margin do not. Although more samples are required before lateral fabrics can be characterized as bipolar or girdle, patterns of a- and b-axis dips suggest that frost thrusting in the intervening fines is responsible for observed patterns of particle orientation and inclination. Much more work is required to establish an adequate link between form and process. Because recorded horizontal movements are not of great magnitude, careful study should be made of the effect of such movement on particle orientation. The influence of clast shape may also be of significance and should be considered in future studies.

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