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Sorted-Circle Macrofabrics

By Fritz Nelson*

Summary: Three-dimensional analyses of clast orientation in the border of a large sorted circle reveal significant departures from uniformity. The long axes of rock fragments lie nearly horizontal and are subparallel to adjacent sections of the cell outline. In contrast, B-axes are steeply inclined, indicating compression by expansion of adjacent fines during the annual freeze. Fabrics in the various geometrical forms of sorted patterned ground are similar, suggesting that frost-thrust compression is common to all.

Zusammenfassung: Dreidimensionale Analysen der Orientierung von Gesteinsfragmenten am Rande eines großen Steinrings zeigen signifikante Abweichungen von einer gleichförmigen Verteilung. Die Längsachsen der Gesteinsfragmente liegen annähernd horizontal und sind subparallel zu naheliegenden Teilen der Zellengrenze angeordnet. Im Gegensatz dazu sind die B-Achsen steil geneigt und zeigen Kompressionen, die durch Ausweitung benachbarter Bodenpartikel während des jährlichen Gefrierens entstanden sind. Die Gesteinsorientierungen in den verschiedenen geometrischen Formen des sortierten Frostbodens sind einander ähnlich und deuten darauf hin, daß frostgebundene Kompression bei allen Formen üblich ist.

INTRODUCTION

Although early investigators (for example, HUXLEY & ODELL, 1924) remarked on the peculiar arrangement of stones in the borders of sorted patterned ground, only recently have statistical studies been undertaken on the fabrics of these features. A surprising number of recent papers make note of clast orientation in the various forms of patterned ground, but disagreement between investigators is common. This may be due in some cases to a lack of measurement, and to inadequate or divergent measurement and analytic techniques in others. This paper extends the treatment given sorted stripes by NELSON (1982) to sorted circles; the ,,eigenvalue method'' of fabric analysis is used to standardize statistical procedures and to allow future comparisons with fabrics from other types of periglacial phenomena.

LITERATURE

Several investigators (SCHMERTMANN & TAYLOR, 1965; FAHEY, 1975; FURRER & BACHMANN, 1968) have shown that radial fabrics are characteristic of the fine-dominated ,,centers'' of sorted and nonsorted circles, and of sorted polygons. Particles usually dip toward the geometric center of the features; the dips may be steep (FURRER & BACHMANN 1968; CORTE 1962) or predominantly gentle (SCHMERTMANN & TAYLOR, 1965). The radial pattern may be related to mass displacement (ANKETELL et al., 1970), or could be attributable to reorientation by repeated freezing and thawing (WASHBURN, 1980: 89).

Radial fabrics are replaced by tangential patterns in the coarse borders of sorted forms. LUNDQVIST's (1949) diagrams show an almost perfect correspondence between the local trend of the patterned-ground cell outline and the orientation of rock fragments within the border, although he found that some stones lie oblique or normal to the border. FURRER (1968) and FURRER & BACHMANN (1968) found that most (50 %) border clasts lie parallel to the local outline, with a substantial minority (30 %) in transverse positions. Although SÖDERMANN (1980) stated that clasts in the borders of patterned-ground features are ,,devoid of any predominant orientation'', his ,,situgrams'' of particle orientation in sorted polygons and stripes strongly suggest otherwise. SÖDERMANN's (1980: 121) comments were apparently directed at the lack of A-axis imbrication. The latter characteristic has also been illustrated by FURRER (1968) and FURRER & BACHMANN (1968), whose situgrams suggest that fewer than 10% of border

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clasts dip ≥ 45°. Similar results were reported by NELSON (1982) in the borders of a large sorted stripe.

WATSON & WATSON (1971) and NELSON (1982) discussed the opposing viewpoints represented in the literature concerning the inclination of tabular blocks in patterned-ground borders. One view holds that blocks are ,,upended'', implying that long axes stand vertically, while a second suggests that blocks are ,,edgewise'', with their B-axes steeply inclined. NELSON (1982) found that in sorted-stripe borders the latter viewpoint was supported. Steeply inclined B-axes were thought by GOLDTHWAIT (1976) and PISSART (1977; cited by WASHBURN, 1980: 144) to result from compression as fine cells expand during autumn freezeback. This hypothesis was also supported by NELSON (1982).

Disparate analytic methods have hampered utilization of the full potential of orientation measurements for inferring mechanisms of patterned-ground development. Most workers (G. LUNDQVIST, 1949; J. LUNDQVIST, 1962; BROCKIE, 1964; BENEDICT, 1970) relied on two-dimensional ,,rose diagrams'' for illustration and inference. FURRER (1968), FURRER & BACHMANN (1968), GRAF (1973), and SÖDERMANN (1980) used the BACHMANN ,,situgram'', which treats two-dimensional directional data axially, but also shows the percentage of stones dipping at greater than a specified angle (usually 45°) by a separate bar. Although superior to the use of only two-dimensional data, ,,situmetry'' treats azimuth and dip separately, and is far less powerful than three-dimensional representation via hemispherical projection. Horizontal girdles, in particular, appear to have no statistical significance when viewed or analyzed two dimensionally, even if they are highly significant in three dimensions. Since the possibility of horizontal girdles seems quite strong based on the diagrams and descriptions of several workers (FURRER & BACHMANN, 1968; SÖDERMANN, 1980; GRAF, 1973; NELSON, 1982), three-dimensional representation should be undertaken in all future studies. Moreover, statistical treatment via the ,,eigenvalue method'' (ANDERSON & STEPHENS, 1972; MARDIA, 1972; MARK, 1973) is increasing the ability of workers to relate fabric shape to depositional environment and/or mass-movement processes (MARK, 1974; MAY et al., 1980).

SITE CHARACTERISTICS AND DATA ANALYSIS

Orientation data were collected from sorted circles located on the tread of a well-developed cryoplanation terrace in the vicinity of Eagle Summit, Alaska (65°30' N., 145°25' W.). In this region, patterned-ground fields are abundant on tread surfaces above 1000 m, although continuous vegetation mantles most fine cells, and a heavy coat of lichen covers blocks of the coarse fraction. Although patterned ground is common, it is often masked by a thin vegetative mat (Fig. 1). The circles sampled for this study are located at about 1240 m on a north-facing terrace tread, and are heavily lichenized and vegetated. REGER (1975) believed cryoplanation terraces in this vicinity to be inactive. Although a few patterned-ground cells display active frost boils, the prevalence of the vegetation cover indicates that most are relicts of a former cold period or one characterized by different snowmelt patterns.

LUNDQVIST (1949) and several subsequent investigators have asserted that the blocks of patterned-ground borders conform directionally with the pattern outlines. This hypothesis was tested by two methods. The first follows the methodology of NELSON (1982); point samples of A-axis dip and dip azimuth, as well as the those of maximum-projection planes defined by the A-B axes, were collected at four locations on the circle's periphery. The latter will for ease of exposition be referred to as the ,,B-axis data''; although there is a distinction between orientation of the maximum-projection plane and that of the B-axis, it is negligible in the present study because A-axis dips are very low. The second method uses a test of circular correlation to assess the correspondence between paired observations of block orientation and the local direction of the border outline.

Point samples of 25 observations each were collected from different parts of the coarse border in the sorted circle shown in Fig. 2. Samples were collected from as small an area as possible, involving no more

Fig. 1: Overview of cryoplanation terrace where fabric data were collected. Crenations on tread surface are relict sorted patterned-ground cells now covered with vegetation. Fabric samples were obtained from the sorted circle in foregound, which lies immediately below the terrace scarp. Rifle in center of circle is 97 cm long and points due north.

Abb. 1: Blick auf eine Kryoplanationsterrasse, auf der Daten über Gesteinsorientierungen gesammelt wurden. Die wellenförmigen Oberflächenformen auf der flachen Ebene sind reliktische sortierte Steinnetz-Zellen, die jetzt mit Vegetation bedeckt sind. Daten wurden gesammelt über Gesteinsorientierungen des Steinrings im Vordergrund, der unmittelbar unter dem Terrassen-Frostkliff liegt. Das Gewehr in der Mitte des Steinrings zeigt nach Norden.

than 0.5 m^2. Sampling within a very limited area was of critical importance, because if the outline-block correspondence is indeed present, sampling over more than a few degrees of arc along the circle's outline could result in an erroneous impression of fabric strength or its statistical significance. Alternatively stated, if clasts from the entire border of the sorted circle were treated as a single sample, a two-dimensional uniform distribution or a horizontal girdle in three dimensions would be expectable under LUNDQVIST's hypothesis. Only tabular schist blocks with A:B axial ratios ≥ 2:1 were measured. The A-axes of the blocks ranged from 12.5 to 49 cm, with mean and standard deviation of 27.4 and 9.24. Due to the large particle size and a lack of fine-soil matrix, measurements could be made directly on the clasts with a Brunton compass. In Fig. 2, A-axis orientation and dip observations are plotted on equal-area projections positioned to indicate the locations at which the samples were collected.

Because no sample is unimodal, treatment of the data by vectorial methods is inappropriate. The eigenvalue method, which has recently received widespread use by glacial geomorphologists, was therefore utilized. The normalized eigenvalues $\bar{\tau}_i$, $i = 1, 2, 3$ ($\bar{\tau}_1$, $\leq \bar{\tau}_2 \leq \bar{\tau}_3$) are computed from a matrix of sums of squares and products of direction cosines derived from a set of trend and plunge measurements. These can be tested for statistical significance by methods outlined by ANDERSON & STEPHENS (1972) and MARDIA (1972, chapter 8; 1975). The eigenvalues are a measure of the length of the corresponding

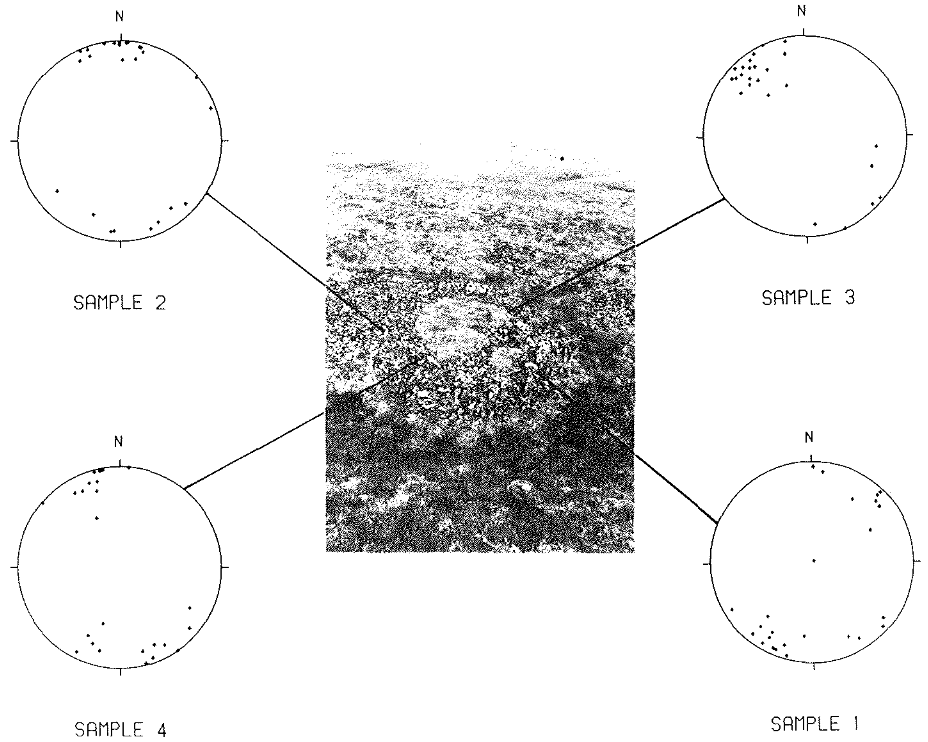


Fig. 2: Sorted-circle border macrofabrics, A-axes. Plotted on Schmidt net, lower hemisphere. View is due north. White scale is 30 cm long.

Abb. 2: Makro-Gesteinsorientierung des Randes der Steinringe, A-Achse. Geplottet in ein Schmidt-Koordinatensystem, untere Hälfte. Sicht nach Norden. Weiße Skala ist 30 cm lang.

eigenvectors t_i, which represent the axes of minimum, intermediate, and maximum clustering, respectively. Fabric shape can be roughly inferred by the nature of the eigenvalues (MARDIA, 1972, Tab. 8.3: 225), while BINGHAM (1964) developed tests of uniformity and rotational symmetry (see MARDIA, 1972: 276—278).

Information derived from application of these procedures to the sorted-circle data is presented in Tab. 1.

sample	$\bar{\tau}_1$	$\bar{\tau}_3$	U	shape	Sg	Sb
1	0.091	0.706	1.607^S	bipolar	14.950	4.084*
2	0.037	0.804	2.549^S	bimodal	22.367	9.740
3	0.056	0.849	2.997^S	bipolar	31.689	1.638*
4	0.069	0.797	2.431^S	bipolar	24.985	2.632*

$\sum_{i=1}^{3} \bar{\tau}_i = 1.0.$

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

^{S} statistically significant (0.05 level); Sg & Sb = test statistics for girdle and bipolar rotational symmetry; * accept bipolar hypothesis of rotational symmetry (0.05 level); Sg and Sb are asymptotically distributed as χ^2_2.

Tab. 1: Eigenvalue and Bingham statistics for A-axis data.

Tab. 1: Eigenwert- und Bingham-Statistik für A-Achsen-Daten.

From this table and Fig. 2, the A-axes are seen to lie parallel to the local trend of the coarse border. All samples diverge significantly from uniformity. The distributions display marked and symmetric bimodality, the modes corresponding with the local trend of the stone border. A-axis dips are relatively low, but the horizontal girdles suggested by FURRER & BACHMANN's description are not present.

To obtain a better indication of how well block orientation conforms to the outline of the sorted circle, multi-sample tests for equality of mean directions and concentration parameters were undertaken for the A-axis data. These procedures are described in detail by MARDIA (1972: 267—271). Since the tests can only be used with unimodal distributions, transformation of the data was necessary. The azimuthal observations of each sample were first rotated horizontally by an amount equal to the angular deviation of the local trend of the sorted-circle outline from north, that is, by the number of degrees necessary to make the sample location correspond to ,,north'' on the projection. This may be regarded as a directional standardization. The resulting azimuth values A lying on the interval $90^\circ < A < 270^\circ$ were then assigned to their two-dimensional antipodes. Because the original distributions were all symmetrically bimodal, the two transformations result in unimodal distributions centered on ,,north''. Dip values were not altered. Tab. 2 supplies the statistics yielded by the multi-sample tests; there is no significant difference in concentration or mean direction between the samples. The observations are in all cases loosely clustered about the local axis of the border outline, which is expectable given the results of earlier workers.

A second method of assessing the correspondence between clast orientation and trend of the sorted-circle border is through correlation of paired values. For this purpose, tangents to the cell outline were measured for 30-cm arc lengths around the perimeter of the circle. The long-axis orientation of a randomly-selected block in an adjacent section of the coarse border was also measured for each length of arc. Only long-axis orientation was measured; the sense of the observation was arbitrarily assigned, as was that of the local tangent, by proceeding in an anticlockwise direction. A sample of 22 pairs of observations was collected for one circle, and for a larger feature 35 observations were recorded.

The data were analyzed by means of the circular rank correlation procedure of MARDIA (1975: 359—361). Note that use of linear correlation procedures would be inappropriate in this application. MARDIA's correlation coefficient ro is given by

$$ro = \max(\bar{R}^2{}_1, \bar{R}^2{}_2)$$

where ro is bounded by 0 and 1, and $\bar{R}^2{}_1$, and $\bar{R}^2{}_2$ are measures of ,,positive'' and ,,negative'' dependence, respectively. The test is invariant under rotation. The value of ro can be compared with a table provided by MARDIA (1975: 360) or an approximation contained therein. Computational details of the correlation procedure are omitted here for brevity, but are available in MARDIA (1975). Tab. 3 contains the results of this analysis. A strong positive relationship exists between block orientation and the local direction assumed by the adjacent cell outline, confirming statements to that effect by G. LUNDQVIST

ANOVA table for multi-sample mean-direction test

source	D. O. F.	S. S.	M. S.	F
between samples	6	0.653	0.109	2.0297^{NS}
within samples	192	10.264	0.054	
total	198	10.917		

Test for equality of concentration parameters:
$U_3 = 11.441^{NS}$
(U_3 is distributed in this case as χ^2_6)

^{NS} no significant difference (0.05 level).

Tab. 2: Multi-sample tests for equality of mean directions and concentration parameters.

Tab. 2: Multi-Sample-Tests für Equalitat von durchschnittlichen Ausrichtungen und Konzentrationsparametern.

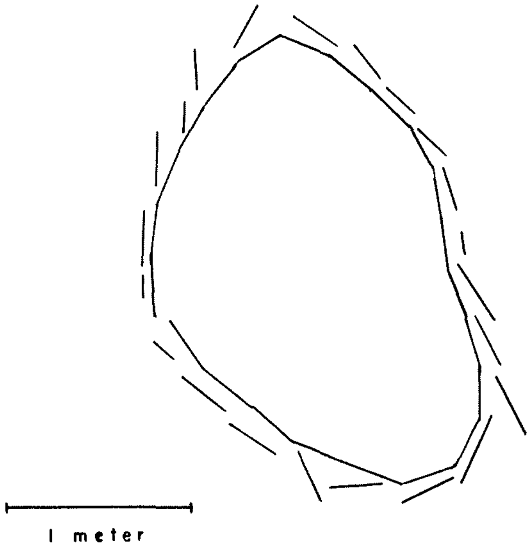


Fig. 3: Relation between patterned-ground cell outline and blocks within the border. Survey closure error is shown. Block lengths and sorted circle drawn to scale.

Abb. 3: Beziehung zwischen dem Umriß und den Blöcken der Frostboden-Zelle innerhalb der Umgrenzung. Das Schließproblem der Untersuchung ist zu sehen. Blocklängen sind größenmässig proportional zum Steinring.

(1949), J. LUNDQVIST (1962), FURRER & BACHMANN (1968), and a number of other workers. This close correspondence between paired observations is perhaps the strongest evidence yet presented for the dependence of block orientation on the trend of the patterned-ground border, and suggests that slope-induced mass-movement processes are not responsible for the fabrics observed in the various forms of sorted patterned-ground borders.

The analysis of NELSON (1982) and the above results indicate that little significance can be attached to A-axis dips in patterned-ground borders. Conversely, orientation of the ,,B-axes'', that is, the dip and dip azimuth of the A-B planes, seems to have a high information content for inferring processes responsible for fabric patterns. For this reason, the B-axis data were analyzed separately via the eigenvalue and Bingham methods. Fig. 4 illustrates these fabrics, while the results of the statistical procedures are summarized in Tab. 4.

Because all samples of B-axis orientation are girdles, the comparative methods used on the A-axis data are not appropriate. Unfortunately, two-dimensional comparative procedures (for example, the uniform scores test) are also inapplicable, due to the fact that many strong girdle fabrics are not statistically significant when reduced to two dimensions. However, as noted by KRUMBEIN (1939), it is possible to analyze or compare samples of azimuth and dip observations separately. Because the B-axis dips are believed to contain the major clue to the processes responsible for patterned-ground border fabrics, recourse was made to linear statistics for sample comparisons. The Kruskal-Wallis test, a nonparametric alternative to the analysis of variance, was employed for comparing the four samples of ,,B-axis'' dip measurements. The Kruskal-Wallis test treats the null hypothesis of equality between medians of the populations from which the samples were drawn (see GIBBONS, 1976: 173—181). Tied ranks were treated by the midrank

sample	$\bar{R}_1^2$	$\bar{R}_2^2$	n
circle 1	0.7838^S	0.0009	22
circle 2	0.7039^S	0.0005	35

Critical values of r_O are computed from: $r_{O}, \alpha = -(n-1)^{-1} \ln(1-(1-\alpha)^{1/2})$ statistically significant ($\alpha = 0.05$).

Tab. 3: Circular rank correlation.

Tab. 3: Zirkulare Rank-Korrelation.

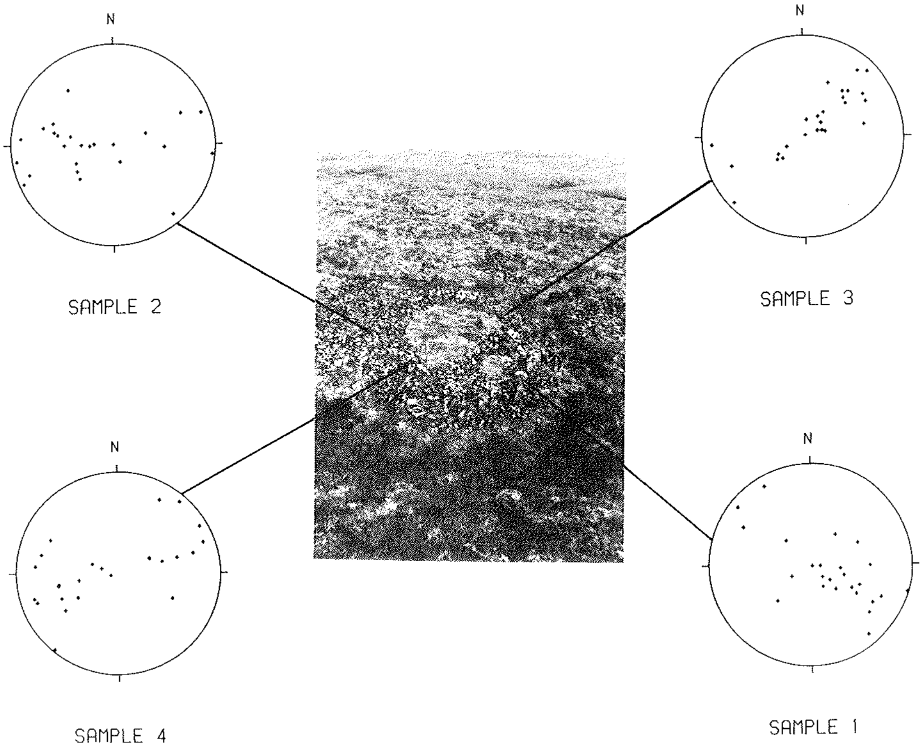


Fig. 4: Sorted-circle border macrofabrics, B-axes. Projection and view are identical to those of Fig. 2.

Abb. 4: Makrogesteinsorientierung eines sortierten Steinrings, B-Achse. Projektion und Sichtwinkel sind die gleichen wie auf Abb. 2.

sample	$\bar{\tau}_1$	$\bar{\tau}_3$	U	shape	Sg	Sb
1	0.070	0.669	1.405^S	girdle	9.462	9.741
2	0.089	0.618	1.070^S	girdle	6.249	19.225
3	0.030	0.663	1.512^S	girdle	6.766	19.856
4	0.084	0.548	0.822^S	symmetric girdle	1.917*	13.271

* accept girdle hypothesis of rational symmetry (0.05 level).

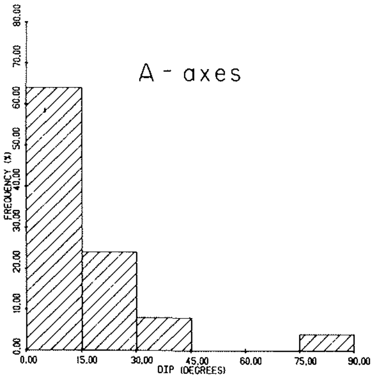
Tab. 4: Eigenvalue and Bingham statistics for B-axis data.

Tab. 4: Eigenwert- und Bingham-Statistik für B-Achsen-Daten.

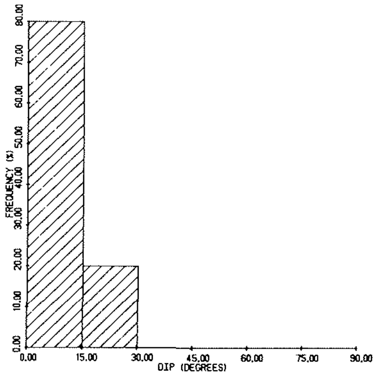
sample	median	mean	Standard deviation	skewness	kurtosis
1	12.00°	16.88°	17.18°	3.05	10.24
2	8.50°	9.04°	6.80°	0.70	-0.66
3	13.50°	16.38°	12.74°	0.81	-0.07
4	13.00°	13.34°	11.94°	1.12	0.92

Tab. 5: Descriptive statistics for A-axis dips.

Tab. 5: Beschreibende Statistik für A-Achsen-Neigungen.



SAMPLE 1



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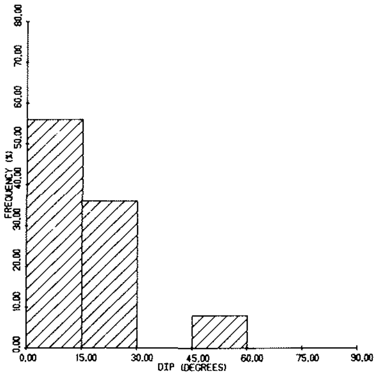
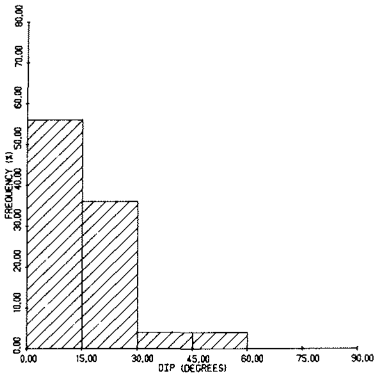
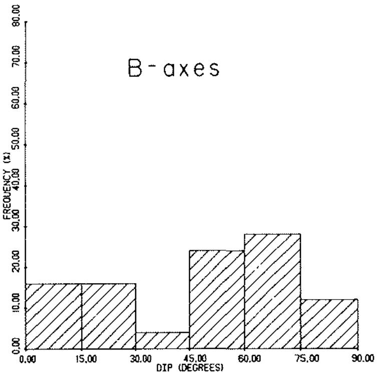


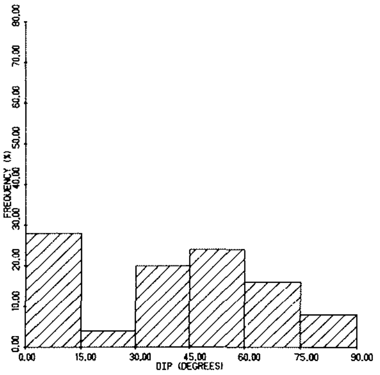
SAMPLE 3



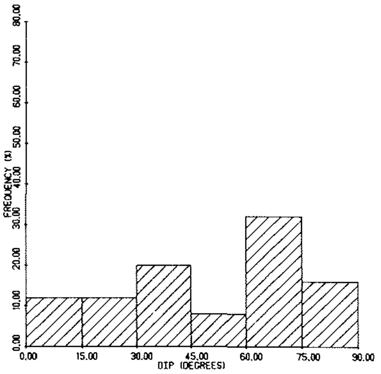
SAMPLE 4



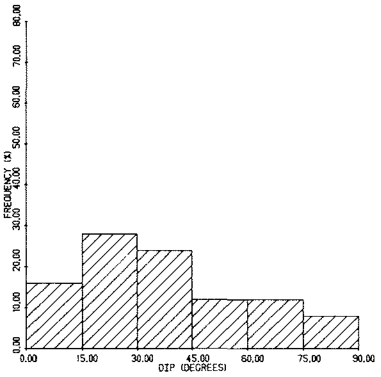
SAMPLE 1



SAMPLE 2



SAMPLE 3



SAMPLE 4

sample	median	mean	Standard deviation	skewness	kurtosis	H
1	46.00°	47.70°	24.65°	-0.30	-0.96	3.021^{NS}
2	38.00°	40.90°	25.34°	0.00	-1.06	
3	41.50°	49.78°	24.57°	-0.28	-1.17	
4	37.00°	37.26°	22.61°	0.35	-0.86	

H = Kruskal-Wallis test statistic.
H is distributed in this case as χ^2_3.

Tab. 6: Descriptive statistics for B-axis dips.

Tab. 6: Beschreibende Statistik für B-Achsen-Neigung.

method. Descriptive statistics for the A- and B-axis data are contained in Tab. 5 and 6 respectively, while histograms of the same data appear as Fig. 5. Tab. 6 also contains the results of the Kruskal-Wallis test; there is no evidence that the four samples of B-axis inclination were drawn from populations with different medians. Moreover, these samples are similar to those presented by NELSON (1982) for active sorted stripes, indicating that little difference exists between fabrics of the various forms of patterned ground, or between active and inactive forms. The overall impression gleaned from the analyses detailed above are that the fabrics originate by compressional forces rather than mass-movement processes.

FABRIC ORIGIN

The results of the preceeding section support those earlier workers who characterized patterned-ground border fabrics as parallel to pattern outlines, with a large proportion of stones lying on edge. The A- and B-axis inclinations of clasts within patterned-ground borders appear to have characteristic frequency distributions, which are positively skewed and platykurtic, respectively. Similarly, three-dimensional A-axis fabrics are characteristically bimodal, the modes coinciding closely with the local trend of the pattern border. Fabrics of the B-axes are girdles, and span the border approximately normal to it.

The fabrics described above are suggestive of compressional stresses exerted laterally by the central areas of fines, as suggested by GOLDTHWAIT (1976), PISSART (1977) and NELSON (1982). ,,Squeezing'' of the coarse borders by lateral expansion of saturated fines during the autumn freeze could be expected to set tabular stones on edge, and may also account for aligned A-axes in situations where adjacent centers exert compressive stresses. NELSON (1982) noted that this hypothesis is analogous to the ,,March model'' of grain rotation within a deforming body of rock. According to this model, an initial fabric parallel to the direction of shortening is rotated into a direction parallel to that of principal extension (HOBBS et al., 1976: 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. 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 trend of the border (Fig. 6a and 6b). The bipolar character of the A-axes supports this interpretation, as does the somewhat relaxed directional concentration about the local trend of the border. The fabric in the border probably becomes well developed only after segregation of the fines and coarse fragments is relatively complete.

Several investigators have documented displacement of border clasts by frost thrusting in the central

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Fig. 5: Histograms of A- and B-axis dips.

Abb. 5: Histogramme der A- und B-Achsen-Neigungen.

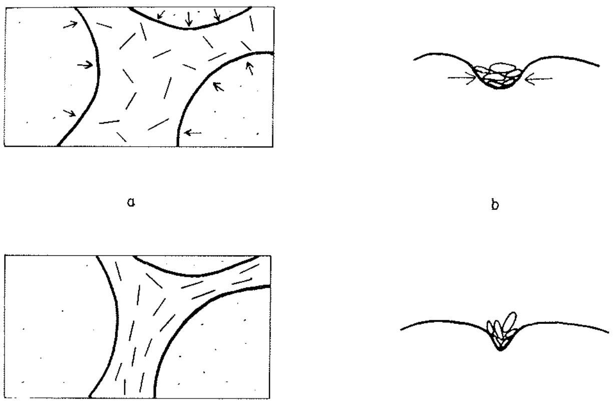

Fig. 6: Inferred development of sorted-circle border macrofabric. a) plan view of cell interaction creating tangential pattern. b) cross-section view showing development of steeply-inclined B-axes.

Abb. 6: Angenommene Entstehung der Gesteinsorientierung des Randes eines Gesteinsrings. a) Grundriß von Zellengefügen, die ein tangentiales Muster hervorrufen. b) Querschnitt zeigt die Genese der steil geneigten B-Achsen.

fines. JAHN (1966: 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: 201) used painted lines to detect movement of tightly-packed stones in sorted-polygon borders. In one ,,frost-disturbed area'' he found that 15 of 20 marked stones were moved during a single winter, apparently by ,,the influence of fine-textured centers''. SCHMERTMANN & TAYLOR (1965: 27) also documented lateral thrust in the central portion of a sorted circle. Expansion of fine centers associated with the autumn freezeback thus appears to be a plausible explanation for the observed patterned-ground fabrics. The compressional interpretation is reinforced by the apparent similarity of fabrics in the various geometrical forms of patterned ground. Because it is applicable to features of all shapes, it is a more general and plausible explanation than others, such as the mass-movement hypothesis rejected by NELSON (1982), which is specific to sorted stripes.

CONCLUSIONS

Sorted-circle border fabrics are similar to those of sorted stripes; judging from the descriptions of other investigators, there is little difference between the fabrics of the various forms of sorted patterned ground. Border clasts characteristically possess gently-dipping A-axes aligned parallel to the local outline of the circle, resulting in statistically significant symmetrically-bimodal fabrics. Strong angular correlations between border clasts and local cell-outline tangents indicate that tangential orientation is a characteristic trait of sorted circles, and that block orientation is dependent on the local trend of the border. The B-axes dip relatively steeply and give rise to girdles which span the border along an axis normal to it. These ,,form-typical'' fabrics appear to be the result of compression due to frost thrusting from opposing directions within adjacent fine-soil cells in mature sorted patterned ground. Although the features investigated in this study were apparently inactive, comparison with data from active sorted stripes (NELSON, 1982) indicates that their fabrics have not been significantly altered. FURRER & BACHMANN's (1968) contention that fossil forms may be recognized in stratigraphic section through fabric analysis is therefore given further support by the present study.

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