Till Fabric in Relation to Direction of Ice Movement

A study from the Fakse Banke, Denmark

By Johannes Krüger

Abstract

The present analysis of till fabric is two-stepped. First, 14 long-axis clast fabrics from undisturbed till in the Fakse Banke are described. The pebbles whose orientation and dip were measured have a length of 1-10 cm and a long-axis dip less than 40°. In addition the ratio between the long and the intermediate axis is defined to be at least 1.50. The orientation measurements are summarized by statistics representing: 1) the direction of preferred orientation, 2) the degree of preferred orientation, and 3) the probability of a preferred, but not random orientation. The study shows that the pebbles statistically parallel the ice flow and that they preferentially dip up-glacier. Secondly, the influence of shape, sphericity, long-axis length, and roundness on the orientation is shown in tables and by graphs. Angular pebbles exceeding a certain long-axis length or of low sphericity and, in addition, symmetrical about their long axis statistically indicate the ice flow more precisely than others.

Introduction

The fact that pebbles are not randomly distributed in till was discussed by *H. Miller* as early as in 1884, but studies supported by quantitative, statistical data were first of all made by *K. Richter* and published in 1932. In ground moraine near Altefähr and Könighörn on the island Rügen he found that the long axes of oblong pebbles tend to parallel the direction of pavement-boulder striae. Richter concluded that a statistical grouping of long-axis strikes indicates the direction in which the glacier was moving at the time of deposition. Later studies from Engebrae and Fondalsbrae glaciers in Norway show that long-axis strike of pebbles imbedded in shear zones of the ice preferentially parallel the direction of glacier flow (*K. Richter*, 1936). In front of the glaciers the till fabric has a similar orientation.Richter concludes, "Die Übereinstimmung ist ganz ausgezeichnet, und zwar in beiden Fällen identisch mit der Richtung der Eisbewegung, so dass hiermit der zwingende Beweis für meine Deutung der Einregelung in pommerschen Geschiebemergeln erbracht sein dürfte".

However, any preferred orientation of elongated pebbles may result from two diametrically opposed directions of ice motion. Richter (1936) call attention to the fact that the long-axis plunge of pebbles imbedded in the ice of the Norwegian glaciers, mentioned above, reflected the dip of nearby shear planes. More recently, in a study of stone orientation in Wadena drumlin field, Minnesota, *H. E. Wright* (1957) has investigated the dip of oblong till pebbles with a reference to the horizontal plane. He found a preferential up-glacier dip and suggests that this might be related to shear planes dipping up-stream in the basal ice. *P. W. Harrison* (1957) has studied the axial orientation and dip of pebbles in two ground-moraine areas near Chicago. Like Wright, Harrison found a preferentially long-axis dip slightly up-stream to the former glacier-movement direction. In the East Anglia study by *R. G. West* and *J. J. Donner* (1956) a preferred down-glacier plung is apparent. However, as pointed out by *J. T. Andrews and K. Shimizu* (1966), a reference to the horizontal plane might result in a misleading statement since it is possible that a subglacial slope during deposition of till has exerted an influence. As mentioned above, the long-axis strike of till pebbles statistically show the ice-movement direction at the time of deposition. But some of the pebbles are oriented diagonally or transversely to this direction. With special reference to this problem *C. D. Holmes* (1941) studied the effect of shape and roundness on the orientation of till pebbles. He found that certain forms and degrees of roundness have a greater-than-average statistical chance for deposition either parallel, to, or transverse to, the glacier flow. Holmes concluded that such pebbles serve as guides to the direction of glacier flow, but he gives expression to the necessity of comparative studies from other regions.

More recent investigations of till fabric have especially aimed at determining the orientation of pebbles in various glacial landscapes and deposits (e.g. *G. Lundqvist,* 1948. *G. Hoppe,* 1951, 1952, 1957, and 1963. *G. Hoppe and V. Schytt,* 1953. *C. E. Johansson,* 1960) as well as to determine the conditions prevailing during till deposition (e.g. *P. W. Harrison,* 1957. *S. A. Harris,* 1968 and 1969. *J. F. Lindsay,* 1970. *G. S. Boulton,* 1970). Thus shape, sphericity, and roundness of till pebbles have not received much attention.

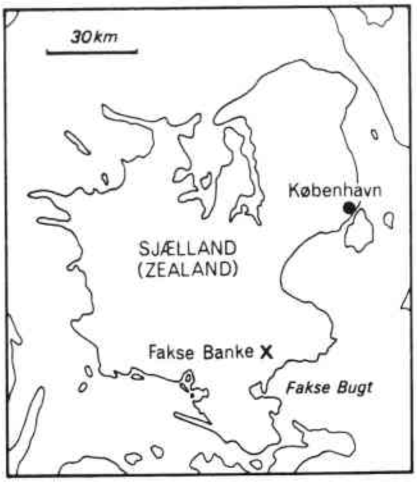


Fig. 1. Map of Zealand indicating the location of the Fakse Banke.
Fig. 1. Kortet viser Sjælland med angivelse af Fakse Banke.

As a statistical device to determine the direction of glacier flows at the time of deposition measurements of long-axis strike of till pebbles have a long time been made in Sweden (e.g. *G. Johnsson*, 1956. *A. Bergdahl*, 1961. *G. Hoppe*, 1959 and 1968), in Poland (e.g. *W. Niewiarowski*, 1969), in Germany (e.g. *K. Richter*, 1933. *H. Reinhard and H. J. Schultz*, 1961. *H. Schroeder-Lanz*, 1964), and in other countries, but this method has only recently been applied to Danish moraine deposits in a regional context (*K. Thamdrup*, 1969. *J. Krüger*, 1969).

The purpose of the present work is twofold. First, it is an attempt to study the variations of fabrics at a given site occupied by an undisturbed till genetically uniform. Secondly, as a basis for selection of "guide forms" very suitable for orientation analyses in order to determine the direction of former glacier flows. In order to be of any validity, the study has been based on a large number of observations. Accordingly, the composite sample includes 700 pebbles.

Location and character of the area

The hill, Fakse Banke, is located in Southern Zealand (fig. 1). The hill is 2.5 km long, 1.5 km wide, 30-50 m high, and directed about N120°E–N60°W. It consists mainly of coral limestone covered by a thin sheet of calcareous till. In this way the Fakse Banke appears morphologically as a rock-cored drumlinoid feature formed by an ice movement from ESE–SE in the last phase of the Würm glaciation (*J. Krüger*, 1969). Altitude of the station locality is about 55 m above sea level.

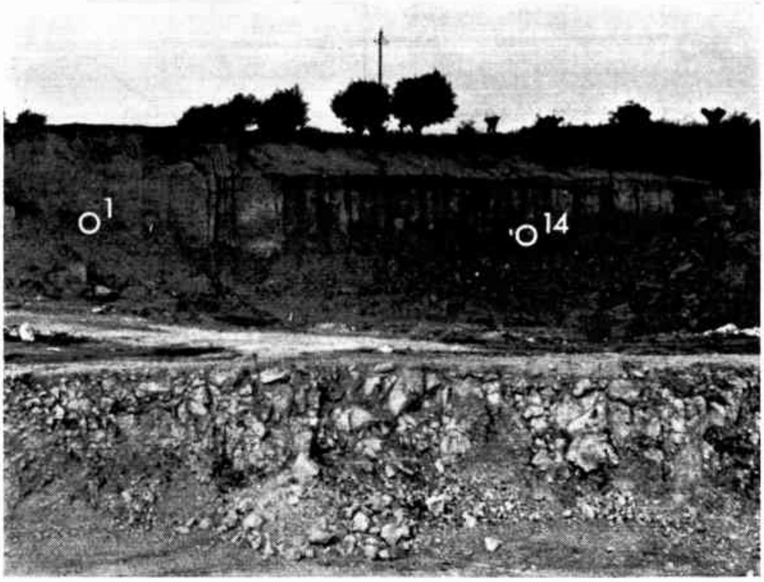


Fig. 2. The northern limestone quarry in the Fakse Banke. In the 10 m high till exposure overlying striated coral limestone the sampling areas No. 1 and No. 14 are shown. Sept. 1970.

Fig. 2. Den nordlige kalkgrav i Fakse Banke. Analysefelterne nr. 1 og nr. 14 er angivet i det 10 m høje moræneprofil, der ses over den isskurede kalkoverflade. Sept. 1970.

Field procedure

In the northernmost limestone quarry in the Fakse Banke the rock has newly been stripped of the till cover (fig. 2). 14 samples of till pebbles have been collected from a till exposure overlying striated coral limestone. The moraine is compact and boulders are not common. 0.5 m below sampling area No. 6 a lens-shaped layer of stratified sand was apparent. The sampling areas were placed 5-7 m below the top of the exposure and 3-5 m above the surface of the limestone in an undulating linear system with horizontal intervals of 2 m of spacing. This way of sampling is based on the apparent homogeneity of the glacial deposit, as there were no visible changes in composition. Instruments required for sampling include a knife, a Silva-compass with clinometer, and a caliper square.

The face of the outcrop was cleaned or scraped and a rectangular sampling area was marked on the face from which successive layers of moraine from inclined as well as from horizontal faces of the excavations were removed carefully by the knife until the desired number of pebbles were obtained. The pebbles were systematically

Fig. 3. Snapshot from analysis No. 9. The compass indicates the orientation of till pebbles "in situ". Juni 1970.

Fig. 3. Analyse nr. 9 under udgravning. Moræmen fjernes med en kniv, og stenene samles systematisk fra hele det afgrænsede analysefelt. Her angiver kompasset orienteringen af sten "in situ". Juni 1970.

collected from the entire face (fig. 3). At each site the long-axis strike of 50 pebbles as well as the angle of long-axis dip to the horizontal plane were determined by use of the compass and the clinometer, respectively. The long-axis dip was measured to the nearest 5° interval. The long as well as the intermediate axis of the pebbles was measured by the caliper square, as the ratio between these two axes, respectively, is defined to be at least 1.50. The long and the intermediate axis of a pebble is considered to lie at right angles to each other and represent the two longer dimensions. Only the pebbles are selected that have a long-axis length of 1-10 cm (only 3 % of the observations have a length of more than 4 cm) and a long-axis dip less than 40°. The azimuth for particles with a long axis dipping more than 40° is too difficult to measure accurately. Their frequency is 9 % of the observations. The selected pebbles were numbered and kept for laboratory studies.

Measurement errors are due to various reasons: 1) From the difficulty to read the compass. In this case the errors are assumed to be randomly spread. 2) From the difficulty to determine the placing of the long axis correctly on certain shapes of pebble. Therefore, in case of doubt the pebble has been inspected critically before measurements. 3) From the removal of the pebble for examination before measurements. However, the impression of the pebble on the till face facilitated the replacement. Furthermore, by an experimental test *A. R. Hill* (1968) has shown that this initial disturbance of the fabric does not influence the fabric analyses. 4) As a result of mental and physical tiredness. Thus Hill demonstrates that the length of time involved in the collection of the data is an important limitation of till fabric analysis. Therefore each analysis consist of 50 pebbles only, and, in addition, only one analysis a day has been carried out.

The uncovered coral limestone mostly exposes a stoss-and-lee topography, as the surface has been smoothed and plucked by glacial action. On suitable exposures the level rock surface was cleaned up with brush and water, and where the faces were polished studies of striations were made to throw light on the direction of the last ice movement. In accordance with this, the different systems of glacial striae were marked with coloured lacquer. Finally, the orientation of the systems was measured and the relationship in age determined. As diverging striae may be wholly the result of local deflections they have been excluded.

Statistical treatment of orientation data

A graphical presentation of the orientation analyses appears from fig. 4. Each histogram indicates the percentage frequency distribution of 50 pebbles classified according to the direction of the longest axis of each particle. The values on the x-axis represent the orientation distributed on classes from north passing east to south. The diagrams are orientated with the north point to the right. The class-intervals have been chosen as 10° each, starting with azimuth 0° as the mid-point of the first class. This defines the classes as 355°–4° (mid-point 0°), 5°–14° (mid-point 10°), etc.

On all the graphs a preferred orientation is evident. Furthermore, the directions of this orientation are almost coincident. The presence of a secondary mode subtransversely to the dominant orientation is characteristic for some patterns (e.g. samples No. 2, 3, 8, 11, 12 and 14). But it should be noted that in none of the graphs such a transverse mode is dominating. For some samples the graph shows a more dispersed pattern (e.g. No. 8, 10, and 11).

In the present study the orientation measurements are summarized by statistics representing: 1) the direction of preferred orientation, 2) the degree of preferred orientation, and 3) the probability of a preferred, but not random orientation.

Re. 1. As pointed out by *A. R. Hill* (1968), one of the most important limitations of orientation analysis is probably the difficulty of finding suitable statistical methods for analyses. In the calculation of the direction of preferred orientation many writers treat their

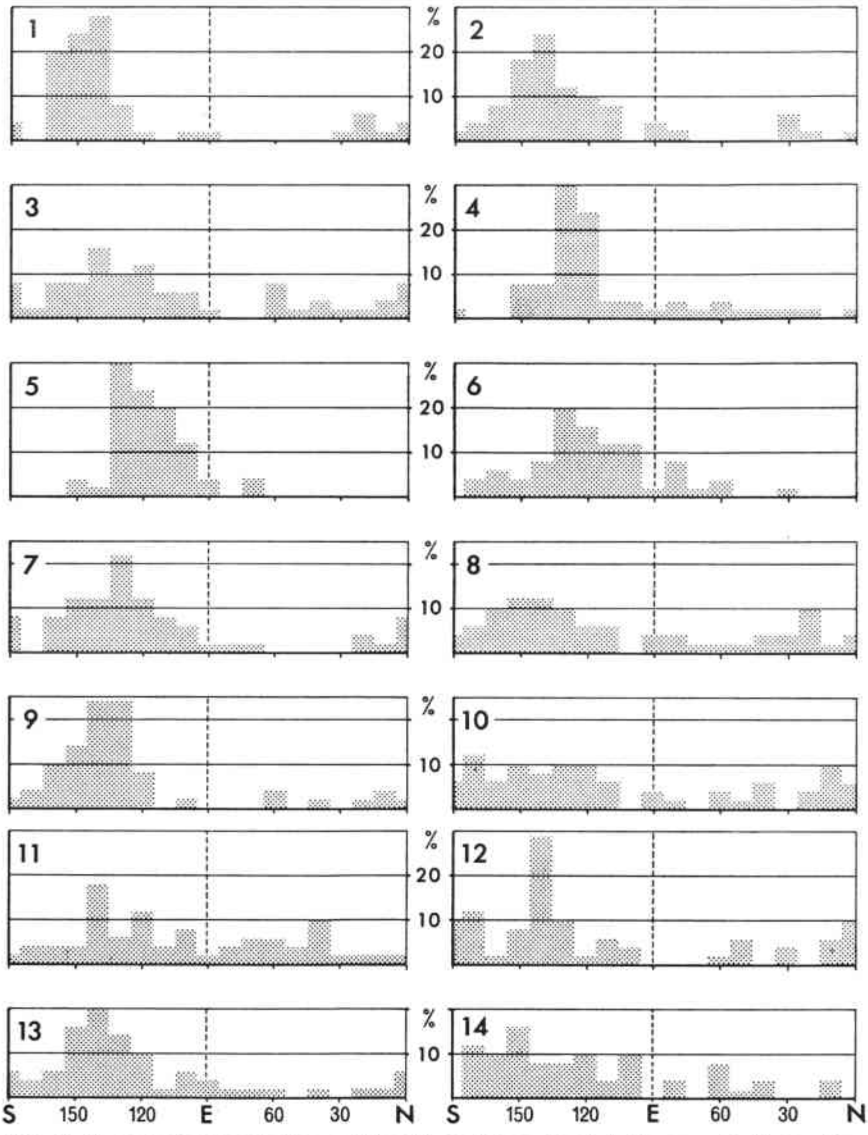


Fig. 4. Graphical presentation of the 14 analyses. Each histogram indicates the percentage frequency distribution of 50 pebbles. The values on the x-axis represent the orientation of long-axes distributed in classes from the north passing east to south. On all the graphs a preferred orientation is evident.

Fig. 4. Grafisk fremstilling af de 14 analyser. Hvert histogram angiver fordelingen af den procentuelle hyppighed på grundlag af 50 observationer. Abscissen angiver stenenes orientering i klasser på 10° hver.

data like linear distribution. Thus *H. Wadell* (1936) and *J. F. Lindsay* (1970) use the mode, or that point on the x-scale at which the concentration is the greatest. H. Wadell computes the mode according to the interpolation formula (*F. C. Mills*, 1924):

$$\text{Mode} = l + \frac{f_2}{f_2 + f_1} \times i \qquad \text{(I)}$$

where l = lower limit of modal class, f_1 = frequency of class next below modal class in value, f_2 = frequency of class next above modal class in value, and i = class-interval. However, from fig. 4 it will be noted that the frequency distribution may be evidently asymmetrical (e.g. No. 1, 5, 10, and 14). In such cases the mode misrepresents the "mean" of the long-axis strikes.

W. C. Krumbein (1938) suggests that the most significant "mean" to use is the arithmetic mean of the orientation values. Referring to *J. R. Curray* (1956), one of the difficulties which arises in such an anlysis is the necessity of choosing an origin in order to divide a circular distribution into a linear frequency curve. A rotation of origin may result in a considerable difference in the arithmetic mean calculated. In addition, if equally developed modes exist at right angles to each other the arithmetic mean will lie in an intermediate orientation and thus mislead the statement about the direction of preferred orientation.

To overcome problems of that kind *P. Reiche* (1938) presented a vector method of interpreting wind direction from measurements of cross-bedded sand. By this method the descriptive statistics used for prevailing orientation direction have the advantage of being independent of origin point. *W. C. Krumbein* (1939) applied the vector method to orientation data of pebbles. Unfortunately, in a 0° to 180° distribution, N and S components tend to cancel each other only, but no W components are present to annul E components. In order to overcome this problem, Krumbein doubled the angles of the class-midpoints, thus securing a nonsymmetric, periodic nature of the distribution (fig. 5). Subsequently, each radius vector is dissolved into components. The ratio of all the E-W components to all the N-S components is as follows:

$$\tan 2\,\overline{\theta} = \frac{\Sigma\, f \sin 2\,\theta}{\Sigma\, f \cos 2\,\theta} \qquad \text{(II)}$$

where θ = azimuth class-midpoint, $\overline{\theta}$ = azimuth of resultant vector, and f = frequency of observations in each group.

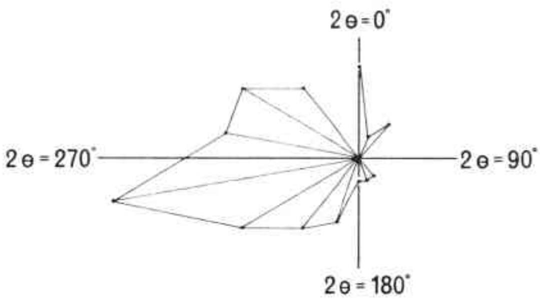


Fig. 5. Radius vector diagram of till pebble long-axis strikes for sample No. 7. θ = azimuth class-midpoint. The angles of the class-midpoints have been doubled in order to secure a nonsymmetric, periodic nature of the distribution.

Fig. 5. Radiusvektor diagram af orienteringen af længste akse for sten i analyse nr. 7 θ = klassemidtpunktet. Klassemidtpunkternes vinkel er fordoblet for at sikre en asymmetrisk, periodisk karakter i fordelingen.

Table I lists the calculated directions of preferred orientation of the 14 samples expressed by the following dimensions: a) the mode, b) the arithmetic mean based on a choice of origin at 0° and at 45°, respectively, and c) the resultant vector.

Some investigators call attention to the advantages of the radius-vector summation method mentioned, as it analyzes circular data directly in their circular form (*J. R. Curray*, 1956. *J. T. Andrews and K. Shimizu*, 1966. *J. W. Harbaug and D. F. Merriam*, 1968). Accordingly, this calculation method answers the present purpose at the best, and the direction of the resultant vector is used as a measure of prevailing orientation direction of pebbles.

The azimuth of resultant vector of the 14 sample varies from N 118°E to N 154°E, a range of 36°. The composite sample shows a preferred orientation in the direction N 138°E (fig. 6).

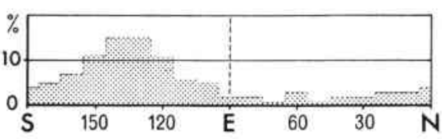


Fig. 6. Percentage frequency distribution of 700 till pebbles classified according to long-axis orientation. The resultant vector N138°E indicates the direction of preferred orientation.

Fig. 6. Den procentuelle hyppighedsfordeling af længste akses orientering for 700 sten. Stenorienteringsresultanten har retningen N138°Ø.

Re. 2. In addition to the resultant vector the observation dispersion about this value is essential as a measure of the degree of preference in the orientation data. Referring to *J. R. Curray* (1956) the calculation is as follows:

$$R = \sqrt{(\Sigma f \sin 2\theta)^2 + (\Sigma f \cos 2\theta)^2} \qquad L = \frac{R}{N} 100 \qquad \text{(III)}$$

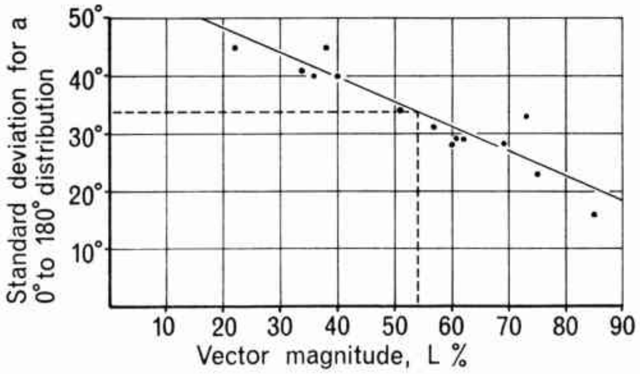


Fig. 7. Relationship between the magnitude of resultant vector and the corresponding standard deviation (corr. coef. = –0.93). For the composite sample the vector magnitude is 54 %. This value corresponds with the standard deviation 34°.

Fig. 7. Relationen mellem resultantvektorens størrelse og den tilsvarende standardafvigelse (korr. koef. = –0,93). For det samlede antal observationer (700) er vektorstørrelsen 54 %, hvilket svarer til en standardafvigelse på 34°.

in which the symbols f and θ have the same sense as in the former formula; R = magnitude of the resultant vector, L = R in terms of per cent, and N = number of observations in a sample. As the vector magnitude may vary from 0 per cent (in a uniform distribution) to 100 per cent (in case all the data lie within the same azimuth class) it is a sensitive measure of dispersion and is comparable with the standard deviation, but as pointed out by J. R. Curray, the vector magnitude is easier to compute since it is directly inferred from the calculation of the resultant vector (fig. 7). The magnitude of the resultant vector, listed in table I, varies in the present case from 22 per cent to 85 per cent, suggesting that estimation of regional variations of speed of the ice flow based on such evidence are questionable, e.g. the results reported by *S. A. Harris* (1968, 1969). The standard deviation for most till fabric generally lies between ± 20° and ± 50° (*J. T. Andrews and K. Shimizu,* 1966) corresponding with a vector magnitude between 85 % and 15 %.

Re. 3. A test of the significance of these results against a model of uniform distribution has been adopted from *J. R. Curray* (1956). No additional computations are involved as the test is a function only of the number of observations and the calculated dispersion. Actually this test originates from *Rayleigh* (1894) who devised a distribution for describing random phases in sound waves. But Curray made this test applicable to orientation data. The formula is:

$$P = [1 - e^{(-L^2 N)\,(10^{-4})}]\ 100 \qquad \text{(IV)}$$

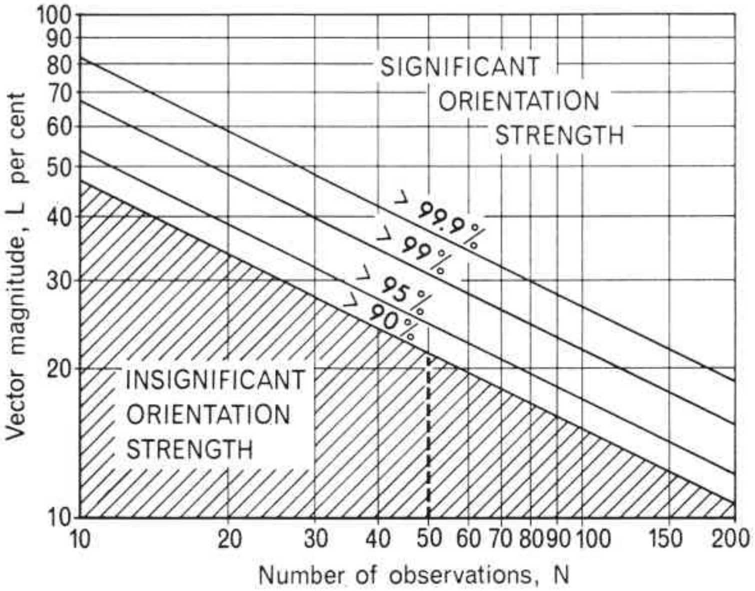


Fig. 8. Rayleigh test of signifiance.
Fig. 8. Rayleigh test på signifikans.

Table I. Summary of calculations of long-axis dip and strike measurements.

No.	Mode	Arithmetic mean		Resultant vector	Deviation between resultant vector and N138°E	Standard deviation	Vector magnitude	Level of signifiance	Dip of resultant vector to the sloping plane
		0-179	45-224						
1	N142°E	N126°E	N151°E	N150°E	12°	23°	75%	99,9%	6°SSE
2	141	124	142	140	2	28	60	99,9	10°SE
3	139	101	138	139	1	45	38	99,9	6°SE
4	127	134	125	126	12	33	73	99,9	8°SE
5	126	117	117	118	20	16	85	99,9	1°ESE
6	128	117	120	119	19	29	62	99,9	8°ESE
7	130	111	136	135	3	29	61	99,9	5°SE
8	145	103	146	151	13	41	34	99	8°SSE
9	136	124	141	143	5	28	69	99,9	9°SE
10	170	101	147	154	16	40	36	99	4°SSE
11	139	99	135	119	19	45	22	90	1°ESE
12	144	107	142	151	13	34	51	99,9	9°SSE
13	140	116	137	138	0	31	57	99,9	11°SE
14	151	119	134	139	1	40	40	99,9	6°SE
Mean	N135°E	N114°E	N136°E	N138°E	10°	34°	54%	99,9%	7°SE

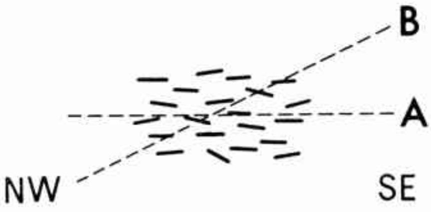


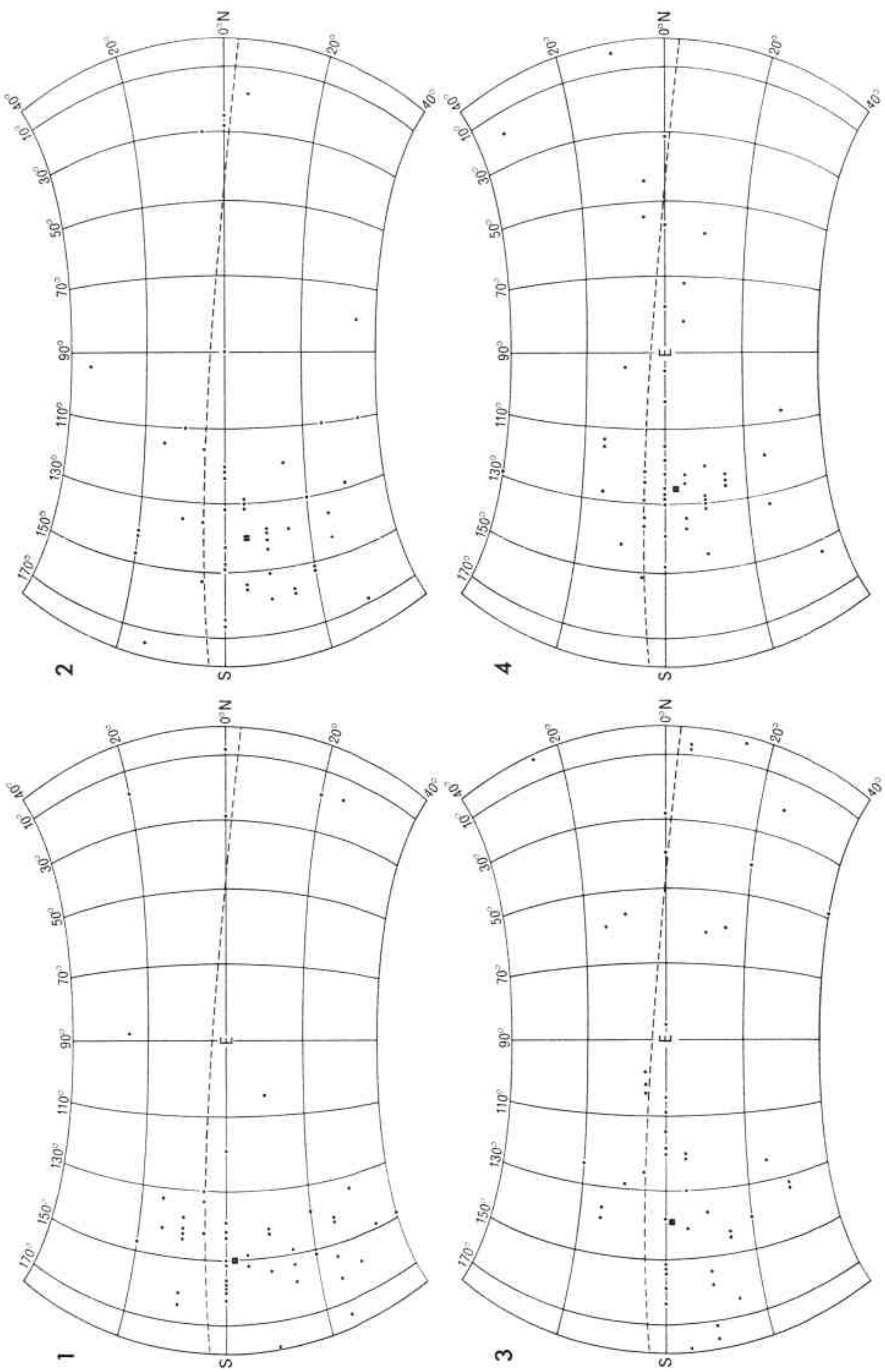
Fig. 9. Relationship between long-axis dip of till pebbles and two theoretical planes (A and B). The diagram illustrates the necessity of referring dip angles to a relevant plane.

Fig. 9. Forholdet mellem hældningen af stens længste akse og to teoretiske planer (A og B). Hvis hældningsvinklerne angives i forhold til det horisontale plan A, hælder akserne mod SØ og NV. Angives hældningsvinklerne derimod i forhold til det hældende plan B, vil alle de længste akser i det foreliggende eksempel hælde mod SØ. Diagrammet illustrerer således nødvendigheden af at referere hældningsvinkler til et relevant plan.

in which the symbols L and N have the same sense as in the former formula; P = level of significance in terms of per cent. Contrary to the chi-square test, where the deviations from randomness which produce a significant result do not necessarily represent a preferred orientation, the Rayleigh test indicates a difference from randomness only for a combination of individual class frequencies which give a certain vector magnitude, and thus a certain preferred orientation (*J. R. Curray,* 1956). The results of the test have been obtained from a graph (fig. 8) and are listed in table I. For all the samples, except for No. 11, the level of significance is very high indicating that a preferred orientation is a reality. Only sample No. 11 does not quite reach the level of significance usually accepted.

Statistical treatment of dip angles

In calculations and graphical presentations numerous investigators refer the long-axis dip of till pebbles to a horizontal plane (e.g. *C. D. Holmes,* 1941, *H. E. Wright,* 1957. *P. W. Harrison,* 1957. *J. F. Lindsay,* 1970). However, as pointed out by *J. T. Andrews and K. Shimizu* (1966), there is a possibility that a subglacial slope during deposition of till has exerted an influence and under such conditions a reference to the horizontal plane could result in a misleading statement. If e.g. the angles of dip are referred to the horizontal plane A shown in fig. 9, the long axes would dip towards the SE and the NW, respectively, and the fabric would show orthorhombic symmetry on a polar projection which is the usual method to presentate orientation data three-dimensionally. Otherwise, if the dip is referred to the sloping plane B, all the long axes would dip towards the SE in the present case. Quite another problem is to plot a horizontal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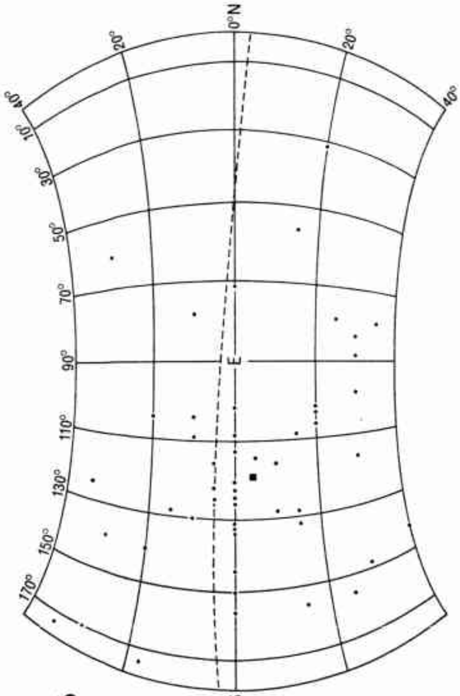
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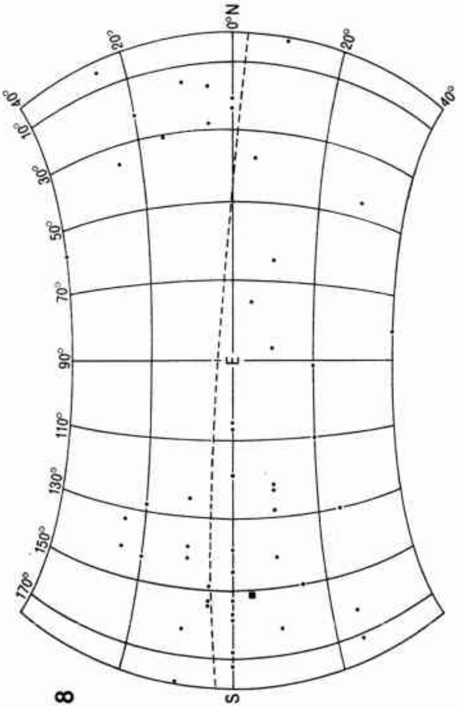
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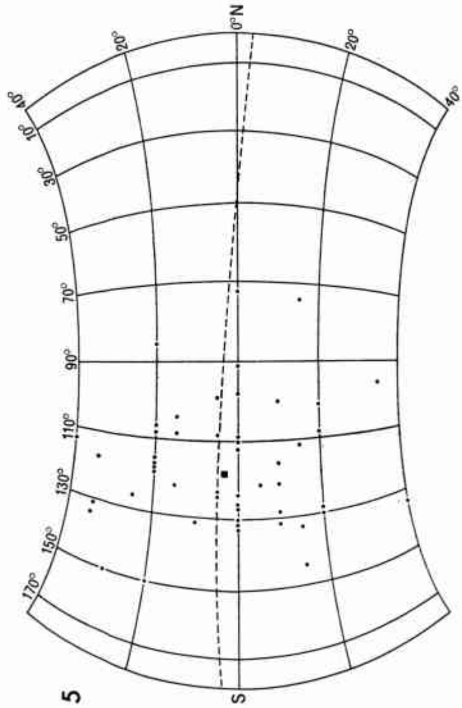
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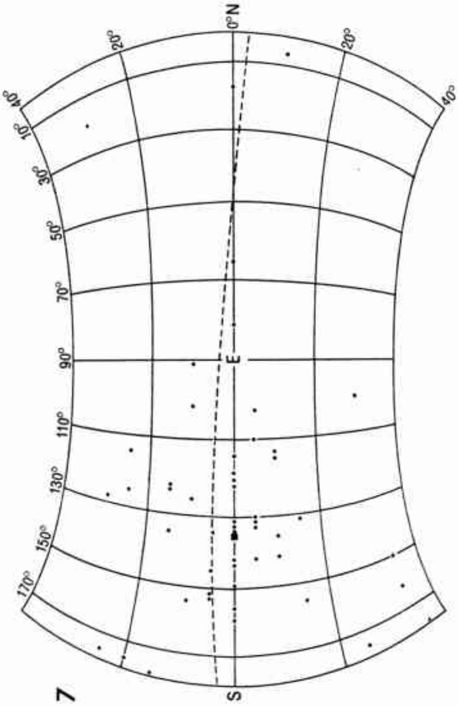
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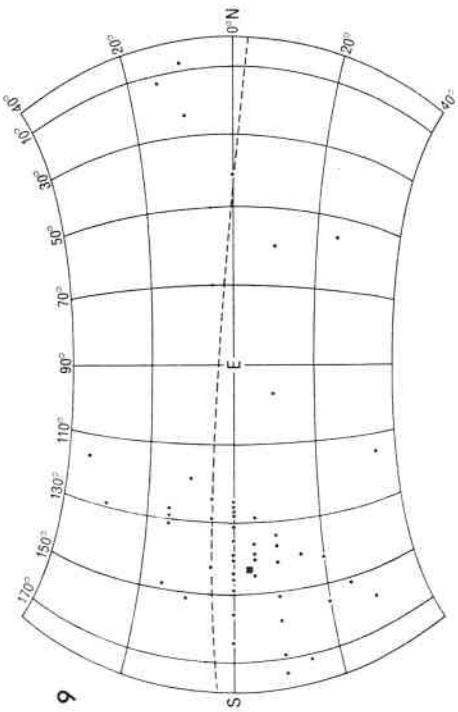
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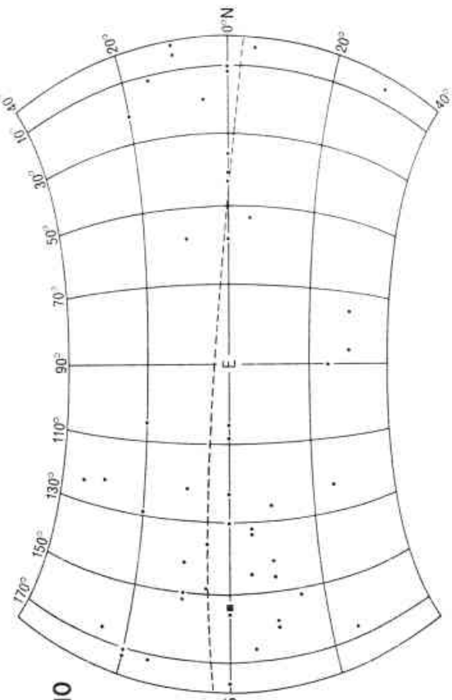
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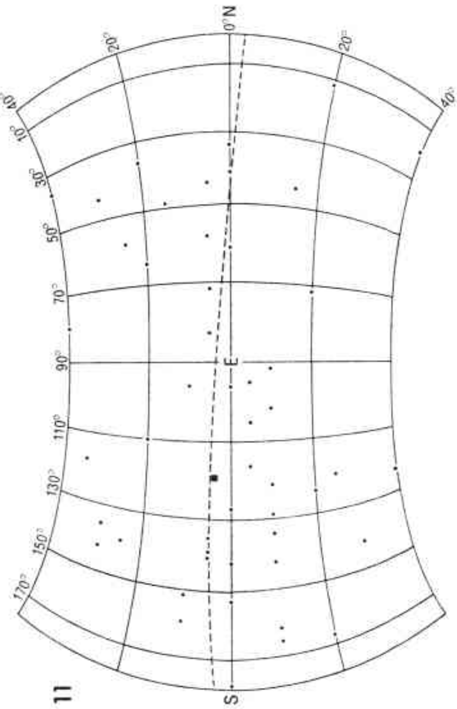
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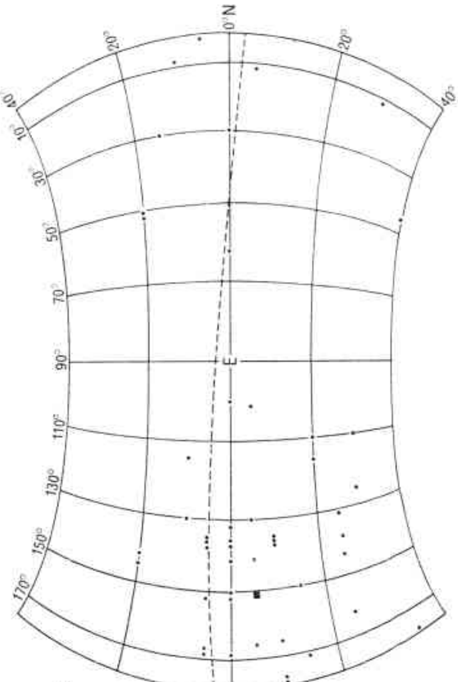
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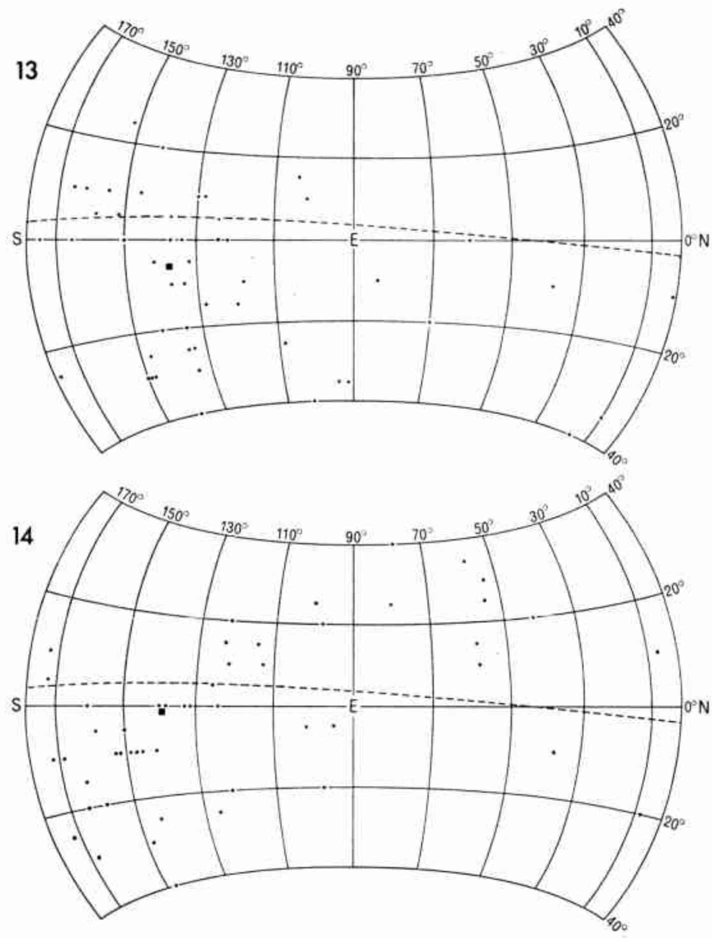

Fig. 10. Three-dimensional presentation of long-axis dip and strike measurements. The eastern part of a sphere is used. The hemisphere has been oriented with the north point to the right and the south point to the left. Hereby the zenith points upwards. On the line N-E-S indicating the intersection of the horizontal plane and the eastern hemisphere, the azimuth is shown ranging from 0° in the N to 180° in the S. The dip values 0°-40° are indicated by the parallels. The upper and the lower part of the hemisphere has been cut off since long axes dipping more than 40° were excluded from analysing. All the pebbles are imagined to be at the center of the sphere. The extension of the long axis of each pebble will pierce the hemisphere at one pole. Poles placed on the upper part of the equal area projection represent long axes dipping towards western direction (e. g. SW, W, NW). The dashed line represents the intersection of the subglacial sloping plane and the hemisphere. It is apparent that the resultant vectors shown by black squares dip 1°-11° towards ESE, SE or SSE in relation to this plane.

long-axis on polar projection as such an axis would be represented by two diametrically opposed directions.

To overcome the problems mentioned, the dip measurements are presented three-dimensionally as equal area projections in which the eastern hemisphere is used (fig. 10). The hemisphere has been orientated with the north point to the right and the south point to the left. Hereby, the zenith points upwards. On the line N-E-S indicating the intersection of the horizontal plane and the eastern hemisphere, the azimuth is shown ranging from 0° in the N to 180° in the S. The dip values 0°-40° are indicated by the parallels. All the pebbles are imagined to be at the center of the sphere. The extension of the long axis of each pebble will pierce the hemisphere at one pole. Poles placed on the upper part of the projection represent long axes dipping towards western directions (e.g. SW, W, NW).

A levelling of the limestone surface directed SE-NW shows a pronounced slope dipping 5° towards the NW (fig. 11). In fig. 10, the dashed line represents the intersection of this sloping plane and the hemisphere. It is worth noting that the great majority of the poles lie below this line.

The arithmetic mean dip of the resultant vectors has been calculated with reference to the sloping plane mentioned above. The resultant vectors shown by black squares in fig. 10 dip 1°-11° towards ESE, SE, or SSE. Concerning the composite sample the dip of the resultant vector is 7° towards the SE (fig. 11 and table I).

Glacial striae

The strike of the youngest system of striae observed on small fields in the norhernmost limestone quarry in the Fakse Banke is listed in table II.

The essential modelling of the rock surface is caused by an ice

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Fig. 10. Tredimensional fladetro gengivelse af længste akses hældning og orientering for sten, der indgår i analyserne 1-14. Det er kuglens østlige hemisfære, der anvendes. Hemisfæren er orienteret med nord mod højre og syd mod venstre. Herved peger zenith opad. På linien N-E-S, der er projektionen af skæringslinien mellem det horisontale plan og den østlige hemisfære, angives azimuth fra 0° ved N til 180° ved S. Hældningsværdierne 0°-40° angives af breddekredsene. Den øverste og nederste del af hemisfæren er udeladt, idet der i målingerne kun indgår sten, hvis længste akse hælder mindre end 40°. Alle stenene er tænkt placeret i centrum af kuglen. Forlængelsen af længste akse vil for hver sten skære hemisfæren i en pol. Polerne i den øvre del af hemisfæren repræsenterer sten, hvis længste akse hælder i vestlige retninger (f. eks. SV, V, NV). Den stiplede linie angiver skæringslinien mellem det subglaciale, hældende underlag og hemisfæren. Det fremgår af projektionerne, at stenorienteringsresultanten, angivet ved en sort kvadrat, hælder 1°-11° mod ØSØ, SØ eller SSØ i forhold til dette plan.

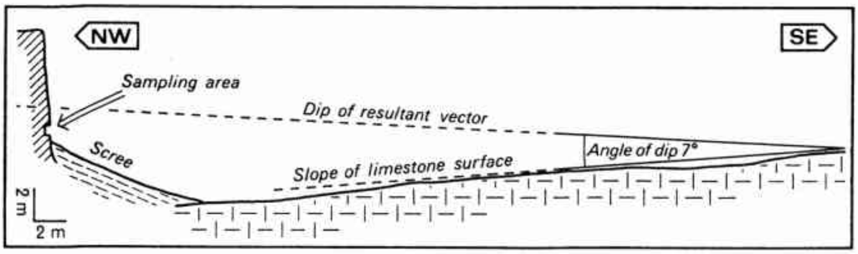

Fig. 11. Profile from the area investigated. The striated limestone surface slopes about 5° towards the NW. By this the resultant vector of the composite sample dips 7° towards the SE in relation to the sloping limestone surface which is synonymous with the former subglacial plane.

Fig. 11. Profil fra undersøgelsesområdet. Den isskruede kalkoverflade hælder ca. 5° mod NV. Herved hælder resultantvektoren for den samlede analyse 7° mod SØ i forhold til den hældende kalkoverflade, som er synonym med det tidligere subglaciale underlag.

movement from ESE (N 106°E) but the youngest and less conspicuous system of glacial striae directed from SE must be related to the deposition of the existing moraine bed, since the last-named system of striae occurs as a general feature. The strike of this system varies from N 124°E to N 150°E, a range of 26°, and the mean strike is N 134°E.

Many writers have described glacial striae from the Fakse Banke. In a study from the northern part of the limestone quarry, *G. Forchhammer* (1843) shows three systems of glacial striae:

1. The oldest and least conspicuous system: N 88°E
2. The most conspicuous system: N 108°E-N 113°E
3. The youngest and less conspicuous system: N 133°E-N 135°E

Based on several observations, *F. Johnstrup* (1882) assumed that N 106°E is the youngest of the glacial striae-systems. However, *O. B. Bøggild* (1899) and *V. Milthers* (1901) carried out some valuable work on glacial striae analyses resulting in a perception corresponding mainly with system No. 2 and 3 shown by G. Forchhammer.

Accordingly, *V. Milthers* (1908) discusses the formation of the striae and mention the direction N 124° E-N 149° E as the most prevailing of the younger systems. The studies made by Forchhammer, Bøggild and Milthers correspond with the observations exhibited in the present study. Thus it is substantiated that the youngest ice movement across the northern part of the Fakse Banke was mostly directed from SE (N 134°E).

Table II. Analysis of glacial striae.

Field number	The youngest system of striae	Remarks
I	N 139°E	Consists of striae and innumerable small scratches and constitute the main system. The surface slopes 5° towards the WNW*
II	N 125°E	Consists of striae and scratches crossing a very conspicuous E-W-system. The surface slopes 7° towards the E
III	N 136°E	Consists of scratches crossing an ENE-WSW-system. The surface is level
IV	N 135°E	Consists of few scratches and some striae crossing an ESE-WNW-system. The surface slopes 4° towards the SE
V	N 124°E	Consists of many striae and scratches crossing a conspicuous E-W-system. The surface slopes 8° towards the S
VI	N 132°E	Consists of few scratches crossing an E-W-system. The surface slopes 5° towards the SE
VII	N 150°E	Consists of striae and scratches crossing a SE-NW-system and an ESE-WNW-system. The surface slopes 2° towards the SW
VIII	N 134°E	Consists of many striae and scratches crossing an ESE-WNW-system. The surface slopes 4° towards the S
IX	N 136°E	Consists of many scratches crossing an ESE-WNW-system. The surface slopes 6° towards the E
X	N 133°E	Consists of few scratches. The surface is level
XI	N 130°E	Consists of many striae and scratches crossing an E-W-system. The surface is level

The average mean strike is N 134° E

* This field is shown by photo in a previous work (*J. Krüger*, 1969, fig. 11).

Interpretation

In the Fakse Banke analyses, the frequency distribution of the long-axis strikes of 700 till pebbles shows a pronounced orientation at N 138°E, well within the range of the youngest system of the glacial striae (N 124°E-N 150°E) and close to the mean strike of the striae (N 134°E).

According to the fact that the resultant vectors (N 118°-N 154°E) coincide approximately with the range of the striae mentioned, the preferred orientation of till pebbles is a reliable index of the direction of the glacier flow at the time of diposition (fig. 12).

It is possible that the individual fabrics may actually represent a deviation from the fabrics of the surroundings rather than represent the general characteristics of the moraine in the sampling vicinity. However, the composite sample including 700 pebbles shows an almost symmetrical distribution about the resultant vector suggesting that the deviations may be random and related to the moderate number of pebbles constituting the individual samples (fig. 6). In this connection it is relevant to mention observations made by *L. K. Kauranne* (1960). He found that the direction of preferred orientation may be considered constant when the horizontal interval between sampling areas does not exeed too many meters. If measurements are made on the same field but spaced some tens or hundreds of meters appart, the orientation varies (each sample consists of 100 stones).

In the present study the tests of significance show that 50 pebbles generally suffice to obtain a preferred axial orientation in the direction of ice movement. However, any preferred orientation of elongated pebbles may result from two diametrically opposed directions of ice motion. Under these circumstances the glacial striae are useful indicating a glacier flow from SE towards the NW at the time of deposition. By this, all the resultant vectors of the long-axis strike actually dip up-glacier with a low angle to the former subglacial slope (fig. 10 and 11). Attention is called to the fact that pebbles situated diagonally or transversly to the ice flow statistically hold a greater plunge than those with parallel orientation (i.g. sample No. 6, 8, 11-14).

At this stage the obtained results make it possible to estimate the process of formation of the till covering the Fakse Banke. According to *K. Richter* (1936), *H. E. Wright* (1957), and *P. W. Harrison* (1957) a preferential up-glacier dip may be related to shear planes dipping up-stream in the basal ice. Very often shear planes have

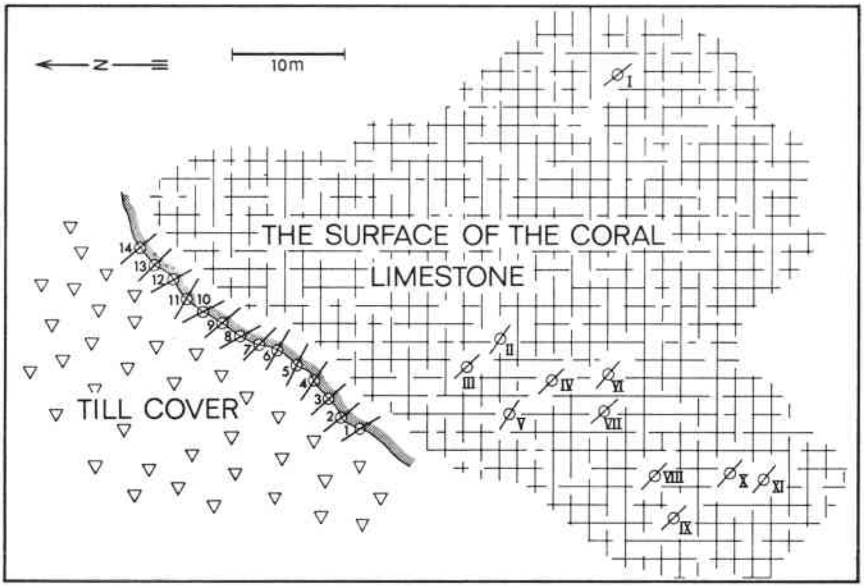

Fig. 12. Map of the area investigated. In the till exposure (hatched) the direction of resultant vector of each sample (1-14) is shown ranging from N 118°E to N 154°E. On suitable exposures of the limestone surface (I-XI) the orientation of the youngest system of glacial striae is indicated ranging from N 124°E to N 150°E. The two evidences of the final ice flow in this area – the glacial striae and the direction of preferred long-axis strike of till pebbles – show a striking accordance. Therefore, it is possible to relate pebble orientation to direction of ice movement with more confidence in these circumstances.

Fig. 12. Kort over undersøgelsesområdet. I moræneprofilet (skraveret) er angivet resultantvektorens orientering for hver analyse (1-14). Denne orientering ligger inden for N 118° Ø-N 154° Ø. På kalkoverfladen er på velegnede steder (I-XI) angivet orienteringen af det yngste skurestribesystem. Denne orientering ligger inden for N 124° Ø-N 150° Ø. De to vidnesbyrd om den sidste isbevægelse på denne lokalitet – skurestriberne og stenenes orientering i morænen – udviser en slående overensstemmelse.

been observed in ice cliffs at the ice cap margins. From Jættebrinken in Greenland *J. P. Koch and A. Wegener* (1911) reported: "Sie (die Grundmoräne) streckt sich zwar als zusammenhängende Eis- und Schmutzschicht die ganze Wand entlang; aber die Schmutzschichten gliedern sich in eine grosse Zahl oft kaum 1 Cm dicker Horizonte, die zwar parallel sind, aber doch häufig auskeiben und über einander greifen, ...". In the summer of 1969 the present writer saw debris-carrying shears exposed in face of ice cliffs at the margin of the Tungnaárjökull in Iceland. On the ablated ice surface successive moraine ridges formed a belt paralleling the ice margin. These ridges rose about 1-3 m above the general level of the ice surface. They are the result of ablation at the surface of debris-bearing shear planes

(*R. P. Goldthwait*, 1951). Shear planes contain debris in which long axes dip preferentially within the inclined dirt bands (*B. C. Bishop*, 1957).

In a recent study, *J. F. Lindsay* (1970) classifies long-axis clast fabrics into types essentially based upon the orientation of the dominant fabric mode as well as on the strength and the plunge of the dominant mode where it is parallel to the glacier-flow direction. A clast fabric is developed, partly during an englacial period, when the particles are being transported by the ice, partly during a depositional period, when the particles are released at the ice-sediment interface.

Concerning englacial clast fabrics, Lindsay reports orientation measurements on pebbles in massive ice from an ice tunnel within the temperate Casement Glacier in Alaska. The long-axis fabric presented a single maximum with an up-glacier dip of 20° to the horizontal plane. This plunge reflected the dip of nearby shear planes. *P. W. Harrison* (1956) describes fabrics from shear planes too. In a long-axis fabric diagram the pebbles show a single transverse mode. In addition, a broad secondary maximum is present with an up-glacier dip of 20°. Concerning the short-axis clast fabric diagram two modes are apparent. The strongest maximum plunged down-glacier at 64° approximately normal to the shear planes which plunge up-glacier at 37°. The weak maximum dipped up-glacier at 15°.

Lindsay regards ice as a tectonite and suggests that the orientation of pebbles is controlled generally by one or two shear domains. When a single shear domain is active (S 1) long-axis fabrics develop a single mode dipping up-glacier. In this position in which the minimum cross-sectional area lies normal to the ice flow, the pebbles offer the least resistance to the motion. When two shear domains are active (S 1 and S 2) the clast fabrics show a dominant mode parallel to the intersection of the two shear domains, i.e. transverse to the ice movement. Generally S 1 dominates and appears as shear planes.

Englacial clast fabrics may survive deposition from a stagnant ice and by deposition of the till to a great extent. If this is not the case, Lindsay suggests that pebbles may be reorientated during their deposition from active ice, partly by rolling at the interface, partly by shear deformation of the till beneath the interface, partly if the interface is at all irregular. The produced clast fabric possesses a broad subhorizontal mode parallel to the ice-flow direction and dipping up-glacier. The majority of the clast fabrics examined by Lindsay lies intermediately to the two extremes mentioned, as they have a definite mode dipping up-glacier but this mode is less regular than that of the englacial clast fabrics diagram. A transverse mode is barely perceptible on a few diagrams of the intermediate type.

The Fakse Banke analyses correspond mostly with Lindsay's intermediate to subglacial clast fabric diagrams with respect to average dip amount as well as to direction and strength of preferred long-axis strike. In addition,the state of the moraine corresponds to the characteristics of basal till (*G. Gillberg,* 1955). Thus it is assumed that the deposition of the till sheet lying over the limestone has taken place during a depositional period and from the base of active ice.

The direction of the "formless orientation elements", mentioned above, corresponds apparently with the major glacial topography of the Fakse Banke classing this rock-cored moraine feature with the directional landscape forms.

Laboratory procedure

The purpose of a further analysis is to determine the influence of physical properties of till pebbles on the orientation when the pebbles were deposited. From this point of view the pebbles have been divided into subgroups on the basis of four fundamental and clearly distinctive properties: 1) the geometric shape, 2) the sphericity, 3) the long-axis length, and 4) the roundness. Subsequently, the mean deviation of these subgroups has been compared.

Re. 1. Concerning their geometric shape the pebbles have been divided into 6 characteristic groups, elliptical (E), rectangular (R), wedge-shaped (W), rhombic (RH), triangular (T), and variform (V) (fig. 13).

Elliptical pebbles possess a convex outline. Rectangular pebbles have parallel faces and, in addition, blunt ends. Regarding wedge-shaped pebbles the outline forms an acute-angled isosceles triangle being symmetrical about the long axis. Rhombic pebbles hold parallel to subparallel faces ending in two acute angles opposite each other. Triangular pebbles show an obtuse-angled isosceles triangle. By this the long axis coincides with the base. Variform pebbles include particles which cannot be classed with the above mentioned shapes in a convincing way. Elliptical, rectangular as well as wedge-shaped pebbles are symmetrical about the long axis, whereas triangular and variform pebbles mostly are asymmetrical. Rhombic pebbles take up an intermediate position.

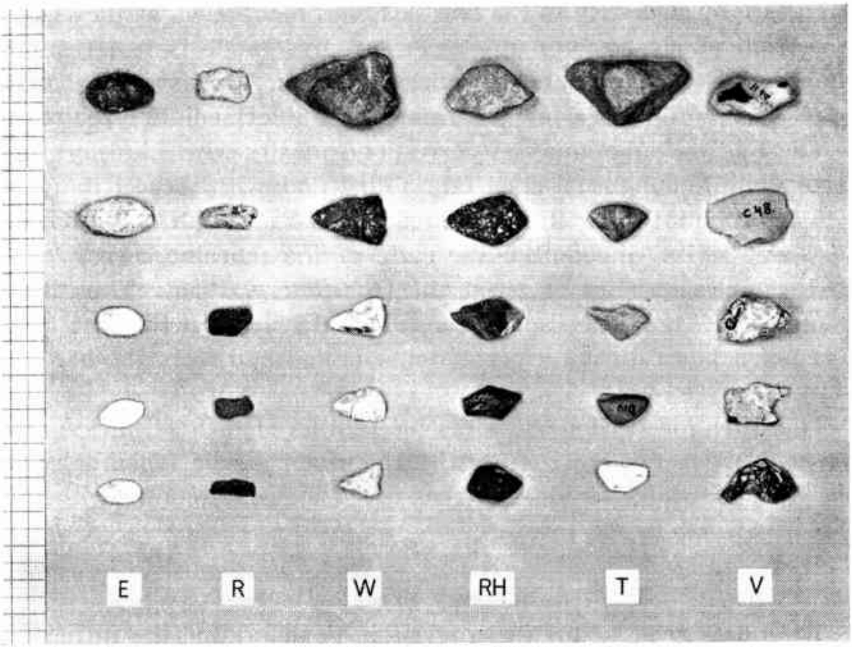

Fig. 13. Shape-classes of till pebbles. E = elliptical, R = rectangular, W = wedge-shaped, RH = rhombic, T = triangular, and V = variform.

Fig. 13. Form-klasser for sten fra moræne. E = elliptiske, R = rektangulære, W = kileformede, RH = rhombiske, T = triangulære og V = variforme.

Re. 2. The sphericity is expressed by the ratio d_n/D_s, where d_n denotes the true nominal diameter, and D_s represents the diameter of the smallest sphere circumscribing the particle (*H. Wadell,* 1932). Referring to *W. C. Krumbein* (1938) the nominal diameter of a particle is found by determining the diameter of a sphere having the same volume as the particle. The volume is determined by the common displacement method in a graduated cylinder filled with water. For small pebbles an ordinary burette is used. After measuring the volume, the corresponding diameter of a sphere of an equal volume is calculated by the equation $d_n = \sqrt{1.92\ V}$, where V is the volume. In the present case the value of sphericity varies from 0.77 to 0.24 with increasing deviation from the spherical form.

Re. 3. The long-axis length is synonymized with D_s or the distance between the two most distant peripherical points situated opposite each other.

Re. 4. H. Wadell (1932) proposed a method to measure roundness, but the task to quantify the degree of roundness is a rather time-con-

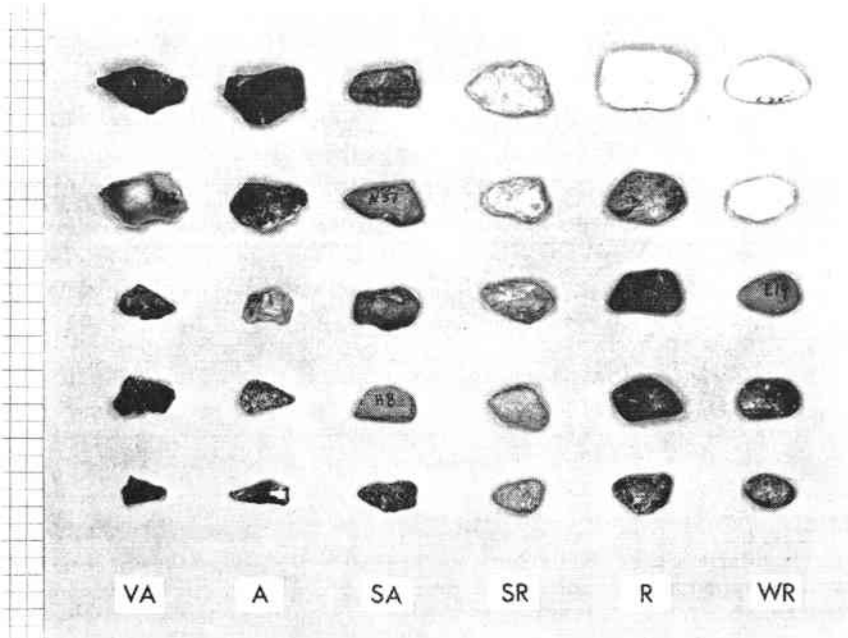

Fig. 14. Roundness-classes of till pebbles. VA = very angular, A = angular, SA = subangular, SR = subrounded, R = rounded, and WR = well-rounded.

Fig. 14. Afrundingsgrader for sten fra moræne. VA = meget angulære, A = angulære, SA = subangulære, SR = subafrundede, R = afrundede og WR = velafrundede.

suming work. A visual comparison chart for roundness is more acceptable in the present case (fig. 14). The 6 classes of roundness which follow are partly from *M. C. Powers* (1953) and *F. J. Pettijohn* (1957).

Very angular pebbles (VA) have sharp edges and corners. In addition there are numerous corners. Angular pebbles (A) possess little evidence of wear, as edges and corners are blunt only. Numerous corners are present. Subangular pebbles (SA) have numerous corners and edges and corners are rounded off to some extent. Original faces are practically untouched. Concerning subrounded pebbles (SR) edges and corners are rounded off to smooth curves, and the original faces are considerably reduced. Rounded pebbles (R) all have original edges and corners smoothed off to rather broad curves, but part of the original surface may be present. Well-rounded pebbles (WR) show no original faces, edges, or corners, as the entire surface consists of broad curves.

Interrelationship of properties

Theoretically, shape, roundness, long-axis length, and sphericity are to some extent only mutually independent. A particle, for instance, may possess a high degree of sphericity but no roundness, or be well-rounded without being a sphere. In natural sediment a close correlation between these properties of clastic particles is present. Fig. 15 A shows that the better rounded pebbles are also the more spherical. However, the mean sphericity is approximately the same for subrounded, rounded, and well-rounded pebbles. The results shown in fig. 15 B suggest that the marked correlation between roundness and sphericity is mainly caused by lithological differences between the roundness-classes, as roundness increases with decreasing hardness. Thus, very angular pebbles consist mainly of flint. Especially flint is often broken into fragments possessing low sphericity. Contrary to this, subrounded to well-rounded pebbles consist mainly of sedimentary rocks. As such they have been objects of modification to a great extent during the period when the particles were transported by the ice. Simultaneously with the smoothing off of the original faces, the sphericity increased. This is in accordance with

Table III. Gradually ordered sequence of deviation-producing properties of till pebbles. Inverse (–) or positive (+) correlation.

1. order	2. order	3. order
Elliptical	Long-axis length (–)	Roundness (+)
Rectangular	Sphericity (+)	Roundness (+)
Wedge-shaped	Sphericity (+)	Roundness (+)
Rhombic	Roundness (+)	Long-axis length (–)
Triangular	Long-axis length (–)	Roundness (+)
Variform	Roundness (+)	Sphericity (–)

Table IV. Mean long-axis length in relation to sphericity and shape classes.

Sphericity		0.30	0.40	0.50	0.60	0.70
Mean long-axis length (cm)	E + RH + T	–	1.8	1.9	1.7	1.8
	R + W + V	2.5	1.9	1.8	1.7	1.5

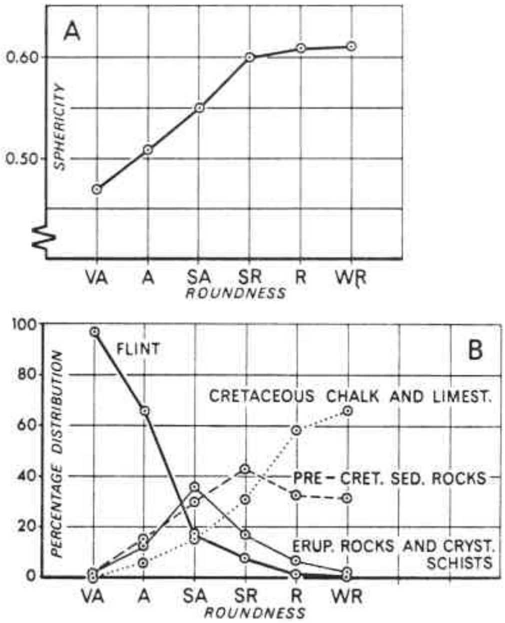

Fig. 15. Relation between roundness end sphericity (A) and relation between roundness and lithology (B). For sake of simplicity each dot in A shows the mean sphericity. The curves have been put in by eye to join the points solely to draw attention to the apparent relationsship.

Fig. 15. Relationen mellem afrundingsgrad og sfæricitet (A) og mellem afrundingsgrad og litologi (B). I A angiver hvert punkt den gennemsnitlige sfæricitet for sten i den pågældende afrundingsklasse. Kurverne forbinder blot punkterne for at understrege relationerne.

results reported by *J. W. Plumley* (1948) on the basis of studies in stream gravels.

Correspondingly, a correlation is apparent between shape and sphericity, as elliptical and rectangular pebbles statistically hold a higher sphericity – and consequently a higher degree of roundness – than those of other shapes (fig. 16 A). This is due to the fact that elliptical as well as rectangular pebbles – unlike wedge-shaped, triangular, and variform pebbles – mainly consist of soft rocks (fig. 16 B).

From fig. 17 a correlation is apparent between sphericity and long-axis length, as pebbles of high sphericity hold a mean long-axis length which is less than that of low-sphericity pebbles.

Order in which properties of till pebbles are deviation-producing

The next step is to determine the sequence in which the four selected properties are deviation-producing on the orientation of pebbles in relation to the direction of ice movement. The process is two-stepped. First shape, roundness, long-axis length, and sphericity have been correlated separately with the deviation. The deviation is synonymized with the difference between long-axis strike and direction N 138°E of resultant vector (fig. 6). As expected, shape holds the highest degree of correlation, and it is thus considered a property of

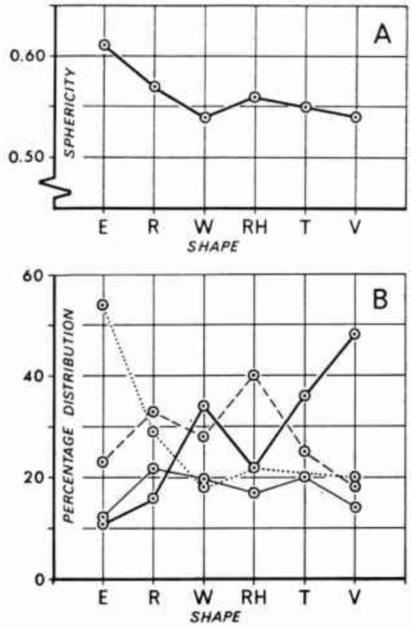

Fig. 16. Relation between shape and sphericity (A) and relation between shape and lithology (B). The signatures correspond with those in fig. 15.

Fig. 16. Relationen mellem form og sfæricitet (A) og mellem form og litologi (B). Signaturerne er de samme, som er anvendt i fig. 15.

first order. Secondly, for each shape-class the degree of correlation of respectively roundness, long-axis length, and sphericity to the deviation has been computed. About elliptical, rhombic, and triangular pebbles the long-axis length has a greater influence on the orientation than that of sphericity. With this the sphericity is excluded from further study. In the case of rectangular, wedge-shaped, and variform pebbles the opposite is evident (table III). Maybe this is

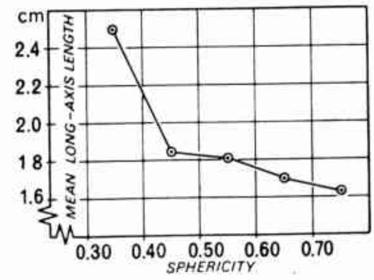

Fig. 17. Relation between sphericity and Long-axis length.

Fig. 17. Relationen mellem sfæricitet og størrelsen af længste akse.

partly due to the absence of a correlation between sphericity and long-axis length among elliptical, rhombic, and triangular pebbles. Contrary to this, among the other shape classes a close correlation exists between the two properties mentioned (table IV).

For elliptical, rectangular, wedge-shaped, and triangular pebbles the sphericity or the long-axis length is considered properties of second order. By this the roundness is a property of third order. Among rhombic and variform pebbles the opposite sequence is evident. The physical laws governing these differences will be discussed in more detail below.

Subdividing the composite group

Subdivisions of the composite group (700 pebbles) were established, first, on the basis of 6 shape characters, and secondly, according to 5 sphericity-degrees, or 4 degrees of long-axis length, and 3 roundness-classes (to obtain statistically significant subgroups roundness-classes have been combined two by two).

Table V shows: A) number of observations for each shape class, B) mean deviations in term of degrees from orientation parallel with the ice flow direction, and C percentage of observations with deviation greater than 34° from this direction (34° = standard deviation for the composite group). It is demonstrated that any radical variation in shape influences statistically the orientation. Thus triangular and variform pebbles hold a greater-than-average deviation, apparently because of their asymmetric shape about the long axis. Conversely, elliptical pebbles have a strong tendency to parallel the direction of the ice movement because of their streamlined form.

Table V. Shape in relation to deviation in orientation.

Shape	Elliptical	Rectangular	Wedge-shaped	Rhombic	Triangular	Variform
A	74	140	167	126	72	121
B	18°	24°	25°	26°	29°	32°
C	12 %	28 %	25 %	29 %	38 %	40 %

Table VI shows the subdivisions of the composite sample. A, B. and C have the same sense as in the former table. The statistical value of subgroups containing less than 7 pebbles (1 per cent of total) seems to be small since they depart irregularly from the values round about. Mean deviations greater than the average (26°) as well as values of more than 32 % are printed in bold-faced types (ideally 32 % of the observations in a symmetrical distribution deviate more than the standard deviation). According to the interrelationship of properties shown above only two elliptical pebbles are angular, as

Table VI A. Subdivisions of the composite sample.

SHAPE ▶	Elliptical				Rhombic				Triangular			
A	74				126				72			
Roundness ▶		VA–A	SA–SR	R–WR		VA–A	SA–SR	R–WR		VA–A	SA–SR	R–WR
▼ Long-axis length		2	21	51		34	72	20		22	37	13
>2.5cm	6		1	5	15	7	7	1	13	5	6	2
2.0–2.5cm	9	1	2	6	17	4	11	2	11	3	6	2
1.5–2.0cm	17		7	10	25	8	16	1	20	5	9	6
1.0–1.5cm	42	1	11	30	69	15	38	16	28	9	16	3
B	18				26				**29**			
▼ Long-axis length			16	20		20	**27**	**40**		**27**	**30**	**32**
>2.5cm					26	16	**35**		20			
2.0–2.5cm	14				26		20		26			
1.5–2.0cm	16		12	18	22	10	24		**32**		**35**	
1.0–1.5cm	21		21	22	**28**	**27**	**28**	**27**	**33**	**39**	**33**	
C	12				29				**38**			
▼ Long-axis length			5	16		18	29	**45**		32	**46**	23
>2.5cm					**33**	14	**57**		8			
2.0–2.5cm	0				24		18		**36**			
1.5–2.0cm	12		0	20	20	0	25		**40**		**56**	
1.0–1.5cm	14		9	16	30	**33**	29	**33**	**50**	**66**	**50**	

well as only a few observations constitute the subgroups of rounded clasts among variform pebbles.

Among elliptical pebbles increased deviation is apparent with increasing roundness. According to table III the influence of sphericity is very small. On the other hand the mean deviation decreases with increasing long-axis length. Thus, contrary to the sphericity the long-axis length controls the orientation of the elliptical pebbles.

It is concluded that a possible factor in the orientation stability of elliptical pebbles is their streamlined form as no edges and corners exist to be hit by obstructions. Such a form must reduce the influence of sphericity on the orientation. On the other hand, with decreasing long-axis length the angle will rise between the direction in which a streamlined pebble slides when striking an obstruction and that in which the pebble is able to pass. If the pebble has been rounded off to a great extent rolling might set in and the pebble assumes a transverse orientation. But as elliptical pebbles very often are a little

Table VI B.

SHAPE ▶	Rectangular				Wedgeshaped				Variform			
A	140				167				121			
Roundness ▶		VA-A	SA-SR	R-WR		VA-A	SA-SR	R-WR		VA-A	SA-SR	R-WR
Sphericity ▼		30	69	41		55	89	23		54	62	5
< 0.40	6	4		2	7	6		1	6	2	3	1
0.40 – 0.50	24	14	10		39	25	14		21	17	4	
0.50 – 0.60	49	8	30	11	64	22	37	5	65	27	36	2
0.60 – 0.70	54	3	26	25	55	2	38	15	28	7	19	2
0.70 – 0.80	7	1	3	3	2			2	1	1		
B	24				25				**32**			
Sphericity ▼		24	24	26		21	**28**	**27**		**32**	**33**	
< 0.40					24							
0.40 – 0.50	21	16	**28**		23	18	**34**		**35**	**32**		
0.50 – 0.60	23	**43**	19	23	26	23	**29**		**31**	**31**	**30**	
0.60 – 0.70	**28**		**27**	**27**	26		26	**28**	**35**	**31**	**36**	
0.70 – 0.80	**35**											
C	28				25				**40**			
Sphericity ▼		**33**	28	24		20	27	30		**35**	**40**	
< 0.40					29							
0.40 – 0.50	25	13	**40**		21	12	**36**		**38**	**35**		
0.50 – 0.60	29	**75**	17	27	25	23	27		**38**	27	**36**	
0.60 – 0.70	30		31	25	27		24	**33**	**43**	29	**47**	
0.70 – 0.80	**43**											

thicker at one end than at the other, the only stable orientation such pebbles can take is parallel to the ice movement.

Among rhombic pebbles the preference for parallel orientation decreases essentially with increasing roundness, as the tendency to rolling rises. It might be expected that the pointed ends would cause rhombic pebbles to slide past obstructions. However, since rhombic pebbles actually show less preference for parallel orientation than elliptical pebbles do, the frequently existing asymmetry about the long axis of rhombic pebbles presumably outweighs the "streamline effect" somewhat. The afore mentioned rules of rhombic pebbles are also applied to triangular clasts, only with the difference that triangular pebbles are more asymmetrical than rhombic pebbles. As rhombic as well as triangular pebbles have pointed ends the orientation is little influenced by sphericity, but the deviation increases with decreasing long-axis length.

Statistically rectangular pebbles hold a higher mean deviation than that of elliptical pebbles. Rectangular pebbles of low sphericity show a much stronger preference for parallel orientation than is shown by pebbles of high sphericity. But apparently, orientation is little influenced by roundness. The subgroup of 0.40-0.50 sphericity and of SA-SR roundness deviates exceptionally. As pointed out by *C. D. Holmes* (1941), the relative persistance in parallel orientation for rectangular pebbles is assumed to be controlled by the four principal surfaces parallel to each other. In addition, the absence of a streamlined form presumably cause the pebbles to turn around obstructions instead to slide past, as the prominent blunt ends catch obstructions. Therefore, among rectangular pebbles the sphericity and not the long-axis length controls the orientation. Experiments have shown that rectangular pebbles of low sphericity obtain again parallel orientation easier than those of high sphericity. Since rectangular pebbles mostly are bladed, rolling is difficult and thus roundness cannot outweigh the effect of existing flat surfaces.

Among wedge-shaped pebbles the mean deviation as well as the percentage of observations directed diagonally or transversly to the ice flow rises with increasing roundness. *J. F. Lindsay* (1970) demonstrates the motion of a wedge-shaped clast at the ice-sediment interface. The pebble is considered a segment of a cone rolling in a circular path through an angle to the ice flow direction. The only stable orientation occurs when the angular velocity is zero, i.e. an orientation parallel with the ice movement direction and with the base pointing down-glacier. Thereby, with reference to the rectangular pebbles, the sphericity has a greater influence on the orientation of wedge-shaped pebbles than that of long-axis length. The orientation of variform pebbles is only somewhat influenced by roundness and sphericity because of their heterogeneity.

As pointed out above, the subgroup of 0.40-0.50 sphericity and of SA-SR roundness deviates exceptionally from the values round about and this concerns rectangular, as well as wedge-shaped pebbles. An explanation hereof has not yet been found.

Interpretation

The foregoing analysis shows that till pebbles differ in statistical preference of orientation parallel with the ice flow according to their varying physical properties. The principal conclusions can be sum-

Table VII. Summary of table VI.

SHAPE ▶	Elliptical				Rhombic				Triangular			
	+				+				−			
Roundness ▶		VA–A	SA–SR	R–WR		VA–A	SA–SR	R–WR		VA–A	SA–SR	R–WR
Long-axis length ▼			+	+		+	(−)	−		(−)	−	(−)
> 2.5cm					(−)	+	−		+			
2.0 – 2.5cm	+				+		+		(−)			
1.5 – 2.0cm	+		+	+	+	+	+		−		−	
1.0 – 1.5cm	+		+	+	(−)	−	(−)	−	−	−	−	

SHAPE ▶	Rectangular				Wedgeshaped				Variform			
	+				+				−			
Roundness ▶		VA–A	SA–SR	R–WR		VA–A	SA–SR	R–WR		VA–A	SA–SR	R–WR
Sphericity ▼		(−)	+	+		+	(−)	(−)		−	−	
< 0.40					+							
0.40 – 0.50	+	+	−		+	+	−		−	−		
0.50 – 0.60	+	−	+	+	+	+	(−)		−	(−)	−	
0.60 – 0.70	(−)		(−)	(−)	+		+	−	−	(−)	−	
0.70 – 0.80	−											

marized as follows: 1) Streamlined pebbles show strong preference for parallel orientation. Conversely, increasing asymmetry in shape markedly reduces this preference. This is in accordance with *C. D. Holmes* (1941). 2) Among shapes with pointed ends directed down-glacier (thus elliptical, rhombic, and triangular pebbles) long-axis length influences the orientation more than sphericity does. Increasing long-axis length rises the chance of parallel deposition. Accordingly Holmes found that elliptical ("ovoid") pebbles of minimum length 5 cm show strong tendency for parallel orientation. 3) Among shapes with prominent blunt ends pointing down-glacier sphericity influences orientation more than long-axis length does. Accordingly decreasing sphericity rises the chance of parallel deposition. Contrary to this, Holmes concludes that the more elongate a stone is the more readily the long axis assumes transverse orientation. 4) Regarding nearly all shape-classes, roundness seems to influence the orientation as the tendency to assume an orientation parallel with the ice flow decreases with rising roundness. This corresponds partly with observations made by Holmes.

On the basis of the present analysis it is now possible to select subgroups of till pebbles very suitable for future orientation analyses in order to determine the direction of ice flow at the time of deposition. In table VII "minus" indicates subgroups deviating more than 26° as well as the percentage of observations deviating more than 34° exceeds 32. Contrary to this, "plus" indicates subgroups deviating less than 27° as well as observations deviating more than 34° make up less than 33 per cent. "Minus" in brackets shows subgroups of intermediate suitability. The thick lines separate selected pebbles or "guide forms" from subgroups unqualified to show direction of ice flow. Pebbles considered "guide form" are the following: 1) Elliptical pebbles. 2) Rectangular pebbles of sphericity less than 0.70. 3) Wedge-shaped pebbles, very angular to subrounded, and of sphericity less than 0.70, as well as rounded to well-rounded pebbles of sphericity less than 0.60. 4) Rhombic pebbles, very angular to subrounded, and with a long-axis length greater than 1.5 cm, as well as rounded to well-rounded pebbles with a long-axis length greater than 2.5 cm. 5) Triangular pebbles with a long-axis length greater than 2.5 cm. 6) Where nothing else is mentioned the pebbles have a long-axis length greater than 1 cm and the ratio between the long and the intermediate axis is at least 1.50.

As pointed out by Holmes, the limitation of "guide forms" must not be ignored, as their orientation preference is only statistical and relative. This is demonstrated by fig. 18 in which A and B indicate the percentage frequency distribution of 275 "unqualified" pebbles and 425 "guide forms", respectively.

Final remarks

The investigation shows that the Fakse Banke moraine consists of till deposited by basal ice, as the till fabrics are systematically oriented in the direction of the ice flow as well as they preferentially dip up-glacier with a low angle to the former subglacial slope. Furthermore, the study demonstrates that pebbles symmetrical about their long axis statistically indicate the ice movement direction more precisely than others. In addition, among shapes with pointed ends directed down-glacier, angular pebbles exceeding a certain long-axis length have a great chance for parallel deposition. In a similar way, within shape-classes with prominent blunt ends in the down-glacier direction, angular pebbles of low sphericity statistically show a preference for parallel orientation. Thus it must be concluded that by use of "guide forms" in orientation analyses a more precise statement can be achieved about the direction of ice movement than other-

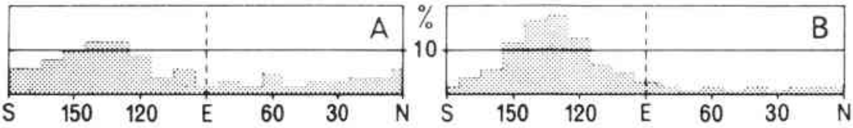

Fig. 18. Percentage frequency distribution of 275 "unqualified" till pebbles (A) and 425 "guide forms" (B) classified according to long-axis orientation. The diagrams demonstrate that the differentiation of "unqualified" till pebbles and "guide forms" is statistical and relative only.

Fig. 18. Den procentuelle hyppighedsfordeling af længste akses orientering for 275 „uegnede" sten (A) og 425 „ledeformer" (B). Diagrammerne viser at differentieringen mellem „uegnede" sten og „ledeformer" kun er statistisk og relativ.

wise possible. Attention is called to the fact that the present work is a pilot study and that further investigations will be needed before satisfactory generalizations of till fabric can be formulated.

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RESUMÉ

Denne artikel behandler variationen i moræenens tekstur på en given lokalitet (Fakse Banke, fig. 1-2), samt relationen til isens bevægelsesretning på det tidspunkt moræenen aflejredes. Undersøgelsen er delt i to trin:

A. Diagrammer af 14 stenanalyser fra en uforstyrret moræneaflejring beskrives med hensyn til længste akses orientering og hældning (fig. 4, 6 og 10). Sten, der indgår i analysen, har en længde på 1-10 cm og forholdet mellem længste og intermediære akse er mindst 1,50. Desuden er kun benyttet sten, hvis længste akse hældede mindre end 40°. Den statistiske behandling af orienteringsmålingerne omfatter:

1. Retningen for fremherskende orientering. Hertil er benyttet radiusvektor summationsmetoden (fig. 5, formel II side 140 og tabel I).
2. Hvor udpræget denne orientering er. Dette udtrykkes gennem resultantvektorens størrelse (fig. 7, formel III side 141 og tabel I).
3. Sandsynligheden for at denne orientering ikke er tilfældig. Hertil er anvendt Rayleighs test på signifikans (fig. 8, formel IV side 142 og tabel I).

Undersøgelsen viser, at stenene i moræenen systematisk er orienteret parallelt med retningen af yngste skurestribesystem på den nærliggende kalkoverflade (fig. 12 og tabel II) og således angiver orienteringen

af isens bevægelse. Dertil kommer, at stenorienteringsresultanterne hælder få grader mod isens bevægelsesretning i forhold til det svagt skrånende, subglaciale plan (fig. 10-11). Det konkluderes, at moræenen på Fakse Banke er aflejret subglacialt af en fremadglidende ismasse.

B. Der redegøres for den indflydelse, stenenes fysiske egenskaber har haft på orienteringen i aflejringsøjeblikket (fig. 13-17 og tabel III-IV). Denne del af undersøgelsen viser:

1. Strømlinieformede sten har stærk tendens til parallel orientering. Denne tendens aftager betydeligt blandt stenformer med stigende asymmetri omkring længste akse (tabel V).
2. Blandt stenformer, hvor en mere eller mindre udtalt spids ende peger i isens bevægelsesretning (således elliptiske, rhombiske og triangulære sten), har stenenes absolutte længde stor indflydelse på orienteringen (tabel III). En større længde medfører en øget chance for parallel orientering (tabel VI).
3. Blandt stenformer, hvor en bred, stump ende peger i isens bevægelsesretning (således rektangulære, kileformede og delvis variforme sten), har derimod sfæriciteten indflydelse på orienteringen (tabel III). Med aftagende sfæricitet stiger tendensen til en parallel orientering (tabel VI).
4. Indenfor næsten alle formklasser influerer afrundingsgraden på orienteringen, idet tendensen til en orientering parallel med isens bevægelsesretning øges med stigende angularitet (tabel VI).

Sluttelig er udskilt „ledeformer" særligt velegnede til at indicere isens bevægelsesretning til brug i fremtidige stenorienteringsanalyser (tabel VII og fig. 18).

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