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Till Fabric

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TILL FABRIC

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by
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Abstract

Till fabric was noticed as early as 1859. Several geologists described it in the latter part of the nineteenth century. However, the concept of a fabric in till was not generally accepted until 1932 when Konrad Richter noted a preferred orientation of till particles in Northern Germany. He supported his findings with statistical data. Comprehensive studies were published by W. C. Krumbein and especially C. D. Holmes a few years later. Extensive work on the subject was conducted by several geologists in the 1950's.

Till fabric is classified as macrofabric and microfabric. The latter is further classified as (1) microfoliation, (2) coarse fragment orientation, and (3) veining.

Several methods used in collecting and measuring the orientation of the particles are discussed. In most cases the particles are reoriented in the labratory.

The data may be plotted either on a "rose diagram" or the conventional "petrofabric diagram." The former allows only the azimuths of the particle axes to be plotted while both the azimuths and dips may be plotted on the latter.

The long axes of till particles is commonly oriented parallel to the direction of glacier flow. However, several geologists have found a transverse orientation of these axes. The shape, roundness, and amount of axial dip of the particle determines its orientation.

Several theories as to the genesis of till fabric are discussed. It is concluded that the theory which is proposed by Holmes is the most acceptable. Parallel orientation of the long axis is believed to be due to a sliding movement of the particle and transverse orientation to a rotating movement.

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Introduction

General Statement

The study of till fabric has proven to be an invaluable tool aiding in the understanding of the directional properties and depositional dynamics of till. The fabric of till has proven to be a useful criterion in determining the direction of glacial movement. Holmes (1941, p. 1301) says that "data from till stone orientation may be as essential as those from striae on bedrock beneath the till." As Flint (1947, p. 107) has aptly stated: "The study of till fabric involves arduous and painstaking effort, but it offers a relatively new field of geologic research from which significant results may be confidently expected."

History

Earliest Recognition of Till Fabric

Preferred orientation of imbedded pebbles in till was recognized as early as 1859 (fide, Flint, 1957, p. 113).

Hugh Miller, Dugald Bell, and Warren Upham were amoung the first to detect a preferred orientation of till particles, according to Holmes (1941, p. 1301-1302).

Miller, in 1884, was probably the first to publish critical observations on anisotropic fabric of tills near Edinburgh, Scotland. He described the "boulder pavement" in this area and noted that the longer axis of the till particles is often directed in the line of glaciation.

In 1888, Bell noted the same phenomenon and concluded that "the tendency of boulders on all glaciers is to assume a longitudinal position."

Although Upham did not record any systematic investigation, he noted in 1891 that flat pebbles imbedded in till tended to lie parallel with the surface of deposition.

G. K. Gilbert (1898, p. 772), whose work on the subject has seemingly been unrecognized by subsequent workers, studied "boulder pavement" near Wilson, New York. In this area he recognized two units of till which were separated at the top of the lower unit by boulders. Gilbert (p. 773) states that "all the boulders strongly glaciated on their upper surfaces were found to have one diameter less than the others, and to lie in such position that the least diameter was vertical."

<u>Prevailing Attitude on Till Fabric from the 1890's to 1930's</u>

The observations of the early workers on till fabric seemingly went unnoticed from the latter part of the nineteenth century to 1932. Geikie (1893, p. 1032) describes till or "boulder-clay" as "unstratified, its material being irregularly and tumultuously heaped together." Pirsson and Schuchert (1915, p. 134), describe it as "consisting of confused debris tumbled together." Twenhofel (1932, p. 86) probably reflects the general consensus of this time by stating that "ground moraine consists of unstratified, unorganized material." This opinion of anisotropic orientation of till particles prevailed until the works of Konrad Richter (1932, 1933, 1936) were published.

<u>Revival and Expansion of Studies from 1932 to 1941</u>

Richter in 1932, 1933, and 1936 published what is probably the first important works on till fabric (<u>fide</u>, Holmes, 1941, p. 1302). He was the first to support his conclusions with quantitative, statistical data. In northern Germany he found that the long axes of particles imbedded in till tended to parallel the direction of striae on glacial boulders in the area. Richter, as did Holmes, (1941), also noted that many of the larger particles tended to have an orientation tranverse to glacier flow. Thus, Richter believed that the parallel orientation was the result of action from later meltwater streams which were competent to reorient the smaller particles but not the larger ones.

Krumbein in 1939 published what is probably the first statistical data on till fabric in this country. Krumbein 1939, pp. 682-683), studied glacial till near Random Lake in eastern Wisconsin and concludes that pebbles in glacial till in this area exhibit a preferred orientation parallel to glacier flow. The average trend of a field of drumlins in this area was determined to be 382° W. The glacier, he presumes, traveled from east to west from the Lake Michigan basin. He notes that the long axes of the pebbles in till were generally in an east-west direction.

Holmes, (1941), who studied till in central New York, published one of the most comprehensive studies on till fabric. He observes that (1941, p. 1301), "there is a tendency of imbedded stones in glacial till to lie so that their longest dimensions or axes approximately coincide with the direction of glacier flow at the time of deposition". He concludes that parallel orientation of the long axes was acquired by the sliding of the particles in contact with the till floor. He notes, as did Richter, that in a few localities the dominant preference of long axes orientation was perpendicular to glacier flow. He believes that Richter's hypothesis on reorientation of particles by meltwater is not valid in the area of central New York.

This area is composed mostly of clays and lacks lenses of silt and sand and other evidences of vigorous meltwater stream action. Holmes concludes (p. 1302) that perpendicular orientation of the long axes of till particle to glacier flow is due to rotation.

<u>Studies on Till Fabric from 1941 to 1957</u>.

Studies from 1941 to 1957 on till fabric include

Dreimanis and Reavley, (1953), Sitler and Chapman (1955), and Harrison (1957).

Dreimanis and Reavley (1953, p. 243), who studied tills along the north shore of Lake Erie, found by statistical analysis that the particles in till were either parallel or transverse to glacier flow; their results were similar to those of Holmes.

Sitler and Chapman (1955) made studies on the microfabrics of till from Ohio and Pennsylvania. They classify and discuss three types of microfabric. These are: (1) microfoliation (2) coarse fragment orientation, and (3) veining.

Harrison (1957) studied the fabric of tills around Chicago, Illinois, and the fabric of englacial debris from the Greenland icecap near Thule, Greenland. Many of his results are not consistent with Holmes' work, and he disagrees with many of Holmes' concepts.

Harrison (1957, p. 285) also made microfabrics studies of the tills around Chicago and noted that the orientation of the long axes of microscopic grains corresponds to that of long axes of larger particles.

Purpose and Scope

It is the purpose of this paper to discuss: (1) classification of till fabric, (2) methods used in the collecting and measuring the orientation of till particles, (3) methods used in plotting the data, (4) various analyses of till fabric, and (5) theories on the genesis of till fabric. The same methods used in collecting and measuring the orientation of the particles and plotting the data used in determining macrofabric are not applicable to microfabrics. Therefore, the methods which are used in microfabrics are considered separately.

Acknowledgments

The writer wishes to express his appreciation for

the personal guidance and helpful criticism rendered by Professor F. D. Holland, Jr.

Classification of Till Fabric

Macrofabric

Macrofabrics of till may be defined as the orientation, or lack of it, of the particles found in glacial till which is determined without the aid of a microscope.

The bulk of the material written on till fabric has been determined by macrofabric studies. In these studies the shape and roundness of the particles are recorded to determine whether or not a relationship exists between these characteristics of these particles and their orientation.

Classification of the particles

Holmes (1941, p. 1306) classified each particle he collected into one of six major forms. These are: (1) discoid, (2) ovoid, (3) tabular, (4) wedge form, (5) rhombohedroid, and (6) varihedroid. He defines rhombohedroids as particles having "two sets of parallel or subparallel sides, the ends being either regular or irregular"; varihedroids as particles with "surfaces too irregular, unsymmetric, or nodular to be assigned to any other form."

Holmes (1941, p. 1306) also classified the particles according to four roundness classes. Table 1 shows these classes and the corresponding class limits proposed by Wentworth (1922).

TABLE 1

ROUNDNESS CLASSES
(from Holmes,1941,p.1305)

Holmes's (1941) Roundness Classes	Wentworth's (1922) Class Limits
Sharply angular	0.00 - 0.01
Slightly rounded	0.02 - 0.20
Moderately rounded	0.21 - 0.30
Well rounded	0.31 - 1.00

Harrison (1957, p. 277) classified the till particles into three shape classes. Table 2 shows these classes and the axial ratios used by Harrison as compared to the axial ratios of the same shapes according to Zingg's classification. The roundness of the particles was not considered by Harrison.

TABLE 2
SHAPE CLASSES
(from Harrison, 1957b., p.277)

Shape Classes	Harrison's Axial Ratio*	Zingg's Axial Ratio
Disks	$b/a > 2/3$ $c/b < 1/2$	$b/a > 2/3$ $c/b < 2/3$
Blades	$b/a < 2/3$ $c/b < 1/2$	$b/a < 2/3$ $c/b < 2/3$
Rods	$b/a < 1/3$ $c/b > 2/3$	$b/a < 2/3$ $c/b > 2/3$

* a = long axis; b = intermediate axis; c = short axis

Selection of the Particles

Only till particles of designated sizes and shapes have been recorded by various workers for macrofabric studies. Holmes (1941, p. 1305) recorded only particles more than 0.5 cm. thick, except tabular particles whose length and width were 3 cm. or greater. Harrison (1957b., p. 277) recorded only the orientation of particles with sizes ranging from 3 to 40 mm. Most of Harrison's measurements of orientation were made on disk-shaped particles and only a few on blade-shaped and rod-shaped particles. The latter two were less numerous than disk-shaped particles in the till he studied.

Microfabric

Microfabrics of till may be defined as the orientation, or lack of it, of particles found in glacial till which is determined with the aid of a microscope.

Extensive work on microfabrics was conducted by Sitler and Chapman in 1955. Harrison (1957b., p. 285) uses the study of microfabric as a supplement to the study of till macrofabric.

Classification of Microfabrics

Sitler and Chapman (1955, p. 262) classify microfabrics according to three types. These are (1) microfoliation, (2) coarse fragment orientation, and (3) veining.

Microfoliation

Microfoliation is defined by Sitler and Chapman (p. 262) as an "aggregate parallelism of silt flakes and silt grains." "Silt grains" are subangular, slightly elongate grains of silt-size ranging from 0.02 to 0.06 mm. and "silt flakes" are micaceous minerals with an average size of about 0.03 mm. They found that a large percentage of silt flakes possesses parallel orientation when the silt grains are very elongate.

Coarse Fragment Orientation

Coarse fragment orientation is a texture composed of larger particles than those of microfoliation or veining. These particles can be seen by the naked eye, however. The orientation is determined with the aid of a microscope. It was noted by Sitler and Chapman (1955, p. 264) that this type of fabric is similar to microfoliation.

Veining

Veining is a microfabric which exhibits a branching, braided, or parallel pattern of silt flakes and silt grains. The veins are generally disconnected and highly irregular.

Size of particles studied and methods of study

Harrison (1957b., p. 285) made thin sections in the vertical plane parallel to the direction of preferred orientation as determined by macrofabrics. Only particles larger than 0.08 mm. were considered by Harrison and most of them were 0.1 to 0.2 mm. in size. He only recorded the orientation of particles with an axial ratio of 3:1 or greater.

Sitler and Chapman (1955, p. 261) made three thin sections cut parallel to the north-south vertical plane, east-west vertical plane, and horizontal plane of each oriented sample. As mentioned earlier, the "silt flakes" they studied averaged about 0.03 mm. and the "silt grains" were about 0.02 to 0.06 mm. The individual "veins" they found averaged about 0.1 mm. wide and 20-30 mm long.

Methods of Collecting and Measuring the Orientation of the Particles

Various methods have been devised to collect and measure the orientation of particles in till. In all cases the samples were taken in undisturbed till and below the zone of frost action. The first method discussed involves the direct determination of orientation of the particles in the field. The second, third and fourth methods discussed involve: (1) the collection and marking of the orientation of the sample in the field and (2) the reorientation of the sample in the laboratory and the measurement of the orientation.

Holmes's Method

Holmes (1941, p. 1307) used a mattock to prepare a horizontal surface about 2 feet long and one foot wide in an exposure of undisturbed till. Successive layers were removed until the desired number of stones to be measured were obtained. The stones were then carefully uncovered, so as not to disarrange them.

The long axes of the till stones were determined by holding an orientometer bar (Fig. 1) horizontally above the exposed particle and parallel to a reference rod (a straight wooden rod placed on the bank above the working surface and oriented north-south). The scale beam (Fig. 1) was then rotated until it coincided with the trend of the long axis of the particle. The direction was then read to the nearest 5 degree interval. The dip of the long axis was determined by holding the orientometer bar horizontally and rotating the scale beam until the beam was parallel with the dipping axes of the particle.

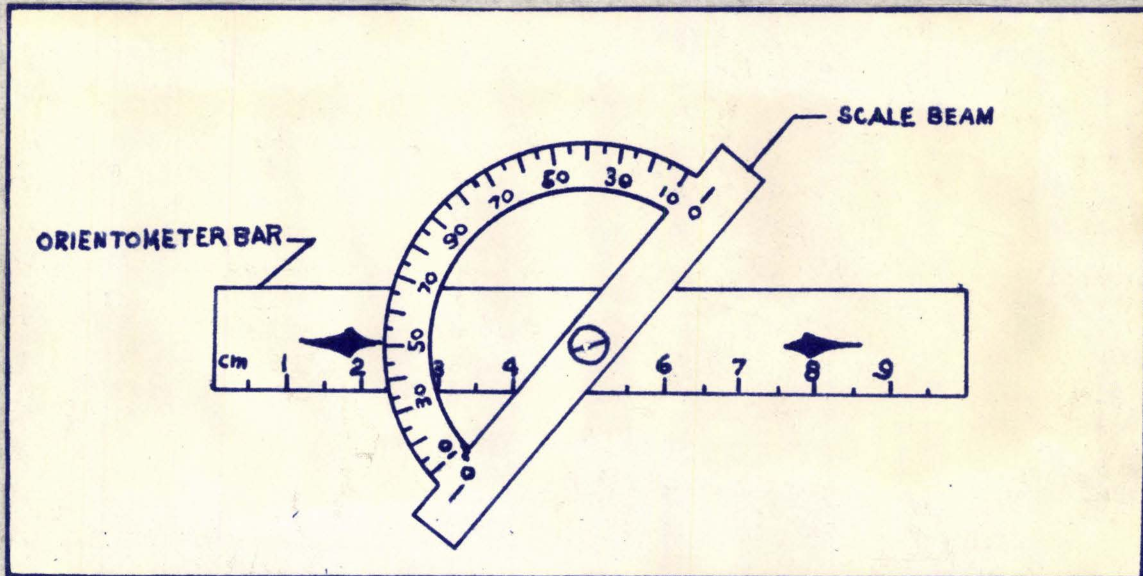

Fig. 1 - Diagram of an Orientometer. (from Holmes, 1941, p. 1345).

Krumbein's Method

Collection in the field.

Krumbein (1939, p. 675), used a 5 x 6-inch rectangular wooden frame (Fig. 2) to collect the pebbles from glacial till. A horizontal and a vertical brass rod is inserted in the frame to form a cross. A small spirit level is fastened to the lower right side of the frame so that it is level when the horizontal brass rod is level. The frame is then placed upright, level, and parallel to the outcrop face so that the point of intersection of the brass rods is in front of the imbedded pebble. A line is then drawn on the pebble in the form of an "L" by guiding the pencil along the right of the vertical bar and above the horizontal bar. This line is drawn around edges and curves on the pebble so that the "L" forms a right angle when viewed with the eyes at the intersection of the rods.

The strike of the outcrop face is then determined by a compass and is expressed as an azimuth on the observer's left as he faces the outcrop.

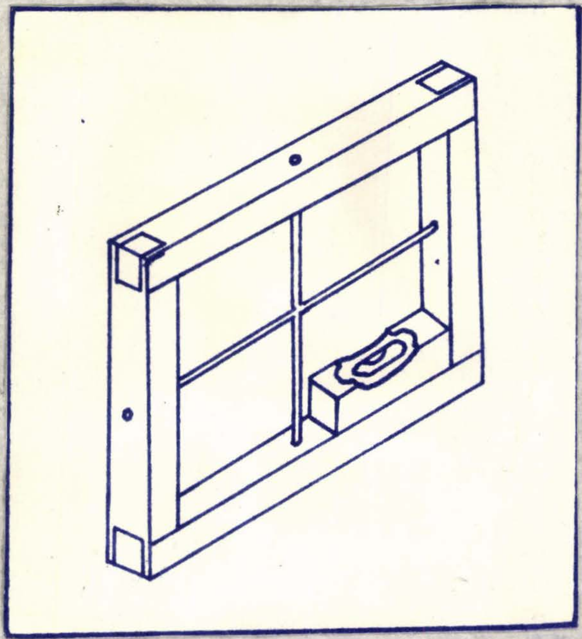

Fig. 2 - Diagram of an Orienttation Frame (from Krumbein, 1939, p. 676).

Reorientation in the laboratory.

In the laboratory the pebble is cleaned and the pencilled "L" is traced with india ink or lacquer. The longest and the shortest axis of the pebble is determined and the extreme points of these axes are marked with india ink or lacquer.

Krumbein (1939, p. 679-680) modified a method for measuring the orientation of the axes which was developed by Wadell. The first step consists of mounting the pebble on the crystal holder of a two-circle goniometer with putty. Next, by keeping the eye on a level with the pebble, the pebble is manipulated until the lacquered "L" forms a right angle as was seen in the field. Finally the position is checked by holding the orienting rectangle in front of the pebble and parallel to the vertical circle of the goniometer. The pebble is now oriented so that it occupies the same relative position it maintained in the outcrop with the vertical circle representing the strike of the outcrop face.

After the pebble has been properly mounted, the following steps are taken to determine the measurement of the orientation:

(1) The value to which the arrow points is read on the horizontal goniometer scale.

(2) The horizontal stage is rotated <u>counterclockwise</u> until the axis to be measured is parallel to the vertical circle of the goniometer and the axis dips from right to left.

(3) The value that the arrow points to on the horizontal scale is again read.

(4) To determine the dip of the axis, a pencil is held in front of the pebble, tilted so that it coincides with the axis. The "dip" of the pencil is then read with the rod and shoe on the vertical scale.

The data is then recorded as shown on Table 3.

TABLE 3

RECORDED DATA FOR REORIENTATION METHOD USING A GONIOMETER

(from Krumbein, 1939, p.680)

Pebble No. (1)	First Stage Reading (2)	Second Stage Reading (3)	Rotation in Degrees (4)	Rotation Added to Outcrop Azimuth (5)	Corrected Azimuth (6)	Dip of Axis (7)
1. . . .	281	293	12	342	342°	18°
2. . . .	153	320	167	497	137°	27°

The first-stage reading (col. 2) is subtracted from the second-stage reading (col. 3). This represents the horizontal angle the axis makes with the outcrop face (col. 4). This, in turn, is added to the azimuth of the outcrop face as determined in the field (col. 5). If the value is over 360° then 180° is subtracted to give the corrected azimuth (col. 6). The dip of the axis is also recorded (col. 7). To avoid confusion separate tables should be prepared for the long and short axes.

Karlstrom's Method

Collection in the field

The method Karlstrom (1952, p. 490 - 491) used for marking the orientation of pebbles in the field was essentially the same as that used by Krumbein. This method differs only in the use of a template in place of a rectangular frame. The orientation template (Fig. 3) is a 5 x 4-inch lucite plate, 1/4 inch thick, in which two slots are cut in the form of a cross. The slots are just wide enough to permit the marking of a line with a pencil. A bubble level is inserted in the plate to enable the operator to level the plate so that one of the slots is horizontal and the other vertical when held in an upright position.

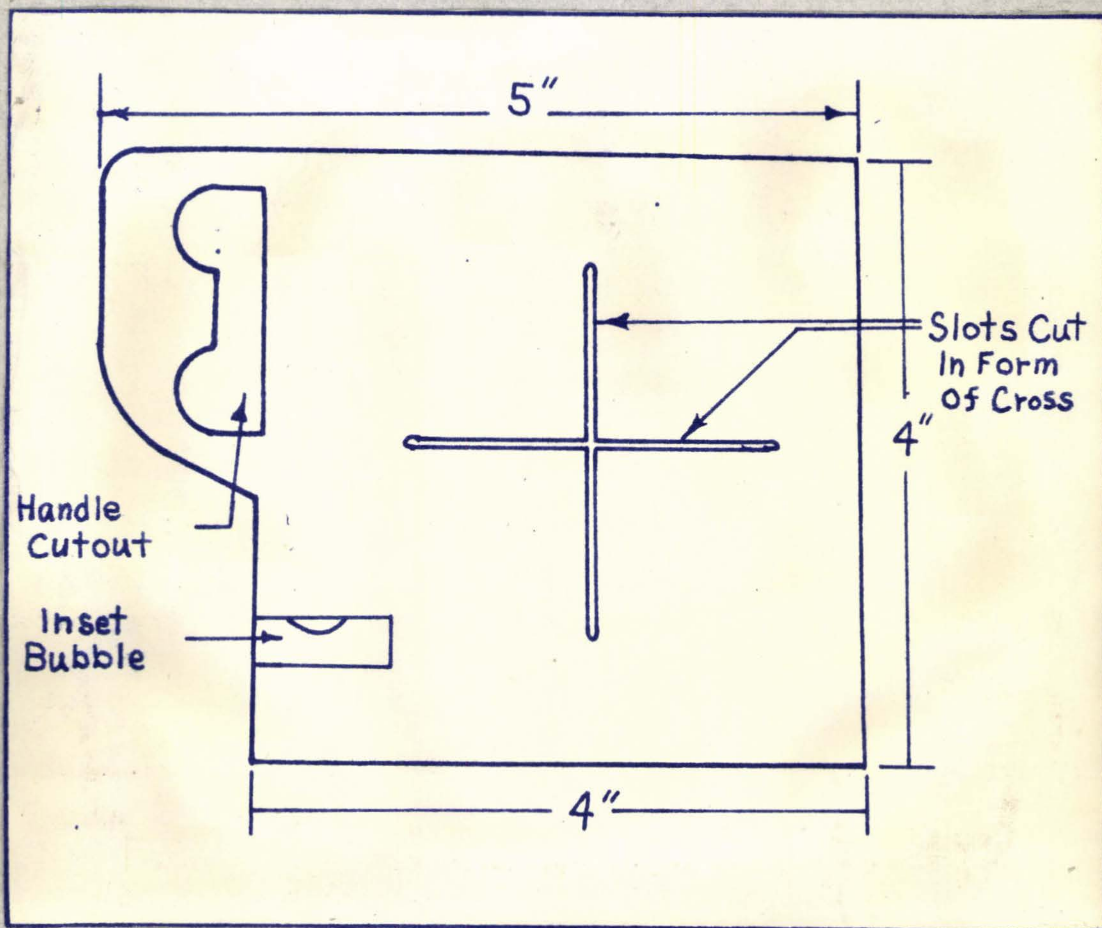

Fig. 3 - Diagram of an Orientation Template (from Karlstrom, 1952, p.490)

The following procedure is used in the manipulation of the template:

1. A vertical face is prepared on the exposure and its azimuth is recorded.
2. The surface of the pebble is cleaned carefully so one will not disrupt its position within the matrix.
3. The template is held in front of the pebble so that the former is upright and level.
4. A cross is marked on the particle by guiding the pencil along the slots.
5. A dot is placed in the lower left quadrant to determine the bottom of the pebble.
6. The particle is then placed in a paper bag and the bag is labeled.

Reorientation in the Laboratory

The particle may be reoriented by the goniometer method, explained above, or by the method devised by Karlstrom (1952, p. 492-493). The equipment used in this method involves: (1) a piece of paper with the compass points marked (at 15^{o} intervals) on it, (2) a lump of clay to be used as a mount, and (3) a transparent glass plate (4" x 4") with a cross marked at its center.

The procedure is as follows:

(1) the particle is placed on the clay mount in the center of the marked circle.

(2) The transparent plate is aligned parallel to the azimuth out the outcrop face. The latter is marked on the circle.

(3) The particle is oriented on the clay mount so that the cross marked on the particle coincides with the cross on the transparent plate.

(4) The azimuth of the axis is obtained by visually extending this axis until it intersects the calibrated circle.

An improvised clinometer may be used to determine the dip of the axis. The clinometer consists of a wooden rod with a protractor attached to one end and a string fastened to the center of the protractor. On the other end of the string is attached a plumb bob.

The clinometer is held over the pebble so that it is parallel to the axis. The value of the dip is read at the point where the string connecting the plumb bob to the straightedge crosses the scale of the protractor.

<u>Harrison's Method</u>

Collection in the field

Harrison's method (1957a., p. 98) requires a cube or block of glacial till cut with a trench shovel. Before the cube is removed a north arrow is cut into its top. A horizontal surface is prepared on the top of the cube and fingernail polish is used to retrace the north arrow and to mark a 4 x 5 square inch rectangle. The specimen is then wrapped and labeled.

Reorientation in the Laboratory

Harrison (1957 a., p. 99-100) also used a two-circle goniometer to reorient the till specimen. A vertical cut is made on the "east side" of the block and a new north arrow is placed on this face. The rest of the cube is trimmed to size (4 x 5 sq. inch) to fit the stage of the goniometer. Parallel strips of tape are placed on the stage so that their edges represent north-south lines when the reading of the horizontal circle is 0°. The block of till is then placed on the goniometer stage so that the north-south trend of the "east edge" parallels the strips of tape and the north arrow of the block points to the north end of the stage.

A stylus is used to expose particles within the till block. By alternately picking and blowing away the pieces of till, the operator approaches a particle to be measured. The cube of till is then moved on the stage so that the particle may be reached by the measuring arm of the goniometer. The east side of block is chedked to see that its edge is still parallel to the strips of tape. To measure a tabular-shaped particle, the measuring arm is adjusted until the lower flat surface of the shoe coincides with the upper planar surface of the exposed particle. The azimuth and the dips of the axis normal to this surface are read on the horizontal and vertical scales, respectively. This axis represents the "pole" and may be plotted directly on polar coordinate paper. The azimuth and dip of an axis may be determined by lining up the long edge of the measuring shoe with the parameter to be measured.

Conclusions on Methods

Holmes's method is the only one which allows a direct determination of the orientation of particles in the field, thus eliminating the transport of bulky samples. Other methods, however, appear to be more accurate. Holmes's method is advantageous where a rapid determination of the general direction of glacier flow is desired.

Krumbein's method is probably the most accurate of those discussed. The procedure seems somewhat tedious and time-consuming, and it involves the transportation of specimens. However, where great accuracy is desired, this method is the best.

Karlstrom's method, as well as Holmes's method, is inexpensive asit does not require a two-circle goniometer. The template Karlstrom developed seems to be more efficient than the reorientation rectangle developed by Krumbein.

The improvised "goniometer" devised by Karlstrom probably is not very accurate. However, if a two-circle goniometer is not available and if extreme accuracy is not required, the former may be considered an appropriate substitute.

Harrison's method is advantageous in that many particles in a till section may be measured without the reorientation of each individual particle. Harrison (1957a., p. 98) has found his method to be accurate over the particle size range of 3 - 40 mm. The average error is as low as 6° - 8° (p. 104). He has also found only 6 - 8 hours is required for a complete fabric analysis of 100 particles (p. 104). However, the procedure requires transporting bulky samples to the laboratory; and if the till is moderately unconsolidated, the specimen must be carefully wrapped and handled.

Methods of Plotting the Data

After the data has been collected, it is convenient to plot it graphically. A method commonly used by Holmes (1941, p. 1309) is the "rose" diagram. Ten degree intervals are marked along a semi-circle, 90° on both sides of north, on a sheet of paper. A suitable scale is used to determine the length of the direction line corresponding to the number of particles recorded for that direction. Table 4 shows the number of particles recorded for each direction and figure 4 illustrates the resulting "rose" diagram. The trend of most of the long axes, which is N30°E-S30°W, is represented by the longest line.

(See Table 4 and Fig. 4 on page 17.)

TABLE 4

METHOD FOR RECORDING NO. OF STONES FOR EACH DIRECTION (from Holmes,1941,p.1308).

80°	70°	60°	50°	40°	30°	20°	10°	N	10°	20°	30°	40°	50°	60°	70°	80°	EW
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	
		x	x	x	x			x		x	x	x	x	x		x	
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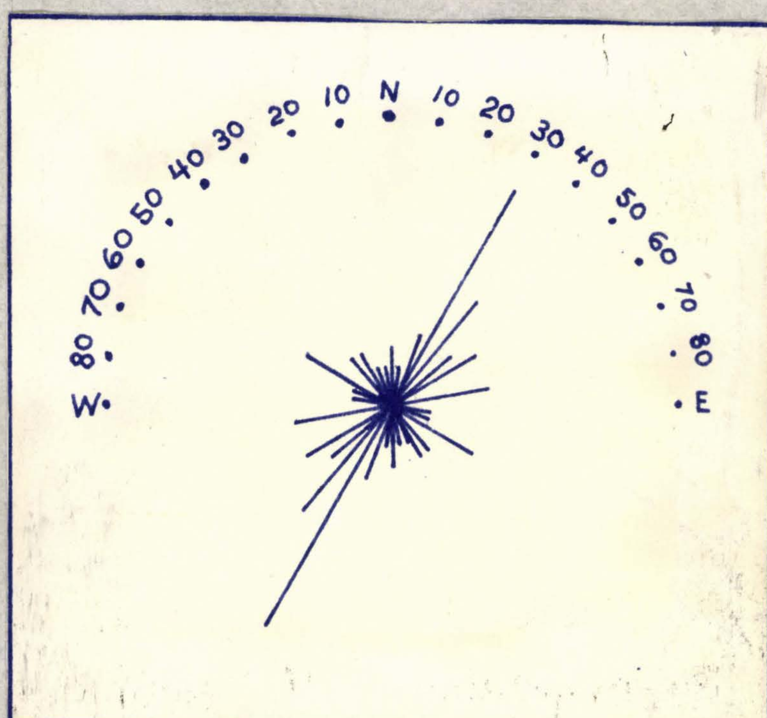


Fig. 4 - The "Rose" Diagram (from Holmes, 1941, p. 1308).

Another graphical means of plotting data is the contoured stereographic diagram or "petrofabric" diagram. This diagram gives the effect of a third dimension, and therefore, the axial dips, as well as the axes azimuth, may be shown. A Schmidt equal area projection of a hemisphere is generally used.

This hemisphere represents the inside lower half of a sphere. Compass directions are marked along the perimeter of the greatest circle which represents a horizontal plane. Axial dips are recorded along concentric circles with the greatest circle marked as 0° and the center, 90°. All concentric circles between the outer circle and the center represent 5° intervals between 0° and 90°, respectively. The direction and dip of the axis is then plotted as a dot at a point where a radiating line from the center, representing the direction, intersects the circle corresponding to the dip. Pettijohn (1957, p. 75) describes the diagram as "if one imagines that each pebble in turn is placed at the center of a hollow sphere in precisely the position that this pebble had in the undisturbed outcrop. The long axis (or any other axis) of the pebble is extended until such an axis intersects the surface of the sphere. The piercing point in the southern hemisphere is then plotted on the 'polar' map of that hemisphere."

After a sufficient number of the desired elements have been plotted on projection paper, contours are drawn to show a clustering of points. The percent concentration of the projected axes at any one point on the projection paper is shown enclosed by contour lines. It shows the density of plotted points per unit area expressed in relative percentages. The unit area is commonly one per cent, however, Holmes (1941, p. 1310) found a unit area of two per cent to be satisfactory.

Plate IA shows the plots of the long axis on projection paper and Plate IB shows the same plots contoured to make up the conventional "petrographic diagram" (page 20).

Commonly, the pole of the maximum projected surface of a particle (the shortest axis) is plotted rather than the long axis. This method is used when measuring the orientation of a disk-shaped particle where a long axis is not present. Harrison (1957), who analyzed mostly disk-shaped particles, used this method.

Usually, data from various stations are combined to form a composite group. The composite group of data may then be used to make a "petrofabric" or "rose" diagram. Holmes (1941, p. 1313) combined data from suitably homogenous stations to form a composite group. The data from each station had to fulfill three requirements: (1) The station pattern must indicate a single direction of glacier flow, (2) the direction of glacier movement at each station must be known from other evidence, and (3) the distribution of the long axes dips must be reasonably symmetrical. He found that of 31 stations, 10 stations comprising a total of 1180 particles fulfilled these requirements. The composite group was then subdivided by Holmes according to the shape, roundness and the amount of axial dips of each till particle.

Analyses of the Fabric

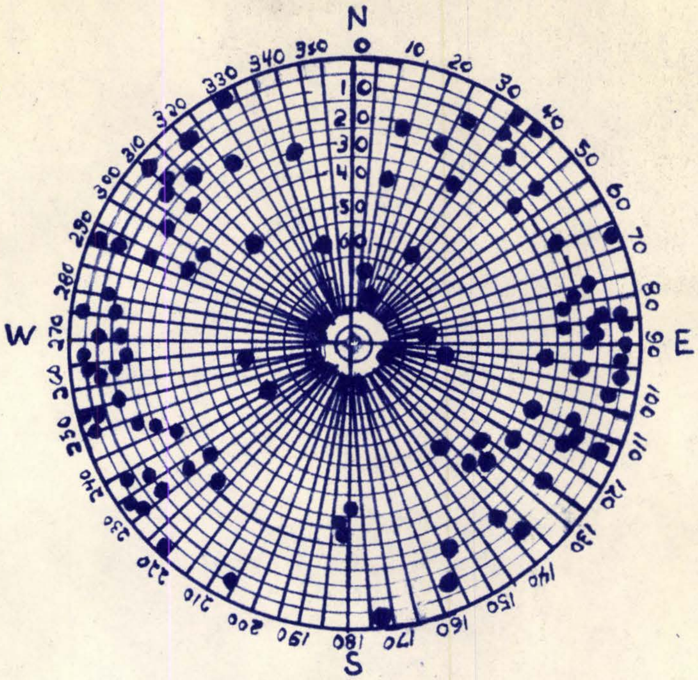
Parallel vs. Perpendicular Orientation

Holmes (1938, pp. 1886-1887) found by analyses of rose diagrams that commonly there were two dominant lines present, one parallel to the direction of glacier flow one and one perpendicular, the latter almost always the shorter. He also noted (pp. 1313-1314) that on a composite petrofabric diagram that the "poles"* tend to concentrate along two girdles. The more well-defined

*(a "pole" is the axis normal to the maximum projection area.)

PLATE I

A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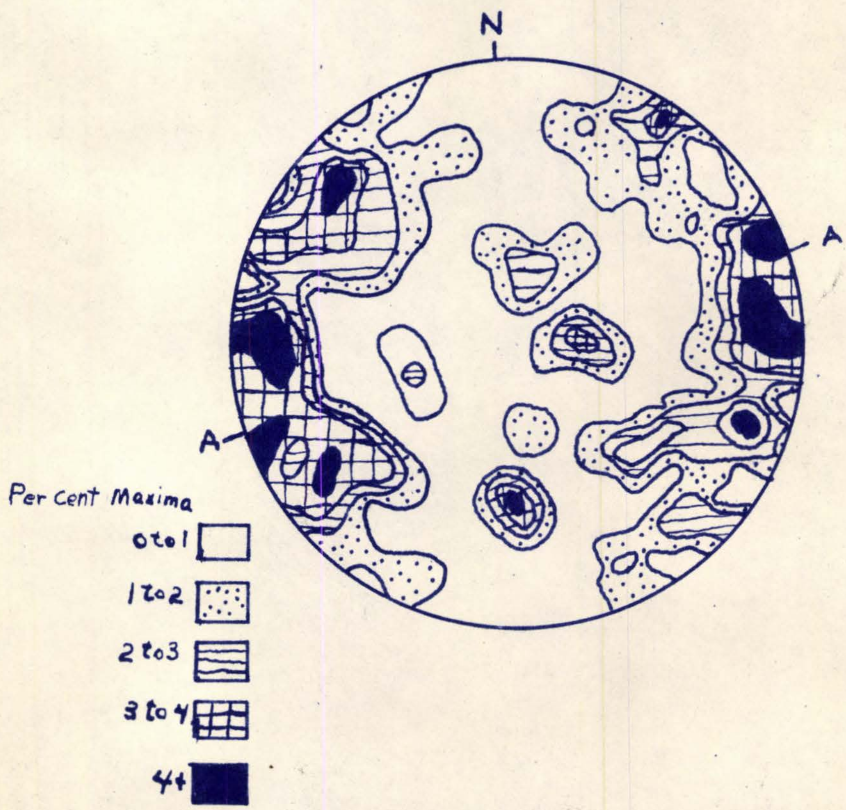
N
A
A
Per Cent Maxima
0 to 1
1 to 2
2 to 3
3 to 4
4+

girdle occupies the peripheral zone (hence, small axial dips) and include both parallel and transverse maxima. The other girdle, less conspicuous, occupied the center of the diagram (hence, large axial dips) and include only the parallel maximum.

Holmes (1941, p. 315) discovered that one-third of the till particles he analyzed were imbedded with neither long nor intermediate axes dipping as much as 10 degrees. Only a few had dips between 10 and 70 degrees, with an increase in number in the 70 to 90 degree interval. Dips of the intermediate axis under 15 degrees were found to be associated with parallel orientation, 20 to 70 degrees with transverse orientation.

The results of Dreimanis and Reavely studies were somewhat similar to those of Holmes. Out of 1495 particles whose intermediate axes had dips less than 70° it was found (p. 243) that 38 percent showed parallel alignment to glacier flow and 14 percent showed perpendicular alignment. Out of 675 particles whose intermediate axes dipped greater than 75 degrees, it was found that 28 percent showed parallel alignment and 29 percent showed transverse alignment.

Krumbein (1939) and Harrison (1957) did not find the perpendicular alignment relationship noted by Holmes. Krumbein (1939, p. 682-83) noted only that the long axes generally exhibited parallel alignment with glacier flow. Harrison (1957, p. 289) found that only two out of 66 petrofabric diagrams showed well-defined orientation perpendicular to glacier flow. He instead noted that commonly till particles tend to be slightly imbricated "upstream" to the former flacier movement direction.

Effects of shape and roundness on orientation

It was noted by Holmes that there is a relationship between shape and roundness of particles and the ultimate position they acquire upon deposition. However, he found that the variance of shape and roundness of the particles shows less contrast in orientation than does a variance in the amount of axial dips, particularly intermediate axial dips.

Holmes (1941, pp. 1331-33) noted that generally a particle with the shape of a rhombohedroid, whose long and intermediate axes dip less than 20 degrees, tends to be deposited with its longest axis parallel to glacier flow. Occasionally, rhombohedroids have their long axes transverse to the direction of glacier in which case the intermediate axes of such particles have a steep dip. The "petrofabric" and "rose" diagrams also show that many of the rhombohedroid particles also tend to have their longest axes dipping steeply with these axes oriented parallel to the direction of glacial flow. However, he found (pp. 1333-34) wedge-shaped particles tend to be deposited with their long axes diagonal to this direction. He also observed (pp. 1342-44) that tabular particles are commonly deposited with their long axes parallel to the glacial flow direction and with their intermediate axes dipping steeply. Holmes (1941) presents his opinions on how the various shaped particles probably acquired their orientation in glacial till (see, Theories on the Genesis of the Fabric).

Microfabric Analyses

Sitler and Chapman (1955, p. 263) found the average thin section shows that a majority of the "silt flakes" have an orientation within 10 or 20 degrees of a common direction and that many of the highly elongate "silt grains" generally show perfect parallelism. It was found that orientation of "silt flakes" is related to the orientation and shape of the "silt grains." They also observed (p. 269) that the perfection of orientation is greater in silty till and lesser in sandy tills. It was noted (p. 264) that microfoliation tends to "wrap around" larger sand particles in a concentric pattern and occasionally in "augen fashion."

Harrison (1957b., p. 287), however, found only one out of the three till microfabric samples he took showed "wrap around" structures observed by Sitler and Chapman. He concludes that the structure was due to postdepositional compaction.

Sitler and Chapman (1955, p. 265) found that the "silt flakes" of well-developed veins generally shows a more perfect parallel orientation than those of microfoliation. They noted that commonly the "silt flakes" lie at a small angle to the vein wall. They also observed (pp. 265-66) that the veins resemble slip cleavage found in phyllite and slate and that each vein may appear as a sharp jog in microfoliation which resembles drag produced by fault planes. They noted that veins seldom tend to deviate around larger particles but usually end before reaching them.

Theories on the Genesis of Till Fabric

Holmes's Theory

Holmes (1952, p. 1003) believes that till fabric originates by the gradual accretion of the till beneath the moving glacier. In order for till to be deposited in this manner, a particle must be set free by melting of the glacier at its base. This melting, he suggests (1952, p. 1004), is either due to the pressure of the overlying ice sheet or to the friction derived from sliding, shearing, and abrasion, or both. "From these considerations," he states (1952, p. 1004), "the possibility of extensive deposition by progressive accretion where glacier flow was most rapid seems exceedingly strong." Another factor which tends to support the theory of gradual accumulation is the compactness of the till which he believes (1941, p. 1320) is original and is due to the weight of the overlying glacier. Holmes (1941, p. 1350) also believes that a glacier moved as a plastic solid flowing according to the laws of fluid mechanics.

To explain the parallel alignment of the long axes to glacier flow, he suggests (1941, p. 1331) that the particles moved by sliding at the contact between the ice and till floor. Particles which have their long axes transverse to glacial flows, he believes (1941, p. 1333) were transported by a rotational movement above the contact of the ice and till and thrust into the till by overriding debris. The shape, roundness, and amount of axial dips of the particles seem to affect their ultimate orientation.

Orientation by sliding

Orientation by sliding seems to be best illustrated by a rhombohedroid particle. As was mentioned above, Holmes found by analysis of the diagrams that rhombohedroids whose dip is less than 20 degrees tend to be deposited with their longest axes parallel to glacier flow. Holmes (1941, p. 1331) offers the following explanation:

> "Where till is accumulating beneath the moving glacier, a stone in contact with the till floor is retarded by friction which may bedome great enough to overcome the forward force of ice thrust. A rhombohedroid sliding thus in parallel orientation and with the two longer axes horizontal presents the least possible cross-sectional area against ice thrust.

> Its third (shortest) dimension affords a minimum projection into the faster-moving ice above the floor, and a maximum basal surface is tending to adhere to the deposited till. Such an orientation is imposed by sliding and thus may easily become the permanent depositional attitude unless the stone is shoved by another in transit before it becomes buried in the accumulating till."

Wedged-shaped particles also tend to move by gliding rather than by rotation. According to Holmes (1941, p. 1333) wedge forms are not adapted to rolling in a transverse direction. Upon rotation the pointed end of the particles would not advance as fast as the blunt end had hence would assume a parallel alignment. This concept of gliding may also explain the reason for more noticeably striae found in wedge-shaped particles. However, a wedged-shape stone may change from gliding movement to a rotational movement.

Orientation by rotation

Holmes (1941, pp. 1333-34)explains the reason for the frequent diagonal orientation of the long axes found in the studies of wedge-shaped particles as follows:

> "A wedge-form stone, sliding forward with the point foremost and with one of the convergent slides parallel to the direction of transport, may change from gliding to rotation. The initial rotation would bring the stone up on the other (diagonally oriented) convergent side, with the long axis in a diagonal direction. If during this movement superjacent debris prevented the rear edge from rising far, the stone would be forced down into the till beneath, with the long axis still in diagonal orientation."

Holmes (1941, p. 1332) found that particles with the shape of either a rhombohedroid or ovoid occasionally exhibit an orientation of their long axes which is transverse to the direction of glacier movement. Usually associated with this orientation are steeply dipping intermediate axes of such particles. He interprets the deposition as follows (1941, p. 1333):

> "The rhombohedroid stone was rotating in transverse orientation along the till floor of the glacier. With each rotation the intermediate and short axis rose alternately past the vertical, and the intermediate axis, being the longer of the two, required a larger vertical range. Other stones carried higher (and therefore moving slightly faster) entered this zone, intercepted the rising edge of the rhombohedroid, and by continued forward movement thrust the rhombohedroid edgewise into the till floor. When the intermediate axis was nearly vertical (or just past the vertical the impinging stone was free to move past, leaving the rhombohedroid permanently imbedded."

Frequently rhombohedroid and tabular stones tend to be deposited with their longest axes dipping steeply and aligned parallel to the direction of ice movement. The hypothesis Holmes offers for this phenomena is similar to the one above differing only in that the axis of rotation was about the intermediate axis rather than the long axis. He proposes the following interpretation:

> "A stone moving forward in rotational orientation (transverse) may assume a parallel orientation on coming in contact with the till floor if forward movement continues. Should the stone then be raised slightly above the floor, as by overrunning a gently sloping obstacle, rotation about the intermediate axis could be induced, and the stone might then be thrust into the till by pressure from superjacent debris which would intercept the rising rear end. When the stone had reached a near vertical position, the impinging stone would be free to slide past."

Harrison's Theory

The hypothesis presented by Harrison (1957b., p. 291) reads: "The bulk of the ground-moraine fabric is inherited, with only a slight degree of modification, from that fabric which was developed in the transportational environment." His theory involves a fabric which was present within the debris-charged, basal zone of the glacier and which was later deposited, unaltered, by slow melting out from the basal zone during the ablation phase of glaciation. The fabric present in the glacier, as noted by the slight imbrication of the particles indicated on the petrofabric diagrams, is thought to be due to vanished slip planes in the basal zone of the glacier.

Harrison (1957, p. 289) does not believe the concept of gradual accumulation of ground moraine so envisioned by Holmes. He states: "If the till really were built up by lodgment of successive increments beneath a moving glacier. . . . . one would find mostly girdles on petrofabric diagrams perpendicular to the a [long] fabric axis instead of the dominant point - maximum fabric patterns."

Harrison (1957b., p. 288-89) also disagrees with Holmes's concept of original rotational movement of particles within the glacier and eventual thrust of the particle into the till floor. As mentioned earlier, he found only two out of 66 petrofabric diagrams with well-defined orientation perpendicular to glacier flow. He states (p. 289): "The rarity of this type of fabric pattern speaks against deposition from the transportational medium by rotation and thrust, as conceived by Holmes for the tills which he studied." He believes that if the particles were thrust into the till from superjacent debris there should be a disturbance of the till matrix around the larger particles. However, he found from microfabric studies that no such results occurred. He also believes that Holmes's concept of a sharp contact between the ice and till floor is not valid. If such a sharp contact existed, he reasons (p. 289), "smearing would be expected along any hypothetical divisional plane between moving ice above and deposited till below." He observed that at two sample sites no such smearing effect exists between the till and included sediments.

Conclusions

The concept of gradual accumulation of the till by "plastering-on" beneath the moving glacier suggested by Holmes seems to be generally accepted. Flint's (1957, p. 120) explanation on the origin of "lodgement till" agrees with the hypothesis. He states: "Slow pressure melting of the flowing ice frees drift particles and allows them to be plastered, one by one and under pressure, onto the subglacial floor and there lodged (in Chamberlin's words) in the accumulating drift." Sitler and Chapman (1955, p. 267), explaining the origin of microfoliation, state: "As successive layers of till accumulated to build up a till sheet, each recorded its own deformation pattern."

Harrison's main objection to Holmes's theory on the "thrusting" of the particles into the till matrix was based on his microfabric analyses which showed that there was no disturbance of the till matrix caused by enclosed larger particles. However, Sitler and Chapman (1955, p. 266) conclude from their microfabric studies that there is definitely a disturbance of the matrix by larger particles. Flint (1957, p. 120) also explain the deposition of till particles as being thrusted or "lodged" into the matrix.

Harrison rejects Holmes's conception of a distinct contact between the glacier and till floor, because he did not find smear between the till and included sediments. Sitler and Chapman (1955, p. 267), on the other hand, believe that the till was deformed by smearing action.

Holmes's hypothesis of permanent deposition from a rotational orientation seems to provide a plausible explanation for the frequent transverse orientation and associated steeply dipping intermediate axes found in certain till particles. The similar results found by the studies of Dreimanis and Reavely tend to support this theory. The hypothesis has also been used by Sitler and Chapman (1955, p. 267), to explain the origin of microfoliation.

The importance, ascribed to by Holmes, on the effect of shape and amount of axial dips upon ultimate deposition seems to be veritable.

It is suggested that these inherent characteristics of the particles should be carefully considered in future work.

Summary

A preferred orientation of particles imbedded in till was recognized as early as 1859. Till fabrics was described by Miller, Bell, Upham, and Gilbert in the latter part of the nineteenth century. Generally, however, up to 1932, till was considered to be heterogeneous with its particles scattered in a pell-mell manner. In 1932, Richter published his first work on the subject and proves by statistical analyses that till does contain an anisotropic fabric. Krumbein, in 1938, found preferred orientation of till particles in eastern Wisconsin. One of the most comprehensive studies on till fabric was conducted by Holmes in 1941. Dreimanis and Reavely in

1953, discovered a preferred orientation of till particles along the north shore of Lake Erie. In 1955, Sitler and Chapman made extensive microfabric studies on till from Ohio and Pennsylvania. Harrison made macrofabric and microfabric studies of till around Chicago, Illinois and englacial debris near Thule, Greenland.

Till fabric is classified as macrofabric and microfabric. Particles used in macrofabric studies are classified according to shape and roundness. Holmes recorded data from till particles of various shapes and roundnesses and concludes that these characteristics and amount of axial dips reflect their mode of deposition. Harrison mostly recorded data from disk-shaped particles. Microfabric is further classified by Sitler and Chapman as microfoliation, coarse fragment orientation and veining.

Several methods have been proposed to collect and measure the orientation of till particles. Holmes's method offers a direct determination of orientation of the particles in the field. A method which is probably more accurate, however, is one which requires the collecting of the particles in the field and reorienting them in the laboratory. The template, designed by Karlstrom, is a useful tool for marking the orientation of the samples in the field. The two-circle goniometer is generally used to reorient the particles in the laboratory.

The method used most commonly for plotting the data is the "petrofabric diagram." This method is advantageous in that it shows both the azimuths and the dips of the designated axes of the particles.

Another graphical means for representing the fabric is the "rose" diagram. This type of diagram, however, shows only the azimuths of a designated axis. A composite diagram is commonly used to illustrate the orientation of a large number of particles collected at various stations.

It is generally agreed, that in most cases, the long axes of till particles is oriented parallel to glacier flow. But, in several cases, it has been found that these axes may be oriented transverse to glacier flow. It has been found that the shape, roundness, and amount of axial dips has an effect on the resulting orientation of the particles.

It is concluded that the fabric originates by the gradual accumulation of the till beneath the glacier. Parallel orientation of the long axes, as proposed by Holmes, is thought to be due to the gliding of the particles at the contact between the ice and till floor. Transverse orientation of the long axis is thought to be caused by rotational movement of the particles just above the till-ice contact and a thrust of this particle into the till by superjacent debris. This hypothesis, of deposition by thrusting, also offers an explanation for the associated steeply dipping axes of the particles.

Harrison's objections to Holmes's theories do not seem to be valid. His findings, upon which he bases his objectives, are not in accordance with those of other workers.

Therefore, it is concluded that the theory on the genesis of till fabric presented by Holmes is the most acceptable. However, further study on fabric of till seems necessary before a definite conclusion can be reached as to its origin.

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