[AMERICAN JOURNAL OF SCIENCE, VOL. 255, MARCH 1957, P. 194-205]

ON THE MECHANISM BY WHICH STONES IN TILL BECOME ORIENTED

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ABSTRACT. In most till deposits the long axes of the stones tend to be aligned parallel to the direction in which the ice flowed. Sometimes there is also a tendency for long axes to be oriented transverse to the flow direction. This transverse peak is particularly noticeable in narrow band tills. Laboratory experiments and theoretical studies by various authors have shown that an initially random collection of elongated objects immersed in a flowing liquid will develop a long axis distribution with a peak parallel to the direction of flow in a very short time, but that if flow is continued for a long time a transverse peak will also develop. The observed orientations could thus be entirely the result of flow in moving ice. Collisions between particles and the mode of deposition could change the relative distribution of long axes between the two peaks. The theoretical results are compared with distributions of long axes found in various tills.

INTRODUCTION

The purpose of this paper is to discuss the mechanisms by which stones in glacial deposits can acquire a preferred orientation with respect to the direction of flow of the ice which deposited them. In order to refer to the various directions relative to the flow of ice, let us consider a block of ice forming part of the bottom of a glacier flowing over a plane bed as shown in figure 1. The direction parallel to the direction of flow will be referred to as the *parallel* direction, the direction perpendicular to the direction of flow but parallel to the bed will be referred to as the *transverse* direction, and the direction perpendicular to both the direction of flow and the bed will be referred to as the *perpendicular* direction. The plane containing the parallel and perpendicular directions will be termed the *plane of shear*, the plane containing the parallel and transverse direction will be termed the *parallel plane*, the plane perpendicular to the direction of flow will be termed the *perpendicular plane*. All of these terms are shown in figure 1.

It has long been known that the stones or rock fragments in till are not oriented at random, but that the long axes of stones tend to have a preferred orientation in the parallel direction. It is sometimes also found that a subsidiary peak of long axis orientations lies in the transverse direction. Holmes

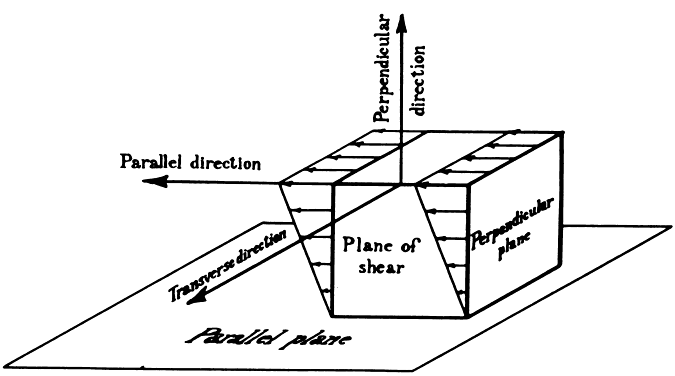

Fig. 1. Diagram to show the terms used for the different planes and directions in a material flowing by simple shear.

(1941) made a detailed study of the preferred orientations of stones in till in central New York State, determining not only the long axis directions but also the directions of the intermediate axes, the form and the roundness of each of over 1000 stones. He noted various systematic tendencies between various characteristics of the stones, and also discussed the mode of formation of the peaks in long axis distribution. He attributed the prominent parallel peak to orientation by gliding of stones in contact with the glacier floor (or possibly along well-defined shear planes in the ice), while he attributed the transverse peak to the tendency of stones totally immersed in the ice to assume an orientation in which they rotate about their long axes.

If these were the only mechanisms which could produce preferred orientations of stones, then conclusions about the nature of ice flow could be deduced from observations of the number of stones near the two peaks in the long axis distributions. Thus a till built up beneath active ice would be expected to give a strong parallel peak, while a till formed by deposition from dead ice might be expected to show a more prominent transverse peak, inherited from the orientations assumed in the flowing ice. However there are physical reasons for suggesting that the parallel orientation can also be produced in shearing ice, without the necessity for any dragging or sliding. This being so, it seems opportune to review all the possible methods by which preferred orientations may have developed, to see what deductions, if any, can be drawn from observations of stone orientations. These results can be compared with measurements of stone orientations taken on tills still surrounded by ice in Nordaustlandet (Donner and West, 1956), where large transverse orientations appeared to be formed only in narrow band tills, and with orientation measurements on deposits in eastern England (West and Donner, 1956).

Although the considerations brought forward in this paper are related to the orientation of stones, similar considerations will apply to the orientation of the microscopic particles in till, although the importance of the various factors will be rather different. Seifert (1954) has studied the preferred orientations in this case, and his results also can be considered in the light of the physical arguments here suggested.

POSSIBLE CAUSES FOR PREFERRED ORIENTATION OF STONES IN TILL

The causes which could be responsible for preferred orientations can be divided into three main groups, those stemming from the method of entrainment of the stones in the ice, those inherent in the flow process itself, and those resulting from deposition or subsequent movement of the deposit.

Entrainment of debris in the ice.—The debris which forms the stones in till may enter the ice in several ways. It may be plucked from rocks which are being shattered by freezing, it may be washed along a melt water stream, or it may fall onto the surface of the glacier from rock walls. All of these processes will place stones in the ice in initial orientations that are probably not random. For example, stones are unlikely to enter the ice with their long axes vertical. It is difficult, however, to estimate exactly what distribution is to be expected, and probably the best assumption to make in computing the effects produced in the subsequent stages is to assume that the stones do in fact enter the ice quite randomly oriented. This assumption is unlikely to lead to spurious preferred orientations.

Flow in the ice.—A stone completely immersed in ice which is flowing by shear will be rotated by the ice as well as being carried forward. The rotation rate depends on the orientation of the stone, and does not remain constant as the stone is moved. The theory of the movement of non-spherical objects suspended in a flowing liquid has been studied for the case of ellipsoids in a viscous liquid by Jeffery (1922). His calculations show that, provided the velocity of flow is small, the ellipsoids, as well as being carried forward, rotate in orbits about their centers, their long axes returning after a time to their original orientation. The rate of rotation varies, being least when the long axis of the stone is most nearly parallel to the direction of flow. For example, for the simple case of a prolate spheroid (i.e. an object shaped like a rugby football) whose long axis is initially in the plane of shear (fig. 2), the long

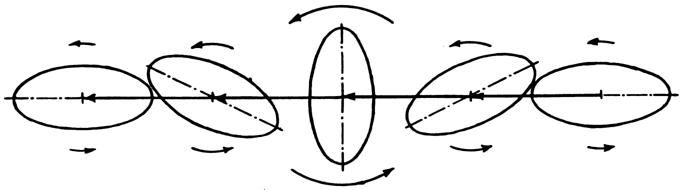

Fig. 2. Diagram to demonstrate the movement and rotation of an ellipsoidal object in a shearing material.

axis rotates so that it remains in this plane, but the angular velocity has a maximum when the long axis is in the perpendicular direction (the position in the center of fig. 2) and a minimum when it is in the parallel direction (at the left and right in fig. 2). The ratio of the maximum to the minimum angular velocity is the square of the axial ratio of the spheroid. The spheroid therefore spends much more time with its long axis near to the parallel direction than it does perpendicular to this. This result is very reasonable, as, when the long axis is perpendicular the top and bottom of the spheroid extend into regions of the fluid flowing relative to the centre of the spheroid at a faster rate than the regions reached when the long axis is parallel in direction.

For a prolate spheroid in a more general orientation the result is similar but more complicated. Jeffery's calculation shows that the angular velocity of the long axis about an axis in the transverse direction still has a minimum when the long axis is in the parallel plane, but there is a further effect, for the angle between the long axis and the plane of shear also varies cyclically and is least when the long axis lies in the parallel plane, and greatest when the axis is in the perpendicular plane. This effect crowds the long axes together towards the parallel direction, and so increases the effect due to the angular velocity variations by which, at any given time, there is a greater chance of finding a given spheroid near to the parallel direction. The preferred orientation resulting from this flow can be calculated from Jeffery's formulae if the initial positions of the spheroids are known. A completely random distribution of spheroids is not stable, i.e. if it existed at one time, then a short time later the flow would have produced a preferred orientation. If it is assumed that the stones are placed in the liquid in random orientations, then the number of stones in any given orbit will be proportional to the angle subtended by that orbit at the centre of the spheroid, i.e. to the number of different orientations that lead to that orbit. However within any one orbit, the chance of finding a spheroid in any given part of the orbit will be inversely proportional to the angular velocity at that part. In this way the probability of any given long axis orientation can be deduced, and from this a rose diagram can be constructed to show the distribution of the projection of long axes on the parallel plane. This computation has been carried out graphically for the case of an axial ratio of 2:1, and thc resulting rose diagram is shown in figure 3. This

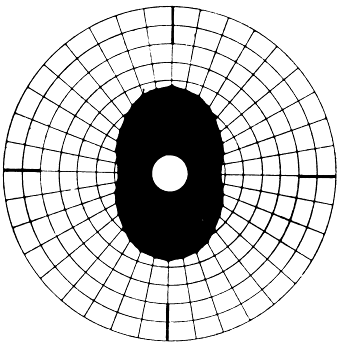

Fig. 3. Long-axis rose diagram computed from Jeffrey's theory for prolate spheroids with an axial ratio of 2:1 in a linear viscous liquid assuming the spheroids initially to have been placed in the liquid at random, The top and bottom of the diagram represent the orientation parallel to the direction of flow.

diagram has been drawn so as to be directly comparable with the rose diagrams constructed from measurements on tills, the radii vectores are measured from the circumference of the small white center circle, and are proportional to the number of spheroids which would have their long axes in the plane perpendicular to the parallel plane and containing the direction of the radius vector. The parallel direction is at the top and bottom of the diagram, the transverse direction at the sides. It will be seen that for this axial ratio, there are just over twice as many stones lying near the parallel direction as near the transverse direction.

In the solution of the viscous problem given by Jeffery there is no tendency of the spheroids to move from orbit to orbit. Thus after all the spheroids have rotated once or twice, the preferred orientation pattern should not change with further flow. In the transverse direction there is a minimum in the rose diagram, and there is no obvious reason why this situation should change. However Jeffery himself pointed out that the energy dissipated by the spheroid is a minimum if the long axis is in the transverse direction. A similar result is true for a more general ellipsoid, while for an oblate spheroid the minimum energy is dissipated if it rotates about a diameter (in this case the discus-shaped object has no definite longest axis, and a diameter is just one of the infinite number of longest axes). Jeffery suggested that higher order terms in the equation, which he had neglected, might be expected to favor the orientation which dissipates minimum energy, though it is to be expected that such a reorientation might take a very long time, and as the viscosity enters into the terms neglected, the higher the viscosity, the longer one might expect this time to be.

Various experiments have been performed to check the results of Jeffery's calculation and his surmise about the transverse orientation. Taylor (1923) immersed both prolate and oblate spheroids in water-glass and studied their behavior during shear between concentric cylinders. He found that the ellipsoids did rotate in orbits of the kind predicted by Jeffery, and he also found that after a long time the particles tended to assume the orientation predicted by the minimum energy hypothesis. Thus the prolate spheroids slowly shifted until their long axes were transverse. However the time taken to establish this reorientation was quite large, the spheroids having rotated about 370 times before their long axes were transverse. Taylor remarks how difficult it is to understand the mechanism by which this reorientation takes place, and Saffman (private communication) has suggested that the cause may not be the terms neglected by Jeffery in his calculation of the solution for the perfect viscous liquid, but may be due to the existence in the liquid of thixotropy, in particular of cross viscosity (i.e. the expansion of the liquid in the transverse direction when sheared). Saffman has found that reorientation occurred quite rapidly in a thixotropic liquid, whereas in a Newtonian viscous liquid no reorientation occurred. The experiments of Taylor and of Saffman were made with spheroids of axial ratio about 2:1, and these results are probably most comparable to the behavior of stones in ice. Most other experiments have been made on very long thin specimens such as hair, paper fibres or fine glass rods (Eirich, Margaretha and Bunzl, 1936; Binder, 1939; Trevelyan and Mason, 1951). All of these workers find that Jeffery's equations correctly predict the behavior of the particles for a short time, but with a long time reorientation occurs. For particles with a small axial ratio (less than 15:1) Binder found that the reorientation was towards the transverse direction, while for greater axial ratios he found that, despite Jeffery's hypothesis, the parallel direction was that to which all particles tended. Eirich, Margaretha and Bunzl also observed that the particles with smaller axial ratios were more inclined to take up the transverse orientation.

To sum up this discussion, objects placed at random in a flowing liquid soon develop a parallel orientation of their long axes, and then, as time proceeds, they slowly develop a transverse orientation if their axial ratios are less than 15:1. Ice is not a linear viscous liquid, though the way in which it differs is not necessarily that assumed by Saffman. For ice the relation between shear stress and shear strain rate is not linear (Glen, 1955), and it is not yet known whether ice possesses cross-viscosity to any marked extent. Jeffery's theory will not therefore apply quantitatively to ice, but it is to be expected that the qualitative deductions will still be quite accurate, as they are based on rather general properties of a flowing material.

Collisions between stones.—Interactions between stones may influence the distribution of long axes. It is not simple to calculate what effect such interactions will have, as the effect of two stones interacting with each other will depend rather critically on the shape of the stones and the exact nature of the collision. Collisions may aid the stones to move from orbit to orbit towards the orbit of minimum energy, and in this way could favor the transverse orientation. In support of this suggestion is the observation of Manley, Arlov and Mason (1955) that the orbit of a single rod remained constant for a long time, whereas when the density of particles was increased the transverse orientation developed. This has led Manley, Arlov and Mason (1955, see also Manley and Mason, paper to be published) to suggest that the reorientation is primarily a collision effect.

A reorientation due to collision is to be expected on grounds other than those connected with Jeffery's minimum energy hypothesis. A stone which is rotating in a given orbit has a chance of colliding with another stone which is larger the larger the volume swept out by the stone in rotating in the orbit. Stones have, therefore, less chance of colliding, and so stay longer in an orbit, if the volume swept out in that orbit is small. Thus, if the main effect of collisions is to move stones from orbit to orbit at random, the effect of collisions will be to favor those orbits which sweep out the least volume. This argument is rather similar to that employed to demonstrate the development of the parallel peak during free shear; the stone spends the longest time in the orbit which sweeps out the least volume. For a prolate stone the orbit which sweeps out the least volume is that in which the long axis is transverse, so that the stone rotates about it. Thus for prolate stones collisions favor the transverse orientation for the long axis, and this happens to be the orientation favored also by the minimum energy hypothesis. For oblate stones, however, the orbit sweeping out least volume is that in which the *smallest* axis is transverse so that the stone rotates about that. This orbit is that of maximum energy dissipation for oblate spheroids, so that for oblate stones the minimum energy hypothesis still favors the transverse peak, while the collision probability favors the parallel peak.

For a stone which is neither prolate nor oblate (i.e. whose intermediate axis is not equal either to the shortest or the longest axis) the orientation favored by collisions will be transverse if the intermediate axis is more nearly equal to the shorter axis (prolate type stone) and will be parallel if the intermediate axis is more nearly equal to the longest axis (oblate type stone). The former case follows directly from the argument above, while for the latter case, the orbit sweeping minimum volume will be that in which the shortest axis is transverse, i.e. in which both longest and intermediate axes are in the plane of shear, and for this orbit the rate of rotation will vary, being least when the long axis is in the parallel direction, which is thus the most probable orientation.

The argument we have used here suggests that due to collisions the stones showing the transverse peak should statistically be more prolate in form than those in the parallel peak. It is perhaps significant that Holmes (1941) found "a slight, though gradual, increase in preference for parallel orientation with decreasing difference in axial lengths". Holmes is here referring to the difference in lengths between the longest and the intermediate axes so that a small difference in length corresponds to an oblate type stone.

Interaction with the bed or across a shear plane.—The next type of interaction that we must consider is that between particles embedded in the moving ice and the stationary layer beneath. This layer may be bed rock, but it is more likely to be deposited till or perhaps even another ice layer, if the moving ice is overriding dead or slower moving ice along a shear plane. As Holmes has pointed out, a stone which projects to the bottom of the moving layer will be dragged along the layer underneath. This will tend to orient the stones in the parallel direction and may also reorient in this direction stones in the underlying layer. Holmes discussed this process in some detail and considered it the primary mechanism by which the parallel orientation is produced; for that reason we will not enter into great detail here. It is obviously a powerful method of orientation, and will, as Holmes has pointed out, tend to orient the long edges of stones rather than their long axes; thus for wedge-shaped stones one of the two sides of the wedge will tend to be parallel to the flow rather than the bisector of the angle. This is confirmed by the observation that wedge-shaped stones tend to have striae parallel to the sides of the wedge.

In confirmation of this type of orientation we can note the observation of Eirich, Margaretha and Bunzl that when their suspension of cylinders in a liquid was forced down a tube, the cylinders near the wall soon assumed a parallel orientation, whereas near the axis of the tube (where there is no strong shearing) the cylinders remained in apparently random orientations.

Deposition of till from the ice.—The process of deposition of the till may well affect the preferred orientation developed during flow. If till is deposited from active ice, so that material is added onto the top of a growing layer, the principal effects will be those due to interaction between the moving ice and the stationary till layer. As we have just seen, this tends to emphasize the parallel orientation. Holmes has pointed out another effect that may enter here. If a stone is rotating about an axis which is not one of circular symmetry, then the theory of Jeffery shows that the longest direction in the plane of shear spends comparatively little time near the perpendicular direction, and so has a preferred orientation which is horizontal. However, the chance of a collision with a stone above is highest when the axis is near to perpendicular, for it is then projecting into a region of much faster moving ice. If while it is rising into the perpendicular direction, a stone above, and thus moving faster than our stone, interacts with it from above, it will tend to force our stone downwards, and thus may push it into the till layer and bring it to rest. Thus in active ice the perpendicular orientation is more favored than would be predicted from the flow orbits alone. When the long axis is transverse, the same argument can be used to predict a greater number of perpendicular intermediate axes than are expected during flow, and Holmes explained in this way his observation that the class of stones with steeply inclined intermediate axes had a larger percentage of long axes in the transverse direction than had the class with low intermediate axis dip.

When till is formed from dead ice the effects will be rather different. Apart from bodily movements of the dead ice mass, the principal effect will be that, as the ice melts, the stones will fall down onto the material below. This will tend to drop the stones down so that their long axes are parallel to the bed (usually approximately horizontal), but will not affect the orientation distribution of long axes projected onto the parallel plane. It is for this reason that the rose diagram is probably a more satisfactory indicator of processes connected with ice flow than the contoured equal area diagram. In the rose diagram the number of stones whose long axes project onto the horizontal within a given angular range is plotted on polar co-ordinates against the angle, and this will be affected by deposition only to the extent that stones twist about a vertical axis as they are released from the melting ice. If the dip of the till stratum is large, then it is preferable to plot rose diagrams for the plane of the stratum rather than for the horizontal, but unless the angle is greater than about 30° no great errors will enter if this refinement is ignored. Contour diagrams, in which the dips as well as the horizontal angles of the long axes are recorded, will be much influenced by the way in which a stone drops onto the material beneath it.

Disturbance of till after deposition.—After till has been deposited from the ice further influences may upset its preferred orientations. Slumping of the whole deposit due to the melting of dead ice beneath may cause complications in the pattern, especially if the deposit itself flows during such slumping. For example a deposit on the edge of a kettle hole may flow into the hole and so obtain a preferred orientation in the direction of flow into the hole. Another process of this sort has been suggested by Hoppe (1952) to account for the observation that in hummocky moraine regions the preferred orientation of the stones is frequently perpendicular to the direction in which the moraine ridges run, even when these form curved loops. He suggested that till is pushed by the weight of overlying ice up into subglacial crevasses and in this way acquires its preferred orientation.

Solifluxion after the retreat of all the ice from the neighbourhood of the till may also be expected to change the preferred orientation, particularly if it is continued for any time, and if a mass movement of the deposit results. None of these effects will in general be related to the old direction of ice flow, and in any case in which stone orientation measurements are used to determine directions of ice flow, care must be taken to select deposits that do not appear to have been seriously disturbed since deposition.

SUMMARY OF EFFECTS PRODUCING PREFERRED ORIENTATIONS

We can now summarize the processes which have been discussed in the last section.

Preferred orientation parallel to the direction of flow: is produced by

free flow in the ice,
stone collisions (oblate stones only),
dragging on a stationary layer or over a plane of discontinuous shear (particularly during deposition from active ice).

Preferred orientation in the transverse direction: is produced by
protracted free flow in the ice,
stone collisions (prolate stones only),

Preferred orientation in the perpendicular direction: is produced by
stones being forced into a stationary layer by faster moving material above.

Preferred orientations unrelated to the direction of ice flow: is produced by
slumping of stones during deposition from dead ice (tending to eliminate large angles of dip),
subsequent flow of the till due to the melting of dead ice or extrusion from under masses of dead ice,
solifluxion.

COMPARISON OF PREDICTIONS WITH OBSERVED STONE ORIENTATIONS AND DEDUCTIONS WHICH CAN BE DRAWN FROM ORIENTATION MEASUREMENTS

We have already mentioned several ways in which the theory of stone orientations in till deposits is confirmed in practice. The majority of undisturbed deposits show either one or two directions in which the orientations have a maximum on a rose diagram. In most the largest peak is parallel to the direction of ice flow. Where there is a second peak it is usually at right angles to the first, i.e. transverse to the direction of ice flow. The second peak may exceed the first in magnitude. In no case does the transverse peak exist by itself. These observations alone show how well the stone orientations agree with predictions. There are probably significant correlations between prolateness and the tendency to have a transverse peak, which we would account for by the effect of collisions between stones. What remains to be explained, however, is why some rose diagrams lack the transverse peak. Two possibilities can be considered. Either the stones have not been in the ice long enough to develop the transverse peak, or they may have had it and lost it during the deposition process. In the former case the stones must have travelled only a short distance actually entrained in the ice, though they may have travelled further while being dragged beneath the glacier proper, while in the second case the deposition process must have involved a protracted period of dragging of the material.

Some confirmation for this approach is obtained from observations on tills in process of formation at Brageneset, Nordaustlandet (Donner and West, 1956). Here it was possible to measure stone orientations in tills which, although free of ice themselves, had ice both above and below them. Large transverse peaks were found only in narrow band tills (cf. diagram 3 in fig. 4), whereas in the thicker deposits only a single major peak was observed (diagrams 1 and 2 in fig. 4 show the extreme cases obtained). If the explanations suggested above are accepted, this would imply that the thick band tills were formed by a plastering-on process of lodgement which effectively eliminated the transverse peak, or that the stones in this till had never been completely immersed in flowing ice for a long time, while the narrow band tills were probably freer from the sliding process in formation, and, being relatively freer to flow with the ice, developed the transverse peak by free flow or as a

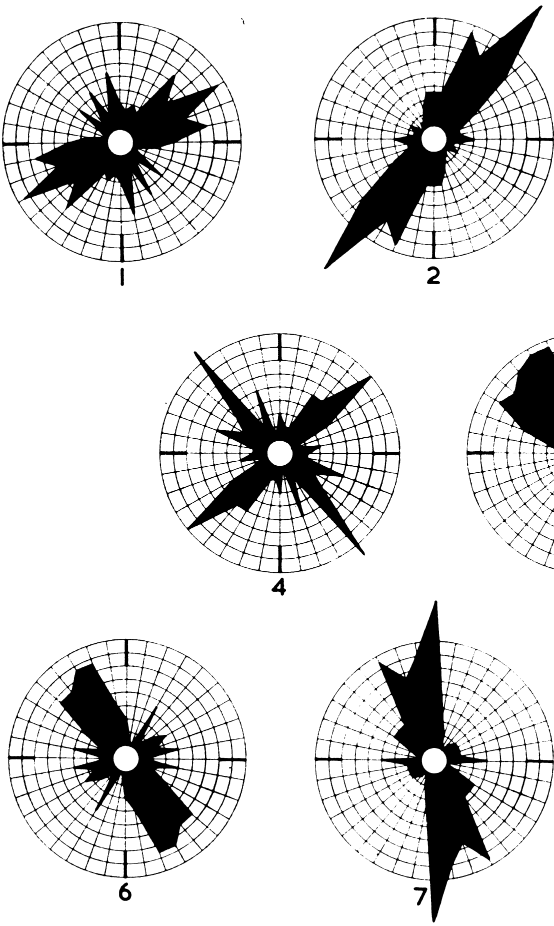

Fig. 4. Rose diagrams showing long-axis orientation of stones in various tills. The four cardinal points of the compass are shown on the diagrams, magnetic north at the top. The diagrams are from the following tills:

1 and 2. thick lodgement tills, Brageneset, Nordaustlandet, Spitsbergen.

3. narrow band till in ice, Brageneset, Nordaustlandet, Spitsbergen.

4. narrow band till from the Contorted Drift on the Cromer coast near Sheringham, Norfolk, England.

5 to 8. various lodgement tills in eastern England.

result of collisions during free flow. It would be dangerous to generalize from this one place and to state that transverse peaks are always associated with narrow band tills, but this experience does show that in the case of the Brageneset deposits there was a qualitative difference in morphology between the deposits with large transverse peaks and those without. The principle may have validity in other locations, however, as observations of stone orientations from a narrow band till in the Cromer deposits (about 20 cm wide) also showed two peaks at right angles of similar magnitude to each other (diagram 4 of fig. 4), a result which was not obtained from any of a large number of thicker lodgement tills in East Anglia. In the thicker tills the predominance of the parallel peak in the preferred orientation rose diagram is usually quite marked, and, provided care is taken to select only sites in which no subsequent movement or disturbance of the till has occurred, this method can be most useful in determining the direction of ice flow. In eastern England it has proved possible to differentiate between different ice advances using this method, as the direction of ice flow differed (West and Donner, 1956). Diagrams 5 to 8 of figure 4 are from these till deposits, and show the kind of preferred orientation found in practice.

The predominance of the parallel orientation has also been confirmed by the work of Holmes (1941) and Lundqvist (1948) and others. Seifert (1954) has used a similar method to determine the direction of ice flow, and hence to deduce the glaciation sequence on the north German coast. He studied the orientation of the microscopical particles in the till. He found that in a thick till layer the parallel orientation was favored near the edge, while the transverse orientation predominated near the centre. This result is different from that found for the larger particles, but this is not very surprising as the relative importance of the various processes influencing orientation must be very different in the two cases. For example, collisions are probably much more important for the small clay particles than for the larger stones. Unfortunately Seifert's microscopical technique did not allow him to distinguish between oblate and prolate particles, but if the particles are mostly prolate, it might be expected that, near the center of a band, the collisions would assist the production of the transverse peak, while near the edge, where the density of particles is less, the parallel peak would predominate. It is difficult to imagine that the interaction over a shear plane is of great importance for these very small particles.

The interpreation of rose diagrams showing the preferred orientations of long axes in terms of the direction of flow of the ice has been shown to be reasonable on physical as well as experimental grounds. Any further deductions made from the nature of the diagrams such as the relative magnitude of the transverse peak, are somewhat more dubious, owing to the large number of processes that could have acted to give the peaks their relative magnitudes. It would seem, therefore, that stone orientation measurements are most valuable for determining the direction of ice flow, but less significant for other purposes.

ACKNOWLEDGMENT

We would like to thank Mr. P. G. Saffman for permission to quote from his unpublished work, and for his help in finding the literature references on the behavior of suspensions of objects in liquids.

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