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Abstract. A mixture of approximately one part of water to two parts of kaolin (china clay) has proved suitable for making model glaciers on scales between 1 : 1000 and 1 : 10,000. The kaolin "glaciers" crevasse and flow realistically, and slide on their beds. They serve well for qualitative demonstrations, and some simple preliminary quantitative experiments suggest that they may also be useful for this purpose.

Zusammenfassung. Eine Mischung von ungefähr einem Teil Wasser und zwei Teilen Kaolin hat sich für Modell-Gletscher in Ausmassen von 1 : 1000 zu 1 : 10,000 als geeignet erwiesen. Die Kaolin "Gletscher" spalten sich und fliessen ganz natürlich und gleiten in ihrem Bett. Sie eignen sich gut für qualitative Erläuterungen, und einige einfachen, einführenden quantitative Experimente lassen darauf schliessen, dass sie auch für diesen Zweck brauchbar sein könnten.

The close resemblance between the behaviour of certain mud flows and of glaciers (Ward [1]) led us to search for a suitable material with which to produce a model glacier, and so to widen the scope of our experimental work in the Physiographical Laboratory of the Department of Geography at Cambridge, which had previously been confined mainly to wave action and stream flow. Any model would have to be reduced in linear scale between 1 : 1000 and 1 : 10,000 and so a substance was required which would exhibit the plastic behaviour of glacier ice but be correspondingly weaker. To satisfy these conditions the material would have to be rigid enough to crack or crevasse when subjected to mainly tensile stresses, and yet would have to yield when subjected to shear stresses, which in the case of ice exceed 1 kg./cm.^{2} The material would also have to slip along a rigid bed. The most favoured substance recommended by the rheologists was jellied petrol, but we hesitated to experiment, at least in the first instance, with this highly inflammable medium. Sir Lawrence Bragg suggested the use of cornflour made into the normal blancmange mixture. This proved satisfactory up to a point and was used for demonstration purposes on several occasions by the late Dr. J. G. McCall and Lewis. It crevassed most realistically, it slipped on the bed if the latter were greased with vaseline, and it bent forwards downhill, as it were, but when the point of active shearing was reached it broke down into lumps, its consistency and its flow properties changed markedly so that it bore little resemblance to a moving glacier.

Bouncing putty, an organosilicon product, had also been suggested to us for this purpose, and Miller was very kindly given for our use by the General Electric Co. of Schenectady, N.Y., a pint of this rather expensive material. Bouncing putty imitates the viscous type flow of a glacier very well indeed. Straight lines ruled across the model glacier are drawn out into curves rather like a line marked by a row of stakes across a real glacier, and match-sticks stuck in to represent such stakes lean over down-glacier in a realistic manner as the movement proceeds. In addition to flowing realistically both with small and large stresses it also slips on a lubricated bed. But in the quantity which we use, it very rarely crevasses. We were considering mixing it with a powder to lower its tensile strength when one of the writers (Lewis) thought of using kaolin (china clay). This material was selected after seeing a kaolin mixture both bending and cracking as it emerged from a large nozzle of a machine in the factory of Messrs. Paragon China Co., Stoke-on-Trent. Moistened kaolin proved to imitate a glacier so closely in its flow properties and colour, and it is so cheap and so clean to work with that its suitability for this purpose deserves to be more widely known.

A useful mixture for experimental purposes is about two parts of kaolin to one part of water. The mixture can be strengthened or weakened by increasing or decreasing the proportion of kaolin to water, and its properties do not change too rapidly when the mixture is strengthened or weakened in this way. A fresh mixture must always be used and the experiment should not continue in a dry atmosphere for longer than a few hours, as evaporation of water from the surface alters the properties. This is not altogether a disadvantage because drying overnight causes the little cracks formed during active flow to open out somewhat and be more readily photographed. If left for a few days, however, the cracks widen unduly. To obviate this disadvantage we used light engine oil in place of water. The mixture then retained its initial flow properties for a week or so, but it is not such an attractive or clean medium to work with.

A trough (Fig. 1, p. 537) was made for qualitative demonstrations. Its internal dimensions are 150 cm. long and 30 cm. wide. Relief was added in hollow plaster of Paris so as to reproduce the full length of a valley glacier from the cirque to the plain, and to include reversals of slope at two sills, the one 24 cm. from the cirque head and forming the lower end of the cirque basin, and a second at the 60 cm. mark. The vertical relief range from the mountain tops to the valley floor is 15 cm. At 90 cm. this little valley is joined by another with the same two sills in the long profile but cut in half longitudinally and bounded by a vertical glass plate forming the side of the trough. The object of this is to enable the movement along the central profile of the tributary glacier to be observed. In practice we found that by well greasing the vertical glass plate the kaolin slipped along the glass with very little drag.

A mixture of 55 parts of water to 100 parts of kaolin (by volume) was placed in the upper portion of the half-valley. It comfortably filled the cirque basin and extended down over the upper sill and ended at the 55 cm. mark on the reversed slope of the lower sill. The surface slope, when the trough was horizontal, averaged 10° except for the usual steepening at the snout. The trough was then gradually tilted to 6° when movement became visible. The surface slope steepened at the cirque head and above the downstream oversteepened slope of the sill. Normal step faults formed at both these places. Two bergschrunds formed more or less parallel with the cirque head-walls and meeting the glass side at right angles. The mixture slipped readily along the bed and very freely along the glass plate. The tilt of the trough was then increased to 8°. The movement quickened and was encouraged by tapping the trough. After 10 minutes from the start the snout had moved forward 25 cm. The trough was then left overnight at an angle of $5\frac{1}{2}$°. No change could be detected in the morning except for the widening of the cracks by drying. The model simulated a glacier far more accurately than the cornflour model, but we thought that the mixture was slightly too liquid. The experiment was therefore repeated with the stiffer mixture of 50 parts of water to 100 parts of kaolin with the results shown in Fig. 2, which was taken one hour after flow started. The centimetre scale is slightly exaggerated as it was placed on the dividing ridge a little nearer the camera than the little glacier. The photograph was taken by Miller vertically, as one of a stereo pair, with the trough horizontal in order to stop the kaolin from flowing. So the gradient when movement occurred was steeper than the photograph suggests.

A very small bergschrund can be seen within 0·5 cm. of the head-wall. At the right-hand side—a position which should correspond with the middle of the glacier—the kaolin has pulled away from the head-wall; 3 cm. from the head-wall is a second bergschrund feature consisting of a series of cracks arranged *en echelon*. The widest bergschrunds occur about 6 cm. from the head-wall, just up-glacier from the point where the surface gradient diminishes. These two bergschrunds curve slightly down-glacier as they approach the glass plate, but the third of the series turns much more markedly down-glacier as it approaches the other normal side of the model valley. The asymmetrical pattern of this bergschrund series illustrates the far greater drag on the " true " side of the valley than on the glass plate, but shows also that some drag was induced by the glass plate. The contrast between the simple clear-cut bergschrund pattern of the left-hand glacier model, shown in the shadow, and that of the right-hand one where it abuts against the glass plate, suggests that at least for qualitative demonstrations the right-hand model can be considered to represent half of a glacier bisected down the middle line. So the view we get through the glass plate is a fair indication of conditions within a complete model glacier.

From this last bergschrund series down-glacier to the sill—near the middle of the scale in the photograph—are four major step faults with many more smaller but quite distinct ones between.

Nye[2] predicted that such step faulting should occur near the head of an over-steepened portion of a glacier, but we, at least, rarely met such striking examples in the field as these little models showed. Fig. 3 shows such step faulting occurring in Lokebreen at the top of the great step from the level of Jostedalsbreen, shown in the background, down to Austerdalsbreen 1000 m. below.

In the zone down-glacier from the scale (Fig. 2) the crevasses formed as a result of the acceleration down the steep slope of the step closed up as the material was compressed by being pushed forwards from behind. A puzzling exception was the section immediately adjacent to the glass side in which the crevasses maintained themselves along most of the remaining length of the "glacier". On the other side a tear fault can be seen approaching the valley side at a small angle. This separated the actively moving material from that more or less anchored to the side wall. Similar tear faults also occurred higher up the glacier on the same side. The lowest few centimetres of the tongue were entirely uncrevassed.

A more accurate way of making the model glacier flow is to imitate the annual increment of snow by placing a wedge-shaped addition (thinning down-glacier) of the mixture on the upper part of the glacier. This new "snow" is then covered with a sprinkling of anthracite dust or coloured sand to represent the dust blown on to a glacier in summer. A second winter wedge is then added and the dusting is repeated. A seasonal rhythm in the glacier movement is then reproduced, and the tilting of the depositional layers and the drawing out of their upturned outcrops is very true to life. Miller took a short 16 mm. colour ciné film of this model glacier in motion.

A puzzling feature occurred in the movement in the zone where step faulting was active. In places a form of upthrusting from below occurred as if the velocity of the lower layers exceeded that of the surface layer. This effect was easy to observe after scattering dust on the surface when clean kaolin would reappear as underlying layers carried forwards beyond the dirty surface layer. Our immediate reaction was to consider that this phenomenon represented a form of extrusion flow (Streiff-Becker[3]; Demorest[4]), but Dr. Glen, who later saw it in action, considers that it is more likely to be a surface tension effect.

The longer glacier shown in Fig. 1 occupying the complete model valley was produced in the same way as the smaller right-hand glacier. The surface of this larger glacier sloped initially at 5° from the head to the second sill at the 60 cm. mark. The slope increased to 15° on the down-glacier side of the sill and continued thus to the end at the 80 cm. mark. The "trim" line, representing the highest level to which the mixture rose, can be seen in the photograph. The kaolin was again made to flow by tilting the trough gradually to a maximum of 20° and the trough was returned to the horizontal position just before the end of the trough was reached. In its upper part this model repeated the features of the half-glacier, but in an even more lifelike manner (Fig. 2). In addition it showed how faithfully the kaolin retained the surface marking initiated by crevassing in the upper steeper reaches, throughout the remainder of its course long after the cracks had closed up again. Fig. 4, a close-up of the section near the lower bend shows this zone along which the cracks were closing and yet remaining visible. It also shows, in the down-glacier portion, the tendency on both sides of the model for moraine-like marginal ridges of material to be left high above the quicker-moving central portion. If these ridges were sprinkled with dust representing debris tumbling down the valley sides on to a glacier, they would be a close replica of the lateral moraines which border many true glaciers. Yet in the model no ablation (which is normally associated with the formation of such lateral moraines) occurred. They were formed in the model much in the manner of the double marginal ridges left behind by a sludge tongue moving downhill under peri-glacial conditions.

The last group of these preliminary experiments represented an attempt at a quantitative reproduction of Vesl-Skautbreen. Our investigations of Vesl-Skautbreen (McCall[5]; Lewis[6]) have given us a clearer picture of its internal and surface movement than that which can be obtained of any other glacier. A model of the cirque was made, again cut in half longitudinally and bounded down this central section by a vertical glass plate. The scale reduction of the model is 1 : 1000.

Fig. 5 (p. 538) shows the representation against the glass plate of the central long section of a glacier about the same thickness as Vesl-Skautbreen but with the surface sloping at 30° instead of 26°–28°. The trough was tilted so that the surface rested at several angles between 30° and 50° and the trough had to be tapped for visible movement to occur. After 10 minutes the surface had moved from the dotted to the dot-dashed line. It had sunk 0·5 cm. in the upper portion and risen nearly 1·0 cm. in the lowest. Then the trough was left for five days with the surface sloping at 50°. During this period almost the only change to take place was due to evaporation of the water. This resulted in very considerable shrinkage. The velocity profile for the central zone was obtained by inserting a thin strip of black paper perpendicular to the surface along the glass plate, as far as possible in a straight line and reaching to the bottom. The change in the position of this strip in the ensuing 10 minutes showed that the mixture did not slip along the bed and that the velocity increased somewhat erratically towards the surface. The smoother curves of the subsequent experiments suggested that the wobbles in this curve were mainly due to the material immediately adjacent to the paper strip sticking to the glass side. As movement did not occur readily in this experiment we decided to make the model glacier thicker.

Fig. 6 shows the result of this further experiment representing a glacier a little thicker and larger, and again with a surface gradient of 30°, perhaps much as Vesl-Skautbreen was when it pushed up most of the great end moraine formed during the 1750–1850 maxima. The mixture flowed slowly but almost came to rest after 10 minutes, by which time the paper strip had moved forwards to the new position indicated. About half of this movement represented slipping on the bed and about half internal adjustment building up to the greatest movement at the surface. Wedge A was then added. This markedly accelerated the movement in which sliding over the bed predominated in the middle section and a rising of the snout in the lower portion. The addition of a new and longer wedge B again accelerated the movement causing both sliding and an upward bulging of the snout. This time, too, the velocity profile as revealed by the paper strip showed that the velocity was greatest within the glacier rather than at the surface. Each subsequent addition accelerated the movement initially but produced no new feature. The tendency for the velocity to be a maximum at between a third and a half of the depth continued to the end of the experiment, and the effects of bed drag became more and more evident. A clearer indication of bottom movement would be obtained if the velocity profile were marked by a line of dye or dust instead of by the inextensible strip of paper which did not reach the bed in the later positions.

Another experiment (Fig. 7) was made with a mixture of 60 parts light motor oil to 100 parts of kaolin. Movement was caused by tilting the trough so that the initial surface slope of 30° became 45°; the surface was plotted and the velocity profile noted after 5 minutes and again after 10 minutes. Finally the surface was tilted to 60° and movement allowed to continue for 10 minutes. A new feature of the movement was the presence of the immobile zone. The velocity profiles suggest that immediately above this immobile zone was one of intense shearing and above this the mixture moved more or less uniformly. The bed was not lubricated beforehand as we assumed that the motor oil would suffice for this purpose. This may account for the lower part of the mixture beneath the tongue sticking to the bed and behaving somewhat as we imagine an embryo drumlin does in the early stages of its formation.

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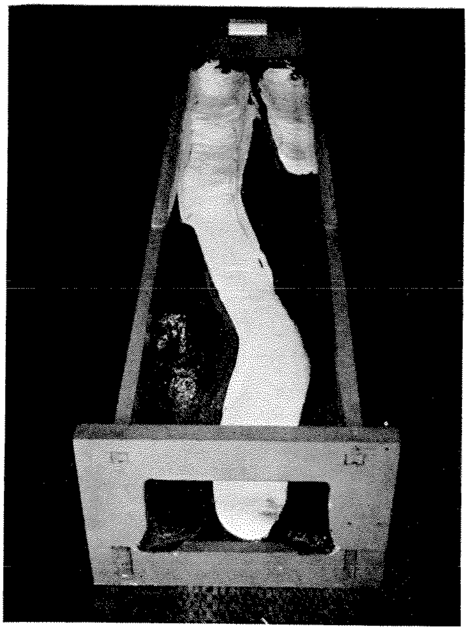

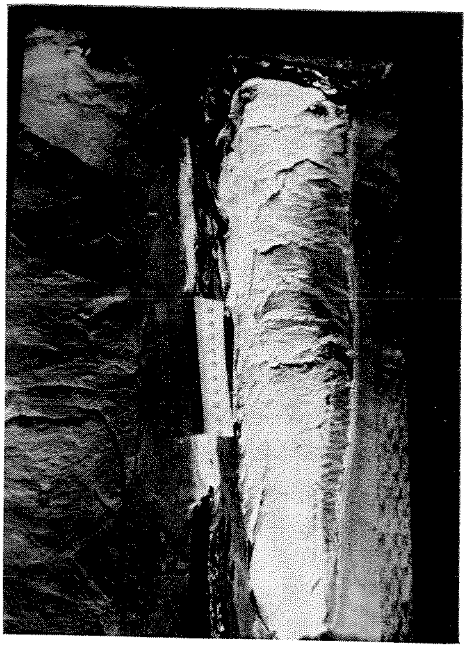

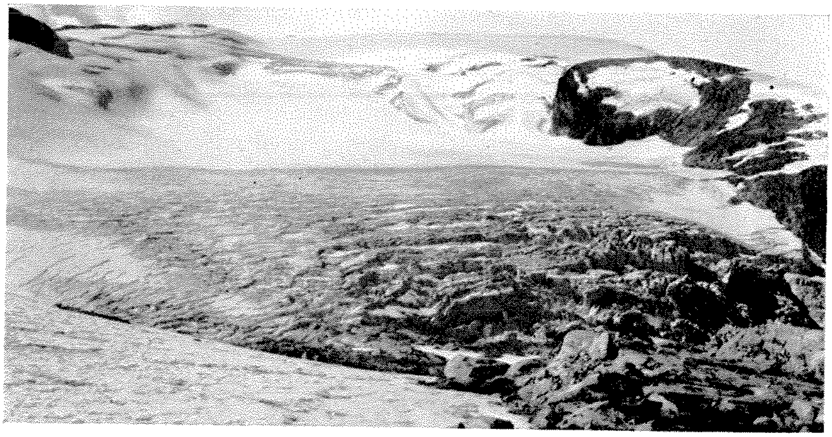

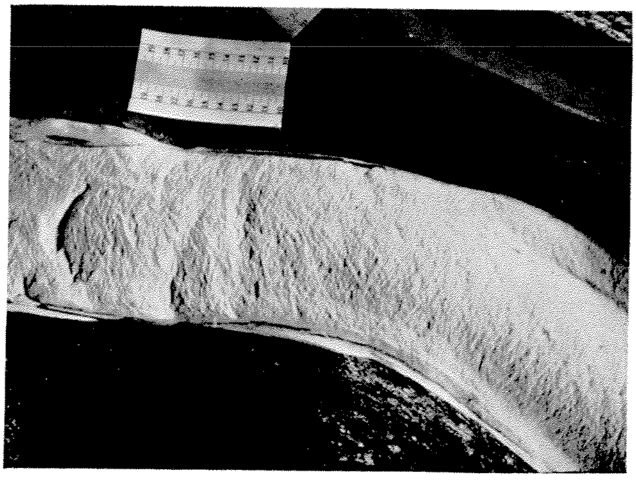

Fig. 1 (left). Two model glaciers in the trough (see p. 534)

Fig. 2 (top right). Close-up of model glaciers showing bergschrunds, step faulting and marginal tear faults (see p. 534)

Fig. 3 (centre). Multiple step faulting in Lokebreen where the glacier plunges down from Jostedalsbreen to Austerdalsbreen 1000 m. below. (Photograph by S. McKibben (see p. 535))

Fig. 4 (bottom). Close-up near the bend in Fig. 1, showing crevasses remaining visible after closing during their journey down glacier (see p. 535)

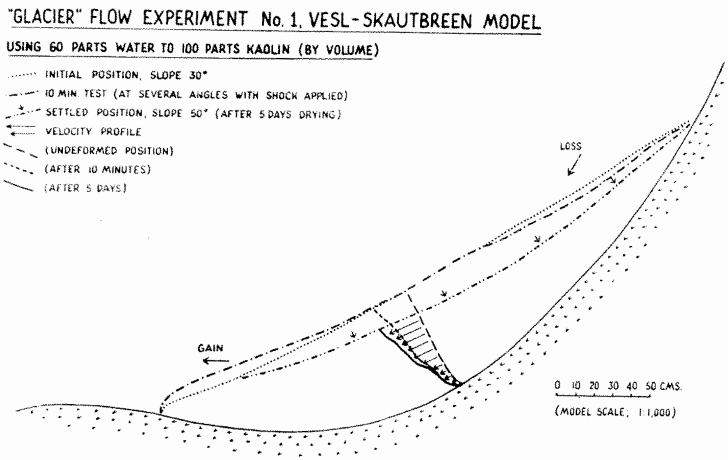

Fig. 5

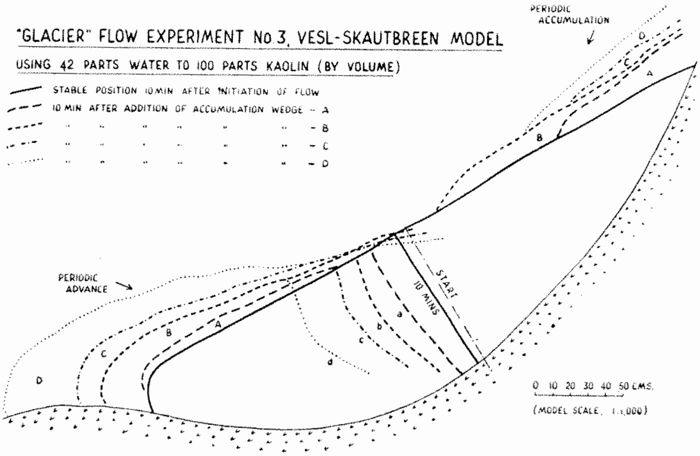

Fig. 6

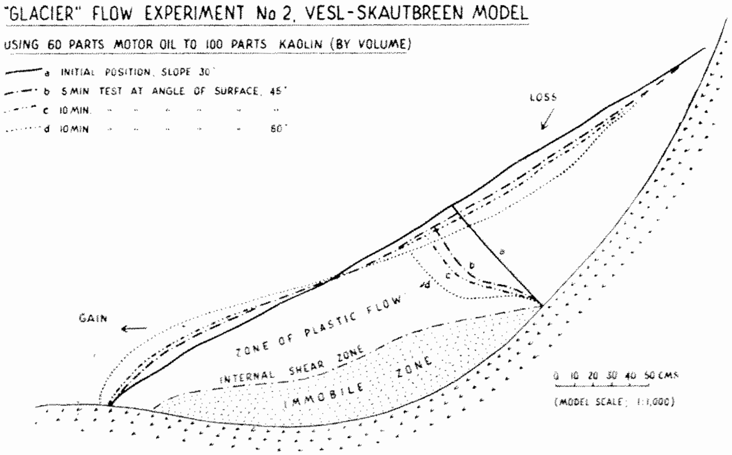

Fig. 7