# No. II.—The Fracture of Homogeneous Media.

By James Weir French, D.Sc., F.Inst.P.

Geologists are concerned with the origin and growth of worlds, in the evolution of which all the complex forces of Nature are involved.

To elucidate the mystery of the earth's creation and to piece together the fragments of its past, the geologist applies the detailed knowledge of these forces as they are disclosed by workers in any of the varied spheres of science. By the application, for example, of the recently acquired knowledge of radio-activity, the earlier conceptions of the age of the earth have been profoundly modified.

Geology as a science has no boundaries, and the observations, therefore, of an optical engineer concerning the surface phenomena and fracture of homogeneous media may be of interest to the members of this Society.

Homogeneity is a relative term. According to Lord Kelvin—

> "The perfect fulfilment of this condition without any limit as to the smallness of the parts, though conceivable, is not generally regarded as probable for any of the real solids or fluids known to us, however seemingly homogeneous. . . . In other words, the prevailing belief is that every kind of matter with which we are acquainted has a more or less coarse-grained texture . . . and in the meantime," continues Lord Kelvin, "we need only say that the definition of homogeneous may be applied practically on a very large scale to masses of building or coarse-grained conglomerate rock, or on a more moderate scale to seemingly homogeneous metals, or on a scale of extreme undiscovered fineness to vitreous bodies, continuous crystals, solidified gums, as indiarubber, gum arabic, &c., and fluids."

There is a remarkable similarity in the prismatic cleavage of very homogeneous and isotropic optical glass and of comparatively coarse-grained sandstone, typical specimens of which are submitted for your consideration. According to the statement of Lord Kelvin, just cited, the sandstone as well as the glass may be regarded, so far as fracture phenomena are concerned, as being truly homogeneous and isotropic.

In the first instance it is most convenient to study the surface phenomena and fracture of a transparent substance in which the strains introduced can be readily observed.

It is now generally recognised that the substance of a polished surface layer of such a material as glass differs in important physical respects from the original substance from which it is produced, and therefore from the underlying material. That vitreous substances differ structurally from crystals is well known. Crystals are built up by the grouping of their molecules according to definite systems. Their surfaces are natural, and, although they may be molecularly smooth, they are unpolished in the ordinary sense of the word. Whatever the material, polishing consists in disturbing the surface molecules to such an extent that their cohesion is sufficiently overcome to enable them to rearrange themselves just as the regular surface of a liquid is attributable to molecular mobility and the action of surface tension forces.

Whereas the molecular arrangement of the crystalline substance is an orderly one, there is no longer a definite arrangement of the surface molecules of the polished crystals. The arrangement of the polished surface molecules is probably a random one, and to the surface layer there has accordingly been applied the term "amorphous."

It may be anticipated that the physical qualities of the polished surface of a crystal will be different from those of a natural growth surface, and, indeed, it is well known that the weathering properties of a crystal are modified by polishing.

Since the substance of glass is itself amorphous, no crystalline structure being observable, to distinguish its polished surface layer as amorphous, as is so often done, is not satisfactory. The molecular arrangement of both the surface and the underlying material is presumably of the same type, a random one, but the surface layer molecules are probably differently compacted from those of the underlying material, and there is good reason to think they are subjected to very considerable tension forces.

Crystals being the results of growth, it is possible to study their surfaces in both the natural and polished conditions. Glass, so far as we know, does not grow with molecular regularity, and to obtain a natural surface is impracticable. It is a substance that can only be obtained in a polished condition, and this polished condition can be attained in several ways. When a piece of glass is fractured, the forces at the advanced edge of the crack are very great. The molecules are profoundly disturbed and rearrange themselves, thus forming a surface akin to that of a mobile liquid. Fracture also produces a polished surface, and again, if a piece of glass is subjected to the required degree of heat, the thermally agitated surface molecules are enabled to rearrange themselves. This operation is termed "fire-glazing."

Chemical action produces the same effect. Prehistoric flint implements that have been buried for ages often present a highly polished patina or surface layer attributable to weathering or chemical action, which exhibits all the phenomena of a polished surface layer.

When glass is rubbed mechanically under suitable conditions, the agitated surface molecules rearrange themselves. Mechanical forces are indeed those that are commonly employed by the optician for the production of polished glass surfaces.

It was the late Lord Rayleigh who first drew attention to the pool-like character of a polished glass surface, to its molecular uniformity, and to the absence of any transition stages of development. Sir George Beilby first attributed the rearrangement of the agitated surface molecules to surface tension forces.

By rupturing metals with great suddenness, Sir George Beilby has obtained portions of the fractured surface that do not show surface tension flow. When a large block of glass is suddenly ruptured, surfaces that appear matte are obtained, but under the microscope these matte surfaces are clearly the result of irregular fracture; each small element of the surface appears highly polished. It is probably the case that no glass that has not an amorphous surface layer has ever been obtained.

In support of the surface layer theory, there is now a considerable amount of evidence. If the surface layer differs appreciably in its physical properties from the underlying layer, there should be little difficulty in practically demonstrating the fact. Crazing of glazed pottery is due to greater contraction of the thin surface layer of glaze than of the underlying clay, the result being that the surface layer becomes subdivided by cracks normal to the surface. If a piece of glass is polished mechanically and is heated to a temperature just below the softening point of the body of the glass, the amorphous surface layer, which is evidently under tension, cracks and becomes subdivided just as in the case of glazed pottery.

This appearance is illustrated in Fig. 1, Plate XIV., the right-hand specimen being an example of crazed pottery and the left hand a highly magnified specimen of polished glass heated as described. The surface in question was quite continuous before being heated.

If a parallel plate of glass is polished on both sides, and if the polished layer of one of the surfaces is then very carefully broken up by fine grinding, the other originally flat polished surface will become concave. Either the polished surface layer is subjected to tension or the rough grinding of the other side has subjected that surface to pressure. It is more probable that the bending is principally attributable to tension of the polished surface. If the second polished surface is ground, thus relieving the tension and possibly introducing some pressure, the plate again tends to become flat. But the experiment is not an easy one to conduct, as the amount of bending to be observed is small and the results may be vitiated by temperature effects, irregular grinding, and residual annealing stresses in the glass.

There are other interesting experiments that in the case of a polished substance suggest the existence of an amorphous surface layer under tension. If, for example, the surface is tapped gently with a hard, rounded point, there will be produced around the point a circular crack which penetrates the surface layer. The forces required to produce these surface cracks are extraordinarily small. They are very much smaller than those that would be obtained from calculations based on the physical constants of the material.

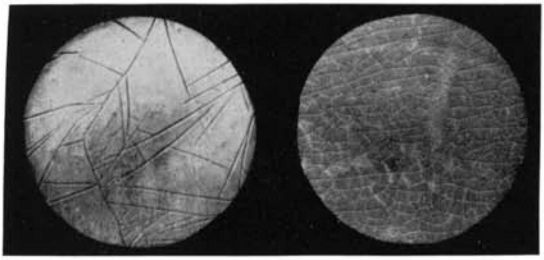

Fig. 1.

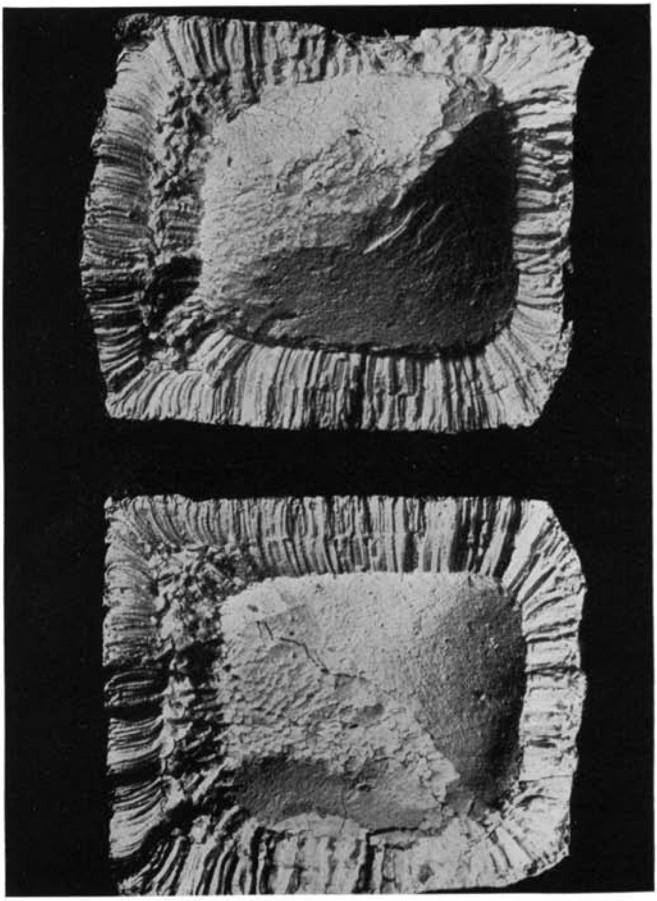

Fig. 14.

Some idea of the sequence of effects that contribute to the fracture of glass may be obtained from Fig. 2, which represents the various stages in the pressure of a steel ball upon a polished cube of glass placed between Nicol prisms in order that the strains introduced may be viewed. A very light pressure on the ball gives rise under crossed Nicols to a cone of white light (*b*) with a small amount of surface light at (*d*); the portions (*a*) and (*c*) appear dark. If the Nicols are paralleled it will be found that a very slight pressure has sufficed to produce a minute surface crack, the stresses at the edge of which are evidently considerable. If the pressure is increased and the Nicols are crossed, there may be seen a coloured sphere of light which is a clear indication of the production of the cone fracture indicated in the fourth view. A stage is next reached when the glass under the ball collapses. Under the impact the cone fracture may be extended in a more or less horizontal direction, and there may be formed diametral plane fractures which are of considerable importance in the linear cleavage of glass by means of a hard point such as a diamond. By further pressure the diametral planes may be extended to the edge of the brim, as indicated in the sixth view. When the Nicols are crossed, the strain is as indicated in the seventh view. Frequently at this stage small coloured spheres are visible within the cone, indicating the presence of subsidiary cone fractures.

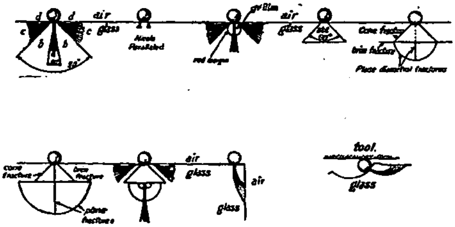

Fig. 2.

In these various examples, the ball having been applied to the centre of the block, the forces on either side are balanced. If the ball is applied to the edge, the central cone A of the first view will be deviated towards the side and ultimately a conchoidal splinter will be formed. From these experiments an idea of what occurs in the abrasion of glass is obtainable. For example, in the ninth view there is indicated the action of a round particle wedged into a depression of the glass surface. The horizontal movement of the tool which grips the particle throws sufficient force upon the glass to produce a conchoidal splinter, and the nature of the process is such that conchoidal splinters are formed instead of cone fractures, the presence of which would be disastrous from the point of view of the optician.

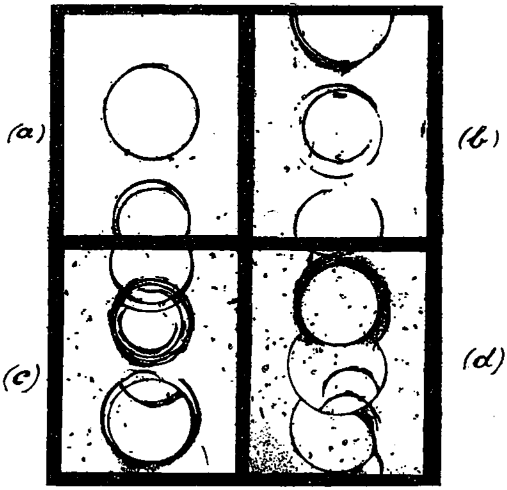

Fig. 3.

Owing to the fineness of the surface cracks, it is not easy to observe them until they have been emphasised by etching. Several types of percussion cracks in a homogeneous material, in this case glass, that have been made evident by etching are indicated in Fig. 3. A truly circular crack will be seen at (*a*); (*b*) shows a spiral crack, doubtless attributable to a slight spiral movement of the ball on the surface of the glass during the application of the pressure; (*c*) shows a number of concentric cracks, and also, in the case of the lower circle, an inner portion terminated by an earlier outer crack. At the top of this figure (*c*) it will be observed that, corresponding with an inner terminated crack, there is another that has been continued beyond, presumably, the original crack. In Fig. 3 (*d*) the central circle is very clearly terminated at the outside of the top circle.

What is technically known as a sleek consists in the ideal condition of a ploughed groove, the sides of which are clean and free from any evidences of percussion cracks or conchoidal fracture. The perfection of the particular sleek illustrated in Fig. 4 will be realised when it is compared with the typical scratch indicated in Fig. 5.

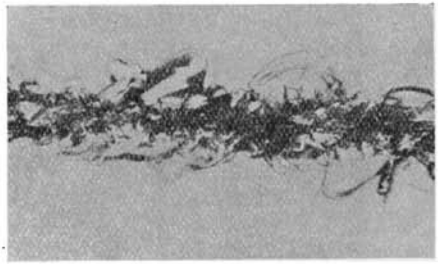

Fig. 5.

Fig. 4.

If a hard point in its passage over the surface of the glass chatters, and provided the impact forces are not too great, there will be produced instead of the sleek a series of surface

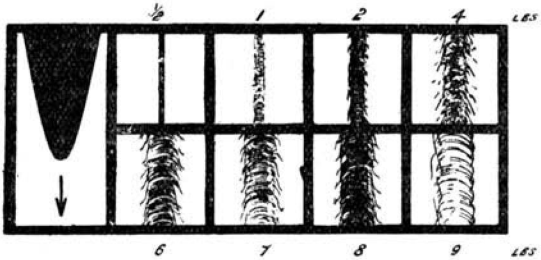

Fig. 6.

percussion cracks, several examples of which are indicated in Fig. 6. Loads varying from half a pound up to 9 lbs. were applied to a gramophone needle of medium hardness, the needle being drawn over the glass in the direction of the arrow. It will be seen that the cracks present their convex sides to the direction of motion. The needle has evidently jumped forward and in striking the material has compressed it in front and pulled it at the rear. It has accordingly parted behind the needle and not in front. At pressures of from 2 to 8 lbs. there will be observed tangential cracks, as if the material had been forcibly torn from the sides, just as a piece of tissue paper or the finished surface of leather can be torn when a point is drawn over it.

Fig. 7 shows the effect of drawing a knife blade over the surface of glass. In this view numerous small lines that have been emphasised by etching are visible. Most lines of this kind are really very fine series of percussion cracks, so fine, in the majority of cases, that careful examination under the microscope is required to distinguish their discontinuous character.

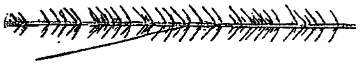

Fig. 7.

The probable existence of amorphous surface layers of the same general type in the case of glass or other homogeneous material that has been fractured, fire-glazed, or mechanically polished, has already been referred to. Surface percussion cracks on a fire-glazed surface are indicated in Fig. 8 at (*a*), and on a fractured surface at (*b*), the loads on the needle point being in each example 2 lbs. and 8 lbs. respectively. In the case of the heavier load at (*a*) the gramophone needle point has become flattened. In the case of the fractured surface under a load of 4 lbs. the needle has been allowed in the first instance to penetrate the surface, a cone fracture with diametral planes has been formed, and in producing the series of percussion cracks the longitudinal plane has been continued. It is evident in the photograph as a central black line of cleavage.

It is well known that marks made on glass by means of a French chalk pencil cannot easily be cleaned off. French chalk is an insoluble material that adheres tenaciously to glass, but these characteristics do not provide a satisfactory explanation of the phenomenon. If a small quantity of French chalk is dusted on the surface of a piece of polished glass and over this there is drawn a metal or even a pencil point, then, after very careful removal of the French chalk so far as possible, the surface when etched will appear fractured as indicated in Fig. 9.

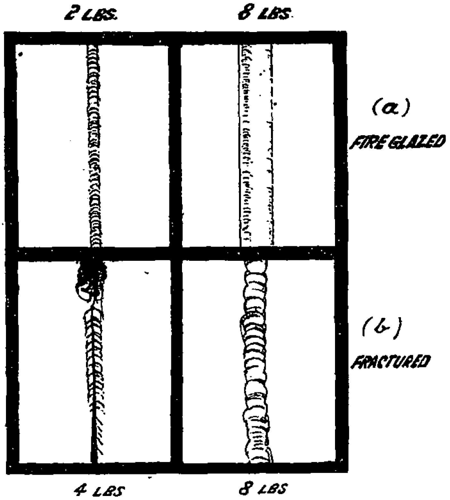

Fig. 8.

Fig. 9.

If the glass in the unetched condition is breathed upon, condensation presumably takes place along the cracks, thus bringing the markings into view, and it is also possible that minute fragments of the French chalk may become wedged into the cracks. To remove them is hardly possible. If the glass is polished they gradually extend into the underlying material, and, although they may not be visible, they can always be exposed by etching. Glass tubing through which a piece of metal has been passed is very liable to crack. The explanation doubtless is that the interior fire-glazed surface layer is under great tension owing to previous solidification of the outer surface and that the passage of the metal produces surface cracks of the type illustrated, which may readily extend themselves.

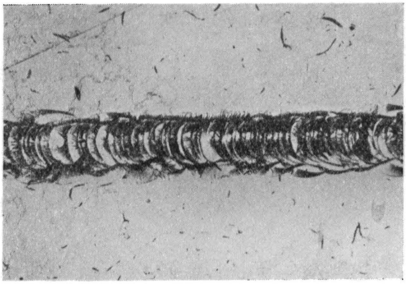

Fig. 10.

To avoid the use of hard materials when cleaning particularly the inner surfaces of glass vessels is very important.

Several chemically clean vessels were obtained direct from the suppliers and their interior surfaces were examined for percussion cracks, which were found in great profusion. It is quite conceivable that these percussion cracks may occlude gases or even liquids in sufficient quantity to vitiate precise physical experiments, and it is quite possible that the difficulty of removing the last traces of gases supposed to be included in glass may be attributable to a similar cause.

Light blows upon a homogeneous substance such as glass produce circular cracks and cone fractures. Similar blows or pressures upon natural crystal surfaces may give rise to the well-known percussion and pressure figures of stellate form. If, however, the crystal surface is mechanically polished, approximately circular percussion figures are obtained, as indicated in Fig. 10 of a polished quartz surface; but it will be observed that the circular cracks appear to spread irregularly beneath the surface layer, tending presumably towards the stellate form in the underlying crystalline medium.

From the geological point of view, ring fractures which have been described by Mr. E. B. Bailey,[1] with particular reference to Iceland, are of considerable importance.

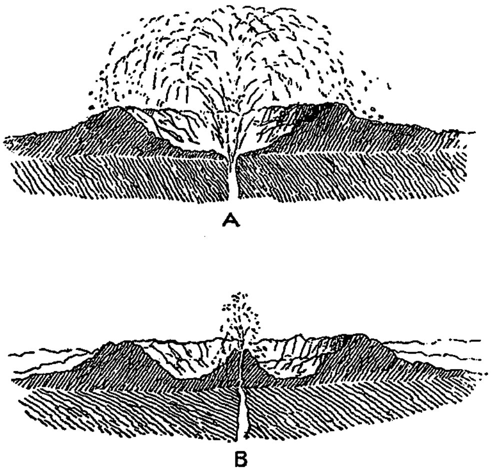

Fig. 11.

That the remarkable circular craters of the moon may also have originated in percussion fractures has been suggested, as for example by Suess. According to James Nasmyth, the circular lunar ridges have resulted from the ejectment of material from a central vent, as at (*a*) in Fig. 11, reproduced from the original paper.[2] At some later date the activity he assumes to have been much reduced, a central cone being thus formed, as at (*b*), and in some cases a level floor was produced by a flow of lava.

That so definite and sudden a change of activity should have occurred in the formation of so many of the lunar craters can

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[1] *Geological Mag.*, vol. vi, Oct., 1919.

[2] *Quarterly Journal of Science*, vol. i, 1864, p. 388.

hardly be credited. There is more reason to suggest that they are the result of percussion fractures, caused by the impact of large meteorites that have fallen into the moon. Although the meteorite might break into fragments which would spread themselves over the surface, there would be produced a cone fracture and possibly central intersecting planes similar to those producible in glass and over these regions of weakness volcanic activity would be most likely to occur. Thus the peripheral ridge and the central cone might be formed simultaneously instead of at two stages, as indicated in Fig. 12.

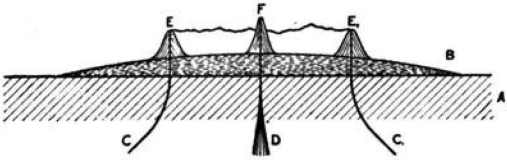

Fig. 12.

There are three craters visible on the lunar map, the arrangement of which has some resemblance to the series of percussion cracks on glass represented in Fig. 13. With regard to these lunar craters, Theophilus, Cyrillus, and Catharina, it is generally considered that Theophilus, the lowest crater, is of most recent date, since in its formation it has invaded and partially destroyed the ring of the presumably older adjacent crater, Cyrillus. But if these lunar craters are the result of percussion cracks, a reversal of the ages of Theophilus and Cyrillus is involved; Theophilus, so far as the cone fracture is con-

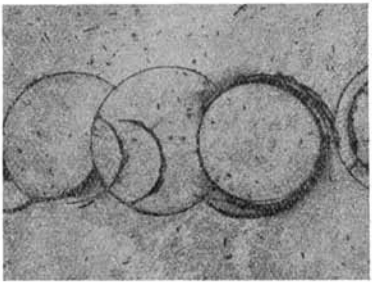

Fig. 13.

cerned, would be first formed, the cone fracture of Cyrillus being evidently of later date, as it is terminated by the former.

Having indicated the ease with which the surfaces of homogeneous media can be ruptured, it will be of interest to consider the extension of surface cracks through the action of tension forces attributable in the majority of cases to differential contraction of the material. Reduction of volume may be due to thermal contraction, as in the case of basalt, or to evaporation of moisture, as in the case of starch, or possibly to chemical changes and crystallisation, but an increase of volume is frequently associated with this last mentioned cause, as, for example, in the case of plaster of Paris that has set, but which continues to expand thereafter for many months.

As reduction of volume is associated with thermal contraction and also with evaporation, it is convenient to consider columnar structure of basalt in comparison with that of starch.

When a block of starch is dried, the outer surface sets while the inner portion continues to contract. Under the tension forces thus created in the interior rupture either partial or complete of the substance will occur at a depth determined by the particular degree of stiffness at which fracture can occur. Thus there is formed a distinct layer which may be entirely separated from the underlying material or separated from it only by a plane or region of weakness.

As the layer continues to harden and contract, prismatic subdivision that has originated at the first hardened surface, that is, the outer, extends normally inwards unless the deviation is modified by some change in what is equivalent in cooling basalt to the isothermal plane. Meanwhile the inner portion has continued to contract with the formation of a series of layers each of which subdivides prismatically, as is indicated in Fig. 14, which shows a block of starch, a portion of the two outer layers of which has been removed, thus exposing an inner core that will later follow the same course.

If the layer is terminated by a surface of weakness not an actual fracture, the prism ends will be irregular or even granular. The columns may extend regularly to the face before its actual formation. When the columns separate they will then frequently be terminated by cup joints, a number of which are visible in the illustration, and the formation of which in basalt has been the subject of so much geological controversy.

If when the under surface of the layer has definitely formed it remains in contact with the underlying material, then the prisms may extend through the surface into the next layer, as is so frequently the case in basalt, but if the surface has definitely separated there may not be continuity across the face. This feature is particularly common in starch formations.

Cup joints, according to Mallet, will generally present their concavities towards the outer face from which cooling or hardening has proceeded, but further transverse subdivision of the basalt prisms between the original joints may result in cup joints, the orientation of which will depend upon the distribution of the longitudinal contraction and must be fortuitous.

Many theories of columnar structure and jointing have been advanced in the past. At one time the spheroid theory of Mr. Gregory Watt received the recognition of geologists of repute. This theory was based upon the frequent occurrence of concentric layers in exposed basalt prisms.

It is of interest to compare this appearance of onion-like layers with the starch specimen (Fig. 14). Pebbles that exhibit similar layers have been illustrated and described by Prof. James Thomson in a lecture which he delivered to this Society in 1877, his lecture being an elaboration of one first published by him in 1862. Prof. Thomson rejects the spheroid theory, which appears to be untenable, and accepts the purely mechanical explanation of fracture resulting from thermal contraction attributable to the cooling of the basalt from one or more surfaces.

In a lecture on the same subject delivered by Robert Mallet to the Royal Society in 1874, the mechanical explanation is elaborated in greater detail, but Mallet does not agree with the explanation of cup or ball and socket joints proposed by Prof. Thomson. The latter regards the basalt column as being unconstrained externally. When the surface has set, further contraction will establish tension in the interior and compression of the outer layer, and this condition is inconsistent with the origin of fracture at the surface. He believed, therefore, that cup fractures start at the centres of the columns and spread outwards.

Mallet, on the other hand, considered the whole column to be subjected to a longitudinal tension force, which would be the case if the contracting columns were constrained say at its ends, and also to a radial tension due to radial contraction. Fracture would then occur normally to the resultant force, the fracture therefore being cup-shaped and originating at the surface.

It is probable that both sets of conditions occur in Nature, as specimens of fracture that corroborate both views are common.

The layers observed in weathered pebbles, several specimens of which are illustrated in Prof. Thomson's paper, are comparable, I believe, with the jointed layers of basalt and starch; but whereas the latter are apparently due to the contraction of the material underlying a fixed outer surface, the layers of the weathered pebbles may be due to the general expansion by weathering of the outer layer, and therefore its withdrawal from the fixed underlying material less affected by weathering. The conditions are as it were reversed in the case of the weathered material.

Prismatic columns extend normally from a surface of cooling, and their straightness thereafter is determined by the shape of the interior isothermal surfaces. Thus in the case of a sphere of glass the columns will radiate from a centre, there being good reason to believe that they originate at the centre and spread towards the outer surface which they may not actually reach. This is consistent with the theory of Prof. James Thomson, and is understandable when the compression to which the outer layers are subjected is considered.

These conditions are not so marked in the case of starch, and it will be observed in Fig. 15 that the prisms are comparatively well defined near the outer surface at which subdivision has commenced, at first in an irregular manner which has quickly become more regular. The radial arrangement of the prisms normal to the Isohygral surfaces, that is, surfaces of equal wetness, is well indicated.

Similar radial structure in glass is illustrated in Fig. 16, which represents portions of two large glass drops that have been quickly quenched.

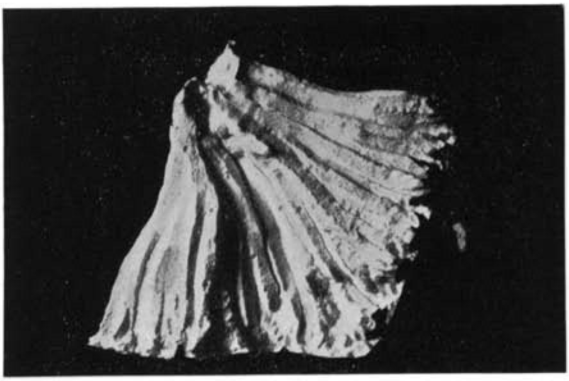

Fig. 15.

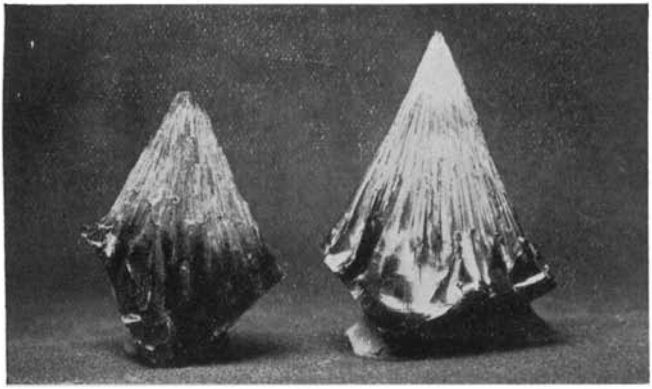

Fig. 16.

Fig. 17.

In neither specimen have the prisms definitely reached the outer layers which must have been under great compression as a result of the tension forces in the interior. At the centre the material is definitely subdivided. Several somewhat indefinite layers are observable in the case of the right-hand specimen.

These two specimens are really portions of very large Rupert's drops, which ordinarily are small beads of glass drawn out tailwise when hot and quenched in water. They are supposed to have been first made in Holland, and were introduced into this country by Prince Rupert, after whom they are named. A glass specimen that shows cup fracture is illustrated in Fig. 17. The rod of glass was gathered layer by layer on the end of an iron tube and was air-cooled, but the cup fracture traverses the successive layers obliquely, particularly at the outer edge. It does not run parallel to the gathering layers.

Radial prismatic structure in glass that has occurred on a much larger scale is represented by the specimen in Fig. 18, which was obtained from a melting of optical crown glass that was cooled at a rate sufficient for the formation of prisms, but not so quickly as to shatter the glass into thin dish-shaped splinters.

As the glass was of the best optical quality that had been stirred for many hours in the process of manufacture, the material may be regarded as being very homogeneous, although not isotropic in view of the stresses due to defective annealing, which must have been considerable but not so great as to give any appearance of colour when tested by polarised light. The dimensions of the pot were 24 inches diameter and 24 inches height, the material being Stourbridge clay mixed with 30 per cent. of burnt clay.

After the final stirring, during which the temperature fell below 1000° C., the pot of glass was withdrawn from the furnace and quenched externally over all with cold water. For about eighty hours thereafter the pot was allowed to cool at a slow and regular rate.

Fracture of the glass contents occurred radially from near the centre to the sides and base of the pot. The specimen illustrated being a portion taken from the right-hand side at a

Fig. 18.

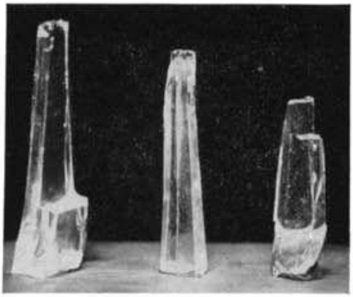

Fig. 19.

Fig. 20.

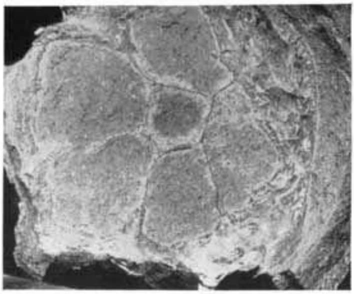

Fig. 25.

Fig. 21.

Fig. 22.

Fig. 23.

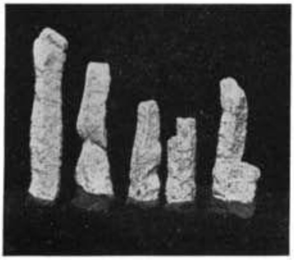

Fig. 24.

position about one quarter from the bottom, its position in the pot was that indicated on the slide, the columns being directed towards a central region just below the surface.

It might be readily assumed that, since the glass was cooled externally where the chilling must have been severe, the fracture would commence at the outer surface and spread radially inwards. These are the conditions that appear to apply in the subdivision of a basalt dyke, chilled, for example, by contact with the adjacent rocks, or in a slab of starch that has dried. There can be little reason to doubt that the subdivision of a homogeneous material into prisms depends upon the particular conditions under which the subdivision takes place, and may, therefore, be very varied.

From the illustration it will be evident that the prisms have not extended to the side of the glass. That they should do so is not to be expected when it is considered that, owing to the very poor heat conductivity of glass, the outer layers must have been placed under compression by the tension of the inner contracting portions.

It was observed that at their inner ends, that is, near the centre of the pot, the prisms were abruptly terminated at a comparatively smooth nodular surface from which they radiated. To break this nodule was difficult; it behaved like toughened glass. There can be little doubt that its surface layers were held in compression by the tension of its interior parts, and, therefore, any surface cracks that might have been formed would be held closed and their extension would be prevented. As the prismatic structure ended abruptly at the surface, there being no sign of its continuation within the nodule, it is evident that the surface of the nodule was not of later date than the surfaces of the prisms. Its formation was the first incident in the series of events. At the moment of separation of the nodule, its material would tend to move towards its centre; its surface would move to a place of smaller area, and, being thereby compressed, the formation of normal fractures would be prevented. But the material external to the nodule would withdraw towards the outside; its surface adjacent to the nodule would move to a position of greater area and would necessarily crack polygonally. These cracks would instantly spread outwards. That the action started from the centre and not the outside is indicated, as was previously stated, by the close adhesion of the prisms at their base, as compared with their inner ends.

Several of the prisms recovered from this particular melting of glass are illustrated in Fig. 19.

Recently, through the courtesy of Mr. Currie, of the Scottish Central Glass Works, Alloa, I had an opportunity of examining the columnar structure that had developed in the lowest sandstone course of the side walls of a small tank glass furnace.

The walls comprised two upper courses of fireclay blocks in which no columnar structure developed, and a bottom course of rough-grained sandstone blocks obtained from the Penshaw Quarries, Durham. Their cross-section was about 1 square foot. Firebrick jack-arching formed the floor of the tank, under which was situated the regenerator, but between the floor and the regenerator there was an intermediate air space.

The sandstone course was laid in August, 1913, and, after almost continuous use of the furnace it was taken down in November, 1921. It was during this operation that the columnar structure that had developed was observed. When the tank was being emptied preparatory to its reconstruction, the floor at one portion failed, and glass discharged itself through the intermediate space above the regenerator roof. Thus, while the walls were being rapidly chilled, the floor was maintained at a comparatively high temperature, but there was no clear evidence that would enable a definite decision to be arrived at as to whether the columnar structure was formed slowly during the working of the furnace or more rapidly during the final operation of emptying the tank. That it was formed during the last mentioned stage, and was, therefore, of recent origin seems, however, to be probable for the following reason:—

At the joint between the sandstone blocks and the superimposed fireclay course a considerable amount of corrosion had occurred, a deep V-shaped groove having been formed.

In Fig. 20 the dark oblique right-hand face of the specimen is a portion of this V-shaped, corroded face, the lower portion of the specimen being the bedded surface of the block. It will be seen that the prisms are disposed approximately normally to the bottom surface, and that at their upper ends they curve towards the oblique, corroded face. This would seem to indicate that a more or less oblique face existed before the prisms were completely formed.

Another specimen which shows straight columns is indicated in Fig. 21, the black lower portion being again a part of the corroded "V" joint.

Some of the prisms were of much larger section and better defined than others. A specimen of this kind is illustrated in Fig. 22, which is a side view, and Fig. 23, which is an end view of the same piece. The true columnar section of the structure is well represented in this latter view.

Several isolated columns are represented in Fig. 24. Their surfaces, it will be observed, are well defined, notwithstanding the comparatively coarse grained and open texture of the Penshaw sandstone, of which they are formed.

In conclusion, it may be of interest to consider the specimen represented in Fig. 25, which shows columnar structure that has been experimentally developed in a layer of baked fireclay of about 1½ inch thickness. The layer in question was the base of a small experimental optical glass pot of 12-inch diameter and 12-inch height, the pot being made of Stourbridge fireclay. The pot, with its contents of optical glass at a temperature of from 1200° C. to 1300° C., was wholly immersed in a tank of cold water for several minutes. Columnar structure that traversed the whole thickness of the fireclay was developed, as indicated. In the glass itself there was no evidence of any columnar structure. If such a structure had occurred also in the glass, it is probable that it could not have proceeded far, as the contents other than the outermost layer must still have been viscous in view of the small heat conductivity of the material. The thin layer of glass adjacent to the fireclay was greatly shattered, as is to be expected, and the presence there of columnar structure could not, therefore, in any case have been detected.