"On the Microscopic Characters of some Specimens of Devitrified Glass, with Notes on certain analogous Structures in Rocks." By DOUGLAS HERMAN and FRANK RUTLEY. Communicated by Professor T. G. BONNEY, D.Sc., F.R.S. Received May 28, 1885. Read June 18.

(Plates 1—4.)

Devitrification is a process which may either take place naturally or be brought about by artificial means. Instances of the former are familiar to us in once glassy rocks which have passed into a felsitic or micro-crystalline-granular condition. The change which has taken place in the conversion of obsidian into felstone is so great that it would not be possible to infer the original nature of the rock, were it not that certain structural peculiarities, often of a very delicate character, are retained. It is, indeed, a most remarkable feature in such rocks that a physical change so complete should fail to obliterate the perlitic structure and the fine streaky markings or fluxion-bands which are common in the vitreous lavas of every age. The microscopic recognition of such structures has of late years added considerably to our knowledge of the rhyolitic rocks and tuffs of Archæan and Palæozoic times, many of which were undoubtedly hyaline rhyolites. Through devitrification their original character has been obscured, and in many instances can only be revealed by the use of the microscope. Although much has been written upon this subject, including Vogelsang's admirable work,* we are still in comparative ignorance of the conditions under which such devitrification has taken place. The experiments of Daubrée,† made upon glass tubes at a high temperature and pressure, in presence of water, resulted in the development of a schistose or foliated structure, corresponding with the cylindrical form of the tubes acted upon: the development in some cases of reticulating cracks, due to contraction, the transformation of the glass into a friable substance with a structure both fibrous and concentric, and also into a hard material with similar structure. Professor Daubrée has likewise in these experiments produced radiating crystalline or spherulitic bodies, microliths, and actual crystals of pyroxene and quartz. The glass upon which he operated contained, in its unaltered condition—

* "Die Krystalliten." Bonn, 1875.

† "Études Synthetiques de Géologie Expérimentale," p. 155. Paris, 1879.

SiO_2	68·4
CaO	12·0
MgO	0·5
Na_2O	14·7
Al_2O_3	4·9
	100·5

while after experiment it contained

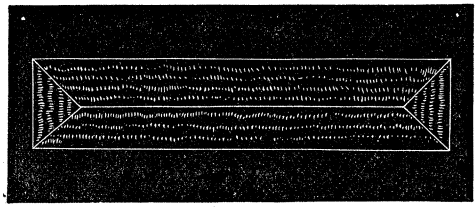
SiO_2	64·5
CaO	21·9
MgO	1·2
Na_2O	6·3
Al_2O_3	1·4
H_2O	4·2
	99·5

The observations recorded in the present paper refer to structures developed in specimens of glass which, for the most part, were prepared, and all devitrified, at the Glass Works of Messrs. Pilkington Bros., St. Helens, and it is possible that they may have a special interest for those who are studying the natural devitrification of obsidians or other glassy or glass-bearing rocks, since in the cases here recorded the precise conditions of devitrification are known, while in the natural process we do not know the precise conditions. We may, however, assume with considerable safety, that within certain limits there will be a more or less close analogy between the results of the natural and artificial devitrification, allowing of course a margin for certain natural conditions which it would be difficult if not impossible to reproduce experimentally. Thinking that some definite laws might be arrived at by devitrifying solids of various forms, we have operated upon cubes, hexagonal prisms, trigonal prisms, spheres, cylinders, flat plates, and other distinct forms, and these we shall first describe. The difficulties attendant upon the microscopic examination of such materials consist principally in their excessive opacity in some cases, and in others upon the readiness with which the substances disintegrate during the process of grinding. The latter difficulty has in many instances been successfully overcome by Mr. Cuttell, by whom most of the sections have been carefully and admirably cut, so that the boundaries of the solids are preserved without injury.

Specimen No. 115 originally formed part of a 1-inch-thick piece of plate-glass, which was accidentally coloured green, during fusion, by

a small quantity of ferruginous material. The plate, measuring about 6 feet by 3 feet 8 inches, was devitrified in the following manner. A layer of sea sand, previously washed, sifted, and dried, was spread to a depth of $2\frac{1}{2}$ inches on the floor of a kiln used for annealing glass-house pots. On this sand the plate was carefully bedded and covered with more sand to a depth of 6 inches, the whole being kept together by a low brick wall. The object of bedding in sand was to prevent the bending and fusion of the plate when the kiln attained its highest temperature. The kiln was then lighted, and the heat slowly raised. In six days it had attained a dull red, and in six days more was at its full heat, a very bright red, sufficient to soften, but not enough to melt, the glass through its covering of sand. This temperature was maintained for twelve days, when the kiln was let out, and quickly cooled by opening the door. The mass of sand, however, retained its heat for a considerable time after it was possible to enter the kiln, for, on removing the dwarf retaining wall four days after the door was opened, the plate broke in consequence of cold air coming in contact with one of the edges, whilst the other parts were at a comparatively high temperature. The glass was thus in the kiln altogether for twenty-eight days, during six of which it was gradually heated to dull redness, during six more the temperature was increased to bright red, maintained at this for twelve days, and cooled during four. It was found to be thoroughly devitrified, and large pieces were ground with sand and water to a fine smooth surface on both sides, by which the thickness was reduced to seven-eighths of an inch. The portion selected for microscopical examination was broken off a corner of one of the large pieces. It is opaque, dull, and porcellanous externally on the ground surfaces, in places which have not been ground the surface is rougher, and has a glazed appearance. The parallel faces are of a pale green colour with a reticulation of white lines, enclosing areas which range from about $\frac{1}{32}$ to $\frac{1}{4}$ inch in diameter, mostly polygonal in form. The specimen was of irregular triangular shape, and the sides and edges formed by cracks, probably produced at an early period of the heating process, are of a uniform greenish-white or pale greenish-grey tint. The hardness appears to be slightly greater than that of the same glass before devitrification, upon which it produces feeble scratches. A cross fracture, revealing the devitrified interior, shows very delicate, slightly undulating bands, which agree in direction with the parallel faces of the plate, and the alternate bands, when viewed in this direction, exhibit a silky lustre like that of chrysotile, satin-spar, and other fibrous substances, only rather feebly. At the marginal extremities of this fractured surface similar bands are seen running in a direction at right angles to the others, and these transverse bands occupy two triangular areas, as shown in fig. 1.

Fig. 1.



In order to ascertain more precisely the nature of this structure, three sections were cut:—

A, at right angles to the parallel faces of the plate.

B, parallel to one of the parallel faces of the plate, and including between the planes of section little more than the greenish superficial layer with the white reticulations.*

C, parallel to one of the short sides, passing through one of the triangular areas near one of the angles, so that the section includes both sets of bands, cutting one set transversely and lying parallel to the other. These sections exhibit the general structure admirably when held obliquely in different directions between the eye and the light.

The following is a description of their microscopic characters:—

Specimen No. 115, Section A. When viewed by ordinary transmitted light under a low power, the banding already described is indicated by transparent or very translucent belts, alternating with bands of very feeble translucency. Both kinds of belts are traversed by fine lines, indicating a fibrous crystalline structure, which commonly shows a radiate arrangement, the divergent groups of fibres emanating from centres situated on or about the margin or edges of the section.† Each radiating group has what may be termed its own allotment, bounded by well-defined straight lines. The boundary of one side of an allotment sometimes consists of a single straight line, at others of two or more straight lines, meeting in very obtuse angles. The boundary lines are not curved. When the section is rotated between crossed Nicols, these allotments form a well-marked and important feature. The divisional lines in this section may be separated into two groups. The first group consists of five lines, viz., a median line, running parallel to the two parallel faces of the plate-glass, and four lines which form a bifurcation at either end of this median line, and enclose the terminal triangular areas. The second group of lines consists of those boundaries of the crystalline allot-

* This layer is not the original surface, $\frac{1}{16}$ of an inch having since been ground off.

† It must, however, be noted that the margin of the section lies about $\frac{1}{16}$ of an inch from the original surface, the $\frac{1}{16}$ of an inch having been removed by grinding.

ments which run approximately at right angles to the surfaces which constitute the boundaries of the devitrified specimen. In polarised light the general aspect of the section is peculiar, and strikingly resembles a patchwork rug made of the skins of tabby cats. Further on we shall endeavour to account for this brindled appearance, which is represented in fig. 1, Plate I, as seen between crossed Nicols. The vertical edge of the section seen on the right of the field is the trace of one of the parallel faces of the devitrified plate-glass. The N.W. portion represents part of one of the terminal triangular areas, while the remainder shows some of the other crystalline allotments.

Specimen No. 115, Section B. This is a particularly interesting section. It is in fact one of the green surfaces of the devitrified plate-glass, *i.e.*, present surface, $\frac{1}{16}$ inch of glass having been ground away, and we can easily trace in it the polygonal structure already alluded to. Between crossed Nicols the polygonal areas are sharply defined and are irregularly clouded with crystalline aggregates, which appear dark. On rotating the section through 90° these dark aggregates become light, while the previously light portions become dark; we are, in fact, looking on the ends of bundles of crystalline rods. These polygonal areas are the cross sections of fasiculi of divergent crystals, and the boundaries of these polygons are shrinkage cracks, giving rise to a columnar structure, while the columns, like those of basaltic lavas, have their longest axes normal to the cooling surface. Fig. 2, Plate 1, shows the general appearance of this section, magnified eighteen linear, between crossed Nicols. As it seemed possible that greater amplification might afford more information concerning the nature of the little crystals which constitute these bundles, a $\frac{1}{4}$-inch objective was used, with the result shown in fig. 3, Plate 1. Only dark hazily-defined spots could be discerned between crossed Nicols, which became light on revolution of the section, while previously light portions became dark. The section has, in fact, the appearance of what is known as crypto-crystalline structure, and resembles, to a certain extent, some of the felstones, which, from other evidence, are known to have been once vitreous lavas. An examination of this section proves then that the polygons are the cross sections of the crystalline allotments of Section A, and that those allotments are longitudinal sections of polygonal, often pentagonal, prisms. Whether or not the polygonal jointing is connected with the crystalline developments, which it sheaths and separates, is a matter open to discussion. The Section B, when held between the eye and candle flame, presents the illusive appearance of being studded with concavities or convexities, from which it, we think, may be inferred that the radiate arrangement of the crystalline fasiculi originates at or about the centre of each polygonal area on the original surface of

the thick plate-glass.* If so it is possible that the strain consequent on crystallisation may have produced the prismatic fission. Fig. 1, Plate 3, might then be taken to represent portion of the surface of the slab at the commencement of devitrification, the dots indicating primary centres of crystallisation, while fig. 2 on the same plate would represent the development of prismatic structure by the formation of cracks between and around these centres of crystallisation. Fig. 3, Plate 3, shows one side (the lower one) of the block, fig. 2 the arrow denoting the direction in which the crystallisation advances. Apart from any hypothesis concerning the possible relation of the prismatic structure to the crystallisation, which may or may not be true, since it is possible that the prismatic structure was developed first, it is evident from the inspection of such a diagram that we may have a section giving prisms of very different widths, the width in section not necessarily representing the actual width of the prism, while in such a case the centre and general axis of the crystalline bundle may appear to be thrown on one side of the prism.

Specimen 115, Section C. This section truncates one of the terminal triangular wedges, of which mention has already been made, so that here we know for a certainty that we are looking on the cross section of the crystalline fasciculi belonging to the triangular area, and here we meet with precisely the same phenomena as those described and figured for Section B. On either hand the adjacent crystalline bundles emanating from the upper and under surfaces of the thick plate are seen lying in the plane of section, *i.e.*, we are looking at longitudinal sections of those bundles. In these we again see the cat-like brindlings. On the broken and partly ground away edges of this part of the section, a power over 500 linear shows that the crystalline bundles are made up of small fibres or microliths, closely packed side by side. The section is in all parts traversed by long, fusiform, or acicular brownish microliths, which lie with their longest axes in various directions, but usually across the general directions of crystallisation.

The brindled appearance in the crystalline bundles of these sections suggests at first sight the idea of pauses in the crystallisation, but when we find that by ordinary illumination the light is very faintly transmitted along these lines, some further explanation seems needful, and it seems probable that in these diverging crystallisations there is a kind of cone-in-cone or divergent composite structure, such as in that met with in the kidney-ore variety of hematite, or in clay-ironstone, the apices of the cones giving rise to a turbidity and being ranged so as to form successive arcs of approximately concentric circles, as indicated in fig. 6, Plate 3. From the evidence afforded by

* The surface of this specimen is $\frac{1}{10}$ of an inch from the original surface, which has been removed by grinding.

the sections now described, it seems certain that devitrification has in this instance commenced at the surface, and has proceeded inwards in directions at right angles to the different surfaces. Owing to its uniform rate of progression, the different sets of crystalline fasciculi have met along lines which divide the devitrified mass in a remarkably symmetrical manner, as shown in fig. 5, Plate 3, which represents one corner of the slab. That unequal rate of progression would cause a deviation from this symmetry is shown diagrammatically in fig. 4, Plate 3, and actually in the deflection of the diagonal line in fig. 1, Plate 1, Section A.*

Specimen G is a plate of flashed glass, about $2\frac{1}{2}$ mm. in thickness, which has been completely devitrified under conditions similar to those described for Specimen 115, that is to say, it was imbedded in silver sand (previously washed and dried), placed in a kiln, and the temperature gradually increased during a period of eleven days up to a bright red. This heat was maintained pretty steadily for eleven days more, after which the kiln was quickly cooled, and the glass withdrawn. The flashed surface is of a deep blue colour, and is incrusted with grains of sand. The opposite face is mottled with small dull green and greenish-white spots, and has a surface like coarse glazed pottery. Flashed glass was chosen in this case, as it was thought possible that some of the pigment might be carried inwards by the crystallisation. This, however, does not seem to have taken place to any great extent, for on examining a thin section taken at right angles to the broad surface of the plate under a power of 250 linear, the blue layer is seen to have remained on the surface, although its boundary is ill defined, and the bluish tint extends for only a very little distance inwards, gradually fading away. On the outer surface of the coloured layer there has, however, been a considerable disturbance of the blue glass, which appears to have been fused, and to have run between the sand grains against which it was bedded, *ff*, Plate 2, fig. 2, forming a cement of blue crystalline sheaves. The crystalline structure of the blue layer is throughout very irregular, consisting of similar sheaf-like aggregates and interlacing crystals. Passing from this layer we find the contiguous glass converted into radiating crystalline groups, separated by sharply defined joint planes,

* *Supplementary Note.*—Specimen 115. Thermal conductivity appears to be uniform on the large parallel faces of the plate, both at the margin and at a distance from the margin. The isothermal curves are also circles on the sides of the plate at right angles to the large faces. On a transverse section of the plate which traverses the crystalline fasciculi in directions both longitudinal and transverse, as in Section C, the wax also melts in circles both on the area of the longitudinal and on that of the transverse sections. This accords with the statement of M. Ed. Jannettaz ("Propagation de la Chaleur," "Bull. Soc. Géol. de France," 3e Serie, t. ix, p. 200) that minerals having a fibrous or lamellar character do not conduct heat better in the direction of the fibres or of the lamellæ than if they had no such structure.

ij. Plate 2, fig. 2, which traverse the plate normal to the large parallel surfaces. These joints are evidently the boundaries of polygonal prisms, and it is the ends of these prisms which cause the green and white spotted appearance on one surface of the specimen, while the reason that no such marking is visible on the other surface is partly due to the screen of sand grains which covers it, while beneath there would be no such markings until we reached the layer of originally white glass, because the joints do not appear to traverse the irregularly crystalline blue layer. Divergent crystallisations, also bounded by prismatic joints, start from the green spotted surface of the plate, and the two sets of divergent crystallisations meet in an undulating line, *ll*., Plate 2, fig. 2, which approximately divides the plate into two plates of about equal thickness. The joint planes on the opposite sides of this line do not coincide, and the halves of the plate if separated along the surface, of which this undulating line is the trace, would doubtless present a mammillated appearance. The general structure reminds one of that of part of a much flattened chalcedonic geode. It will be seen that in this specimen the devitrification has taken place on precisely the same principle as in the thick plate previously described. There has been a prismatic structure developed normal to the bounding surfaces, divergent crystallisation occurs within the prisms, and these crystalline fasciculi advanced in opposite directions until they arrested one another, but the line of arrest in this case is sinuous, while in the preceding specimen the lines of arrest are straight. On examining the section under a power of 50 diameters, fine lines, like small scratches, are seen to cut across the divergent crystallisation. Under much higher powers they appear as rod-like microliths, and they lie with their longest axes in all directions, but mostly transverse to the divergent fibres.

Specimen I is part of a completely devitrified square prism of plate-glass. The devitrification of this specimen was brought about by two separate operations. The whole of the prism, about 4 inches in length, was bedded in silver sand and heated during four days to a temperature gradually increasing from that of the atmosphere up to a red heat, maintained at that for two days more, and then quickly cooled. When cold it was broken in two and found to be regularly devitrified to a depth of about $1\frac{1}{2}$ mm., the interior being unaltered. One of the halves was then burnt again, this time for the same period and under exactly the same conditions as Specimen G, *i.e.*, bedded in sand, brought gradually to a bright red, maintained steadily at that heat for eleven days, and then quickly cooled. The faces are of a pale greenish-yellow, have a glazed appearance like that of pottery, and are traversed by a network of very fine cracks. When the specimen is held before a strong light these surfaces present a spotted appearance, similar to that seen on the plane surface of other devitrified

solids. Under the microscope it is seen that the crystallisation has advanced as usual from the surfaces inwards. After passing through a distance of about $1\frac{1}{2}$ mm. from the surface there has been a pause, marked by a fairly well-defined line, indicating the extent of the devitrification produced by the first heating to a red heat. This line is not straight, but has a series of slight convexities directed inwards, each convexity being bounded by joint planes normal to the surface. The prism therefore had first of all a devitrified envelope, the inner surface of which was mammillated, and each mammillation was the termination of a small prism. As the crystallisation advanced from the inner surface of this envelope, a fresh series of less numerous joints was developed, giving rise to a coarser prismatic structure, and between these joints we see in section a beautiful divergent crystallisation, each divergent group originating on the inner surface of the first crystalline envelope, a single prism sometimes containing only one such group, at others several. The general direction of these prisms is normal to the surfaces of the devitrified specimen, and the lines of arrest would join the opposite angles of the square section, were it not that in this particular slice an irregular pentagonal area occurs, against four of whose angles the lines of arrest abut. This irregular pentagon is a transverse section of another set of divergent crystallisations, whose longest axes would diverge from the axis of vision, and they evidently emanated from one of the basal planes of the large devitrified square prism, or from a transverse fracture as the prism was broken across after the first heating. Had the specimen been a cube, a section taken parallel to two of its faces and passing accurately through the centre of the cube, would merely have shown two continuous lines of arrest joining opposite angles and intersecting in the centre of the square section, assuming, of course, that the crystallisation advanced equally from all six faces. Such a structure would divide the cube into six equal four-sided pyramids, as indicated in the diagram, Plate 3, fig. 7. In the specimen before us the crystallisation has advanced rather irregularly, and the lines of arrest are consequently not continuous straight lines, but continuous series of straight lines, a repetition, in fact, of the conditions indicated in the diagram, fig. 4, Plate 3.

Specimen H is portion of a similar square prism of plate-glass, heated gradually for six days to a red heat under exactly the same conditions as the first operation on Specimen I. It differs from the preceding specimen in having been devitrified for only a slight distance from the surface. A section of the crust through one of the angles presents an appearance precisely similar in character to that of the crust of Section E_2 (a six-sided prism), figured on Plate 2. These are groups of divergent crystals which pass from the surface inwards, and are separated by prismatic jointing. The inner surfaces of each

crystalline group is convex, the convexity being directed towards the interior of the solid. When magnified between 500 and 600 diameters these convex surfaces are seen to be fringed by the projecting terminations of the divergent crystalline fibres.

Specimen K. This is part of a completely devitrified trigonal prism of plate-glass, devitrified by two operations, under precisely the same conditions as Specimen I, and the section has been taken parallel to the basal plane. The general principle of devitrification elucidated by the examination of the preceding specimens may also be clearly recognised in this case, but the crystallisation, after the first envelope was formed, advanced in a somewhat irregular manner, which needs interpretation. The irregularity in the crystallisation of this specimen may be attributed to the fact that there is a flaw in it. The general structure is shown in Plate 3, fig. 8. Here we notice first of all the envelope or devitrified crust, due to the first heating operation, in which there is prismatic structure and a series of divergent crystallisations trending inwards. Next comes a similar but coarser series of prisms also normal, or approximately normal, to the sides of the trigonal prism, and in these the divergent crystallisation has also travelled from without inwards. So far there is no deviation from the general principles of devitrification which we met with in the preceding specimens, in fact the crystallisation has proceeded inwards as usual, in directions approximately normal to the limiting planes of the devitrified solid. We now meet, however, with an apparent exception to the general rule, for the three sets of crystalline fasciculi, instead of continuing their course until they arrest one another in three straight lines joining the angles and the centre of the triangular section, are suddenly arrested and enclose an area rudely shaped like a three-rayed star, this being subdivided into three irregular portions. The deltoidal areas are traversed by cracks, and from points along these lines we have groups of crystals diverging on *both sides* of the lines. They have consequently travelled from within *outwards*.

The different areas of devitrification are by no means symmetrically disposed. Diagram, fig. 8, Plate 3, shows, with approximate truth, how the parts of the actual section really occur. It will be seen on reference to this figure, that at the point *a* there is a crack which extends in a curve towards *b*. From a point on the curved line *ab*, about opposite to the middle of the edge in which the crack *a* occurs, another nearly straight crack passes to *c*, and from the inner surface of the devitrified crust a third crack extends in a curve from the little fissure *a* to the point *d*. The crystallisations diverge on both sides of these three cracks. They are bounded by prismatic joints, which are continuous across the cracks, and each pair of crystalline fasciculi diverges from a common centre situate on the crack and between a pair of prismatic joints. These three distinct areas of crystallisation

are very irregular in form, and this has already been attributed to the presence of the flaws emanating directly and indirectly from the fissure. There appeared to be no reason why in such a solid the devitrification should not proceed steadily inwards until the three sets of prisms arrested one another along three lines passing from the three angles of the triangular section, and meeting in its centre.

With a view to settling this point another trigonal prism (Specimen No. 143), free from any flaws, was devitrified. A transverse fracture through this devitrified prism shows three distinct and similar areas of crystallisation; each is an isosceles triangle. These triangular areas are bounded by the three sides of the prism and by three straight lines of arrest, which accurately join the centre or axis of the prism with its three angles or edges, fig. 9, Plate 3. This demonstrates conclusively that the irregular devitrification seen in Section K is due to simultaneous crystallisation along flaws.

Specimen D heated twice under same conditions as Specimens I and K, is part of a completely devitrified six-sided prism of plate-glass. The surface has a glaze like that of pottery. The transverse section of the prism is not a perfect hexagon, and it has not been cut quite at right angles to the principal axis. There is a well-marked crust of divergent crystalline fasciculi due to the first short heating, prismatic joints being also present, but they are not well defined. Devitrification has then proceeded inwards in directions approximately normal to the lateral faces of the prism in broad divergent crystalline groups, separated by joint planes, which preserve at the best a very imperfect parallelism. In fact the prismatic structure which they indicate seems very irregular, and in the section a prism is often represented by a lanceolate or an irregularly shaped area, while the divergent crystallisations do not all seem to be formed in directions parallel to the plane of section. These crystallisations show brindled markings, similar to those seen in Specimen No. 115. There is strong chromatic depolarisation in this, as also in the preceding Sections I and K.

Specimen E is part of a six-sided prism of plate-glass, 2 cm. in diameter, which has been devitrified to a depth of barely $1\frac{1}{2}$ mm. under precisely the same conditions as Specimen H. The devitrified crust is yellowish-white, and has a glazed surface like that of pottery. Two sections have been cut from this specimen, E being taken transversely to the principal axis, and E_2 parallel to it and to one of the faces of the prism. The latter section consists, in fact, only of the devitrified crust of one of the faces of the prism.

Section E, taken transversely to the principal axis of the six-sided prism, shows a devitrified crust, which by reflected light looks white, while by transmitted light it appears under the microscope of a brown or yellowish-brown tint. It consists of divergent groups of very delicate acicular crystals, but even under high powers their termina-

tions, where they shoot into the unaltered glass, cannot be clearly made out. In most cases their terminations appear to be rounded, while in others they have a rectangular aspect, suggestive of a basal plane or an edge normal to the principal axis. The groups are not separated by prismatic joint planes, but the divergent crystals of adjacent groups appear to slightly overlap. The directions of extinction indicate that they are possibly rhombic forms. When magnified about 570 diameters the individual crystals seem frequently to consist of linear aggregates of minute globulites, but this appearance is possibly deceptive, and in some cases the crystals exhibit no such structure. The terminations of the crystals pass rather irregularly into the adjacent glass, giving the edges of the crystalline groups a fringed aspect somewhat like the pile of velvet. The adjacent glass shows colourless spheroidal specks or globulites.

Section E_2 is taken parallel to one of the faces of the six-sided prism, and is, indeed, a shaving of the devitrified crust. Mr. Cuttell succeeded in making a section the full size of the face, and from this the drawing, fig. 1, Plate 2, was made. In this drawing a basal and lateral edge are shown, and it will be seen that from these edges divergent groups of crystals pass inwards. With the exception of this fringe, which represents more or less oblique sections of the crystalline groups which constitute the devitrified crust, the remainder of the face shows only a polygonal network, the polygons being the cross sections of prisms. It has, in fact, the same structure as the margin, only the crystalline groups are in this part cut transversely to the direction of their growth, while at the margin they are cut obliquely, for the section being taken a little distance inwards from the surface of the face trenches slightly upon the crystalline groups of the adjacent faces, both lateral and basal. The section as originally cut was so feebly translucent that an endeavour was made to reduce its thickness. This, however, resulted in its almost total disintegration along irregular cracks without materially increasing its translucency.

Specimen F. This is a completely devitrified sphere of light-coloured bottle-glass 18 mm. in diameter, devitrified in two operations under the same conditions as Specimens I, K, and D. Under the microscope a section taken through the centre of the sphere shows a somewhat irregular circumference, which is accounted for when the surface of the original specimen is carefully examined, for it is seen to be pitted with numerous small cavities, and to have a rough fritted and imperfectly glazed aspect. The irregularities of this surface are due to the impressions of sand-grains, a few of which may still be detected adhering to the surface. The glass has evidently undergone incipient fusion, and the crystallisation in the immediate neighbourhood of the sand-grains is very small and confused. This irregularly

crystalline margin is bounded internally by a sinuous crack, showing the extent of the devitrification produced by the first heating to which the specimen was subjected, while other irregular cracks traverse this portion circumferentially as a rule, but they sometimes pass through the margin radially. The latter are few, penetrate but a short distance, and are mostly fringed by delicate crystalline fibres normal to the crack, and usually terminate in a radial group of fine acicular crystals or fibres. In one or two spots the cracks are seen to follow the contours of small cavities, from which sand-grains have been stripped in the process of grinding the section. Inside the wavy circumferential crack the crystallisations have shot inwards in long divergent groups, which towards the middle portion of the sphere give place to large irregular radiating groups of crystals, so large, in fact, that there does not appear to be more than half-a-dozen of them in the section, and these are in most instances cut through in a plane remote from their centres, thus giving oblique and transverse slices through the crystalline rods. Had these groups been able to crystallise freely they would have resulted in spherules, and this, indeed, might have been the case had the devitrification of the sphere been incomplete; as it is, they seem to have rudely polygonal boundaries. The devitrification of this specimen seems in part to be of a micro-crystalline-granular character under a magnifying power of 18 linear, but under a power giving an amplification of 570 diameters this is seen not to be the case, the mass being resolved into a closely matted aggregate of little acicular crystals with a general tendency to radiate grouping, as shown in fig. 4, Plate 1. In fig. 5 on the same plate the general aspect of a portion of the sphere at and near the margin is shown. The circular hole near the margin is where a sand-grain, around which the glass has fused, has been stripped out in grinding.

Specimen No. 78 is portion of a large hemispherical mass of completely devitrified sheet-glass taken from a mass of many tons which burst from the furnace in the liquid state and ran into a "cave" underneath. The mass solidified rapidly, but owing to its great bulk remained at a high temperature for several days. In the specimen there is a fragment of uncombined lime, indicating that at the spot from which the specimen was taken the fusion of the raw materials composing the glass was not quite complete. This specimen exhibits a curious and very rough concentric scaly or platy structure. It is of a pale greenish-white tint, and the broken surfaces are covered with small glistening hair-like crystals. It feels rough to the touch like a piece of unglazed porcelain, which it rather resembles, and it has a distinctly vesicular structure. The vesicles are spherical. In thin section it is very feebly translucent, and consists of a mat of minute groups of radiating crystals. The aspect of the surface of a

roughly broken piece of this specimen magnified four diameters is shown in fig. 5, Plate 2.

Specimen No. 105 is a piece of plate-glass 12 mm. in thickness, having the uneven surface usual in plate-glass before it has undergone the process of grinding. Devitrification in this case has given to the glass the appearance technically known as "burnt," and it was brought about in the ordinary process of annealing owing to the kiln being too hot. The glass was in the stiff, pasty condition suitable for rolling when introduced into the kiln, and was kept at a bright red by flame playing almost directly upon it for about half an hour, during which, and possibly during a short period of subsequent cooling, the devitrification was effected. The devitrification of this specimen is quite incipient, and affects merely the two parallel surfaces, one of which is uneven and scratched owing to contact when in a soft condition with the rough bed of the kiln. This latter surface is extremely interesting, as it shows a reticulating series of irregular cracks, traversed in places by straight belts of spherules which are apparently in no way connected with the cracks, and begin and end abruptly in a seemingly capricious manner, fig. 4, Plate 2.* The cracks are similar to those produced in glass by heating it and plunging it in water. Other isolated and larger spherules are also to be seen upon both surfaces of this specimen. Fig. 3, Plate 2, shows one of these surfaces—the upper, as seen by ordinary transmitted light, and magnified 32 linear. The shaded spots represent incipient spherules which fail to show any depolarisation; the darker spots are decided spherules with strong depolarising power. The unshaded portion of the section also transmits light between crossed Nicols, and is therefore in a state of strain. Under a magnifying power of 1150 diameters the incipient spherules can merely be resolved into brownish granular patches, sometimes approximately round, not uncommonly dumbbell-shaped, or like two coalescing spheres, but usually they are of irregular form, and their general aspect is nebulous.

Specimen L. A piece of pale greenish sheet-glass transferred, when in the semi-fluid state suitable for working, to a small pot in which it was maintained during four or five hours at a temperature barely sufficient to permit of its being "gathered." It is traversed by rudely parallel, irregular, flocculent, milky bands. Under a power of about 250 diameters numbers of minute crystallites are visible; they show no double refraction. Some are stellate, others fusiform or acicular. The latter are often wholly or partially surrounded by fine dusty segregations, which frequently seem to be diminutive divergent spicules. The most common forms have the aspect of monoclinic or

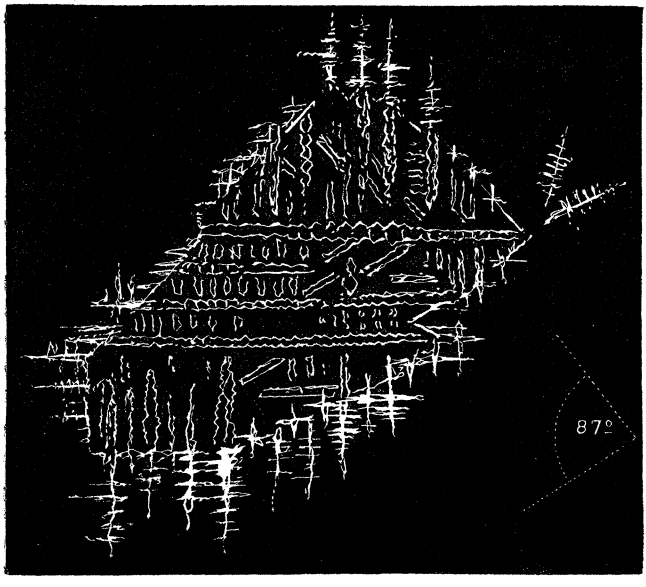
* This specimen closely resembles some of the spherulitic obsidians of Montana, U.S. Compare this figure with fig. 5, Plate XX, "Quart. Journ. Geol. Soc.," vol. xxxvii.

triclinic crystals. Their angles vary considerably; one gave 150°, another 116°, but these measurements are of little value, as it is doubtful whether the individuals measured were lying parallel with the planes of section. Some of these forms are shown in fig. 6, Plate 2, not represented as they are actually grouped in the preparation, but selected from various spots. They closely resemble some of the crystallites met with in the slags of blast furnaces. They occur in the white turbid bands in the glass, the transparent portion being almost free from them.

Specimen M is a piece of clear sheet-glass, about 2·5 mm. thick, from a pot containing somewhat less lime than usual. Owing to the furnace being rather cold during the time the glass from this pot was being worked, devitrification in the form technically known as "ambitty" set in, and increased to such an extent that blowing was stopped and the pot emptied by ladling. The specimen was blown shortly before the ladling operation was commenced; it contains a few very beautiful crystallites similar to those figured in Plate 8 of Vogelsang's "Krystalliten." One of them, which closely resembles one of the usual forms of snow-crystals, being a skeleton hexagon or six-rayed star, gives angles of 60° between the component crystalline needles. These exhibit double refraction, and undergo extinction in directions parallel to and at right angles to their longest axis. Between crossed Nicols depolarisation from strain is visible in the adjacent glass, the minute brushes of light being more intense about the points of the principal needles. It would appear from the depolarisation and directions of extinction that this crystallite may be referred to the rhombic system, twinned somewhat after the manner of chrysoberyl. This seems the more probable, since some of the forms in Section L also resemble certain rhombic forms. The crystallite just described is seen when examined under a power of about 280 linear to be traversed by an irregular network of strong cracks lying in the same plane as the crystallite, and extending nearly to but never beyond its margin. In the centre of the crystallite is a dark spherule. The fact that the reticulating cracks are restricted to the area occupied by the crystallite indicates a relation to the latter, and the depolarisation of the adjacent glass indicates strain. Since this strain-depolarisation only occurs at the margin of the crystallite, we may infer that the strain is connected with its development, and the cracks are no doubt the result of this strain. Had the body been a completely developed crystal and not a skeleton form, the strain would probably have resulted in the development of a perlitic crack, and not in a reticulating series of cracks which possibly arise from strain about a number of points. Another crystallite in the same piece of glass is very different in appearance to that last described; its general outline is that of an irregular hexagon. It is traversed by four well-

marked crystalline rods, apparently composed of piles of octahedra like those of alum, and where they touch the margin of the crystal they usually pass beyond it, forming little spicular crystallisations like fir-trees or like the crystals formed in cast iron. They throw out branches at right angles to the main spicule. The crystallite is also traversed by other crystalline rods of a like character, but at right angles to the first set, and these also pass out in little fir-tree-like crystallisations. There are also small rods which run in two directions obliquely to the former, and which intersect in an angle of about 87°. The form therefore is not cubic, as might at first sight be thought. The larger spiculæ also show double refraction. There is some depolarisation in the glass around this crystallite due to strain, but no cracks are developed. The spiculæ extinguish parallel to and at right angles to their longest axes. At least they appear to do so, but it is difficult to tell, and the colour difference is so slight when a Klein's plate is employed that it is impossible to speak with any certainty on this point. On the whole we are inclined to regard these crystallites as belonging to the rhombic system. The one last described is a twinned form, and exhibits several re-entering angles. A rough sketch of it (fig. 2) is appended.

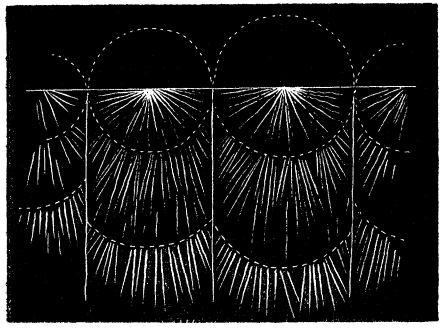
Fig. 2.



Generalisations.

From the microscopic examination of the specimens already described,* it seems evident that the devitrification of solids of the nature described in this paper takes place in a definite and apparently uniform manner, to which Specimen No. 105 is no exception, for the incipient spherules and the well-developed spherules are but rudimentary phases of the divergent groups which we generally meet with, and which have been already described. In Specimen 105 they are essentially superficial, and we can imagine them as hemispheres, as represented in fig. 3, ready, as devitrification advances, to be continued inwards, in which case we cease to recognise their spherulitic

FIG. 3.



character. In solids free from flaws the devitrification appears then, as a rule, to consist in the development of divergent groups of crystals, the divergence being usually limited by a network of minute joints, which give rise to small polygonal prisms. These crystals and joints extend inwards from the different faces of the solid, and may or may not ultimately meet. The crystalline groups in their respective prisms are banded by arcs of circles, which we may assume are related, but perhaps obscurely, to the initial pseudo-spherulitic structure of the superficial crust of the solid. These arcs indicate successive stages of growth. The crystallisations from the different faces of the solid ultimately, in small masses, arrest one another, and devitrification is then complete. In the case of the sphere, Specimen F, already described, the process has gone on in much the same

* With the exceptions of Specimens 78, L and M, in which devitrification was produced during cooling from the fluid state, and Specimen 105, which was probably still somewhat soft when devitrification commenced, all the specimens described were devitrified whilst in the solid state by more or less prolonged periods of heating.

manner for a slight distance from the surface, after which an irregular crystallisation has been set up from independent centres; but it should be remarked that difference in the chemical composition is known to influence the mode of procedure, as well as the character of the devitrification. The direction of the prismatic structure always seems to be approximately normal to the surfaces, and the divergent sheaves of crystals advance from the surface inwards by successive growths within the prisms. It seems quite possible that in the absence of such prismatic jointing the whole mass would become spherulitic, or would consist of an irregular felted mass of crystallites. The near resemblance which some of the specimens just described bear to devitrified and partially devitrified obsidians shows how close the structural relationship is, and that, allowing for difference in the conditions under which the process takes place, the principle of devitrification is the same.

Specimen No. 122*d*, a piece of ordinary sheet-glass, which was bedded in white sand and heated during a period of only four days to a temperature gradually increasing from that of the atmosphere up to a blood-red—a temperature somewhat lower than that employed for any of the specimens previously described, shows purely superficial devitrification by the development of globulites and spherules or spherulitoid crystallites, like fig. 11, Plate 3. In this particular crystallite, which is of a pale brown colour, no structure can be made out. It seems merely to consist of an aggregate of globulites, but in other cases bodies of precisely similar form show a decided radiating crystalline structure, like that of the brown spherules, which occur with them in the same specimen, the only difference between these crystallites and the spherules consisting in the external form or limiting surface. It is for this reason that we propose to call them spherulitoid crystallites. Fig. 10, Plate 3, drawn from the same piece of glass, shows part of the network of cracks by which the surface is cut up, and the curious manner in which the globulites have segregated along these cracks, so as to leave the fairly well-defined circular and oval spaces in which the globulites are less densely packed. Spherules sometimes occur within these clearer areas, but the latter do not seem to have any necessary connexion with the development of the spherules.

In Specimen No. 122*b*, superficially devitrified under the same conditions as the preceding, a tendency to the formation of perlitic structure is seen around some of the spherules.

Specimen 126, a piece of rough plate-glass, $\frac{1}{2}$ inch thick, bedded in white sand, contained in a small fire-clay pot, and placed in a kiln, the temperature of which was gradually raised during a period of $8\frac{1}{2}$ days, by which time a dull red heat, about 650° C., was attained. As it was known by comparative experiments with similar pieces of

glass contained in other pots in the same kiln, that no appreciable change had taken place in the glass up to this time, we propose to reckon, in this and subsequent experiments, what may be called the *active* period of devitrification, from the first attainment of 650°, neglecting altogether the time required to bring the specimen up to this temperature, which necessarily varies in different cases, and is known to be without appreciable effect on the glass. The pot containing Specimen 126 was withdrawn from the kiln 29 hours after its first attaining the temperature of 650°, by which time the heat had slightly increased. The pot with its contents was allowed to cool during about four hours, when the glass was removed from its covering of sand, which had cooled down almost to the atmospheric temperature. This specimen shows devitrification only on the surfaces, the alteration being so slight that writing can be clearly read through the glass when it is placed close over it, but when raised an inch above the writing the latter appears blurred and illegible. The devitrification, which is quite incipient, consists in the segregation of vast numbers of minute granules and globulites about various points on the surface of the glass, and in very many cases small stellate crystallites lie in the midst of these segregations. They are colourless and translucent, but too small to show any double refraction, even if they possess the property. Under an amplification of 120 linear the specimen shows portions of its surface which are still quite clear and unaltered. The margins of the unaltered areas show some fine nebulous segregations which envelope no crystallites, but the majority contain the stellate forms already alluded to. Of these, the simplest form is a four-rayed star or cross, the arms of the cross being apparently at right angles, but most of these crystallites are many-rayed, as shown in fig. 13, Plate 3, which was drawn with a magnifying power of 820 linear. On the top and left hand margin of this drawing portions of a crack are shown, and on certain parts of the surface of this specimen the nebulous and crystallite-bearing spots are separated by a network of irregular cracks.

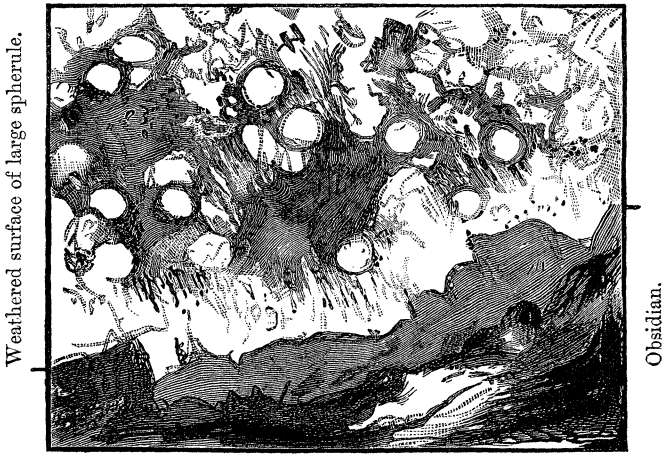
Specimen 127, a piece of polished plate-glass, $\frac{3}{4}$ inch thick, treated in the same pot as Specimen 126, and under exactly the same conditions. This is another instance of incipient and purely superficial devitrification. The general appearance is somewhat like that of No. 126, but in this case, although a few imperfectly developed spiculæ are present, there are no distinct stellate crystallites, possibly because in glass of this kind, containing a considerable quantity of lime, stellate crystallites do not occur so frequently as in the quality represented by Specimen 126, and the alteration of the glass consists merely of delicate nebulous spots, which under a power of 820 linear are seen to be composed wholly of globulites, and this is the most rudimentary phase of devitrification touched upon in this paper.

The little nebulous patches are mostly circular in form, and these circular patches often coalesce. There are a few instances in which the globulites occur within sharply defined circular or approximately circular boundaries, but for the most part the nebulous patches shade gradually away into the glass. One of these patches magnified 820 diameters is shown in fig. 12, Plate 3. The structure foreshadowed in this and in Specimen 126, may be regarded as spherulitic.*

Specimen No. 147 is especially interesting on account of the perfect manner in which it demonstrates that devitrification takes place from the surfaces of a crack, just as from any other surfaces. The

* A very interesting example of a like structure, but on a much larger scale, is seen in a specimen of obsidian collected by Mr. John Arthur Phillips, at Hot Springs, near Little Lake, in California. The obsidian is black and contains several greyish-white, or yellowish-white, spheroidal bodies (lithophysen of Richthofen), which range up to an inch in diameter. These, when examined carefully, are seen to consist of numbers of small spherules, about $\frac{1}{32}$ of an inch in diameter, but many of still smaller dimensions. The minute spherulitic structure of these large spherules is best seen on weathered surfaces, but even on fractured surfaces the spherules may still be seen, though their spherical character is less clearly visible, owing to interstitial matter, which becomes removed by weathering. In these larger spherules there is evidence, though obscure, of a radiating structure. The mimicry of the little spherules built of globulites, in Specimens 126 and 127, by these large spherules built of little spherules, in the obsidian, is very striking, but it is quite probable in the latter case that the smaller spherulitic structure was set up in the large spherule after its formation, the vestiges of a radiating crystalline structure tending to confirm this view.

Fig. 4.



Part of large spherule in obsidian from Hot Springs, near Little Lake, California.

Fig. 1

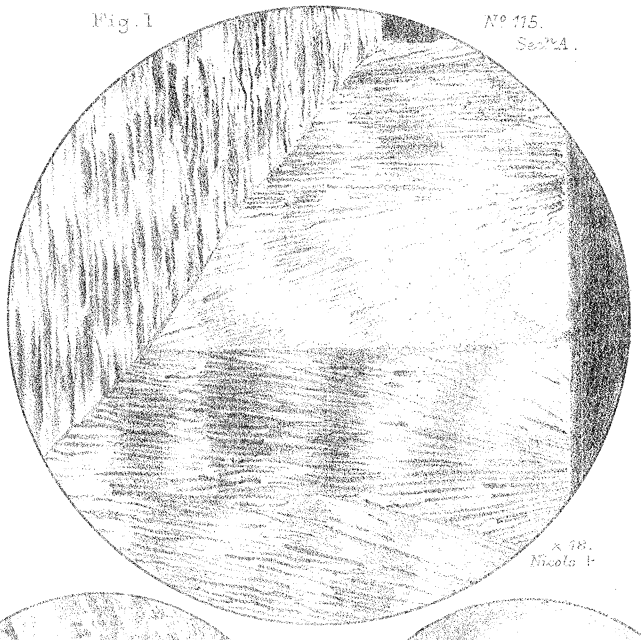


Fig. 2.

Fig. 3

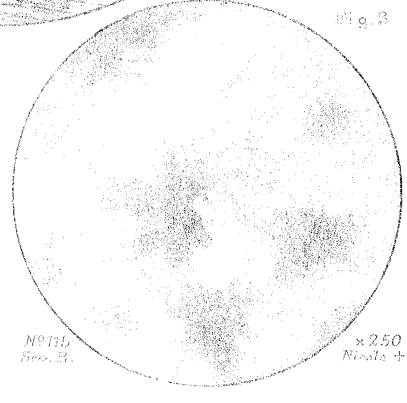


Fig. 4

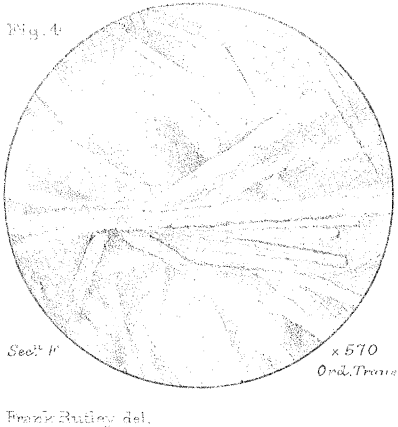


Fig. 5.

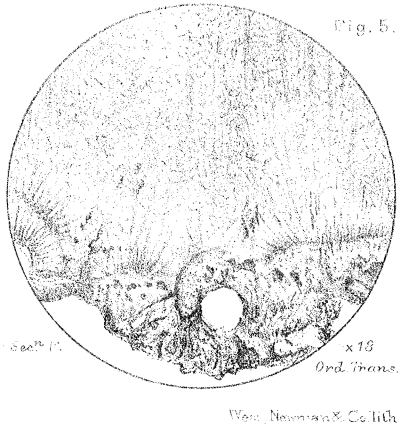


Fig. 1.

Fig. 2.

Fig. 3.

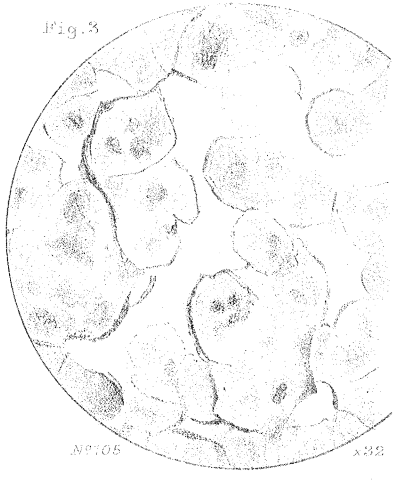


Fig. 4.

Fig. 5.

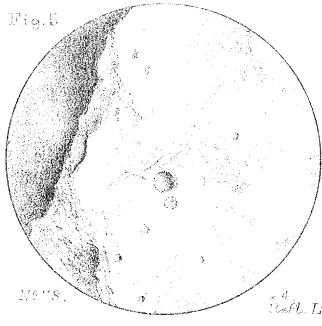


Fig. 6.

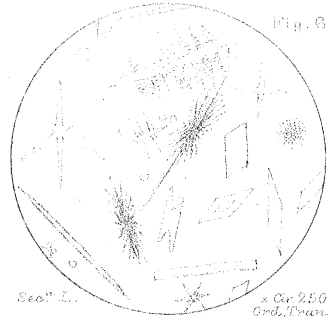


Fig. 1.

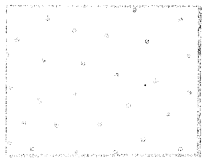


Fig. 2.

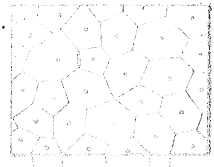


Fig. 3

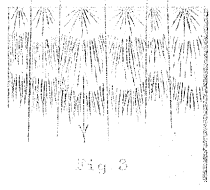


Fig. 4

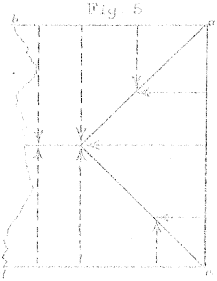


Fig. 5

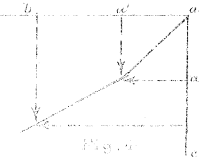


Fig. 6

Fig. 7

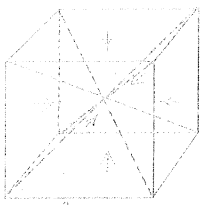


Fig. 8
Sec.n K
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Fig. 9
Nº 143
Nat. size

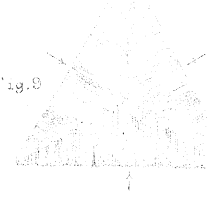
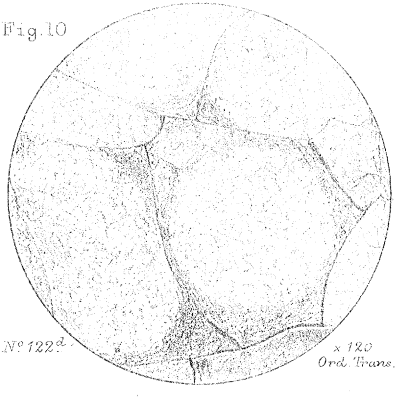
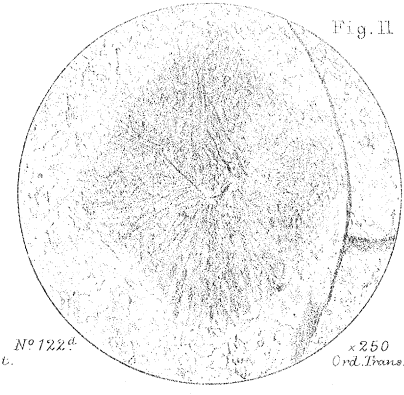


Fig. 10



Nº 122d x 120
Ord. Trans. Lt.

Fig. 11



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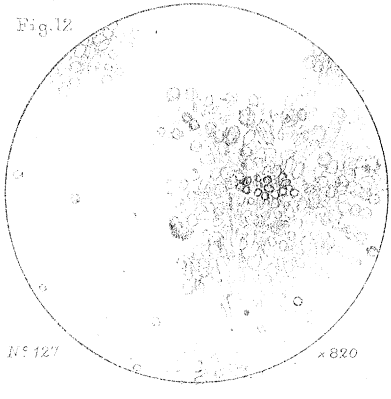
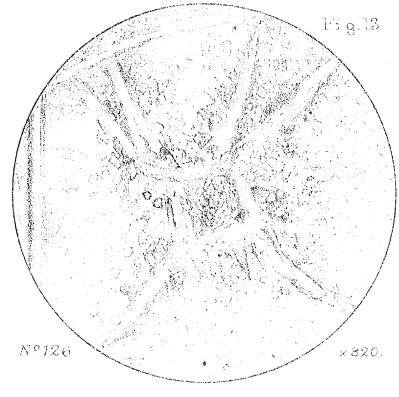
Ord. Trans. Lt.

Fig. 12



Nº 127 x 820

Fig. 13



Nº 126 x 820.

Frank Hurley del. West, Newman & Co. lith.

No. 111 Nat. size.

Fig. 1.

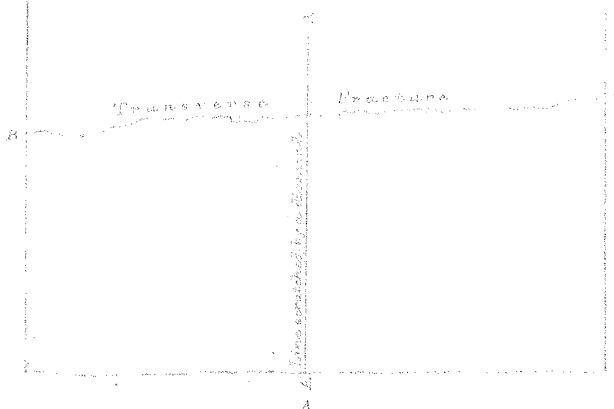
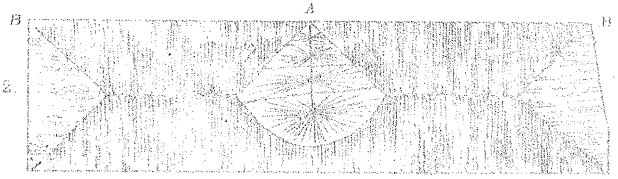


Fig. 2.



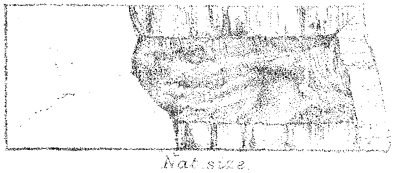
Fractured surface along the line BB.

Fig. 4.

Nat. size.

Fig. 5.

Fig. 3.



Nat. size.

Nat. size.

Frank Ratley del.

West, Newman and Co. lith.

specimen is a slab of $\frac{3}{4}$-inch British plate, about 4 inches by 3 inches in diameter, and upon one of its surfaces a straight cut or scratch, about 2 inches long, was made by a diamond, producing an exceedingly fine crack, extending at the edge of the plate to a depth of over $\frac{1}{2}$ inch in a direction approximately normal to the surface upon which the scratch was made, and gradually dying out to the end of the diamond cut. The crack was sufficiently fine to show Newton's rings. The specimen was then completely devitrified by heating continuously for nine days at a bright red heat, a temperature considerably higher than was employed in the case of Specimen 126, 127, and it was subsequently cracked across in the direction of the line marked BB in fig. 1, Plate 4. Fig. 2 represents the fractured surface. At each end are the usual triangular areas, formed by lines of arrest, but the line of arrest which usually joins the apices of these triangular areas is here interrupted by another series of crystallisations which have emanated from the crack produced by the diamond scratch. In the half of the plate nearest to the scratched surface we have, indeed, a reproduction of what has taken place at the outer edges of the plate, the result being a nearly equilateral triangular area of crystallisation, bisected by the crack already mentioned. This crack, however, passes a little beyond the median line of arrest, and from its termination the crystallisation radiates and ends against a curved arrest line, as shown in fig. 2, Plate 4.

That devitrification does not always proceed in the orderly and uniform manner seen in Specimens 115, 147, and, indeed, in nearly all of the examples already described in this paper, will be best realised by reference to the figures of Specimens Nos. 132 and 136 on Plate 4, figs. 4 and 5. Fig. 3 in the same plate, Specimen No. 137, is a small slab of glass partially devitrified. The crust has been formed in the usual way by crystallisation proceeding from the surface inwards, but the process has been arrested, and where the outer crust is broken away a core of somewhat cracked but perfectly clear glass is seen, in which no spherules or other crystalline bodies are visible. In Specimens 132 and 136, however, the result has been different, for after a slight external crust has been formed, devitrification has also started from numerous points within the glass, giving rise to a well-marked spherulitic structure.

Why these spherules have been formed instead of a gradually increasing crust is a matter which we hope to explain in a subsequent paper.

FIG. 1.

FIG. 2.

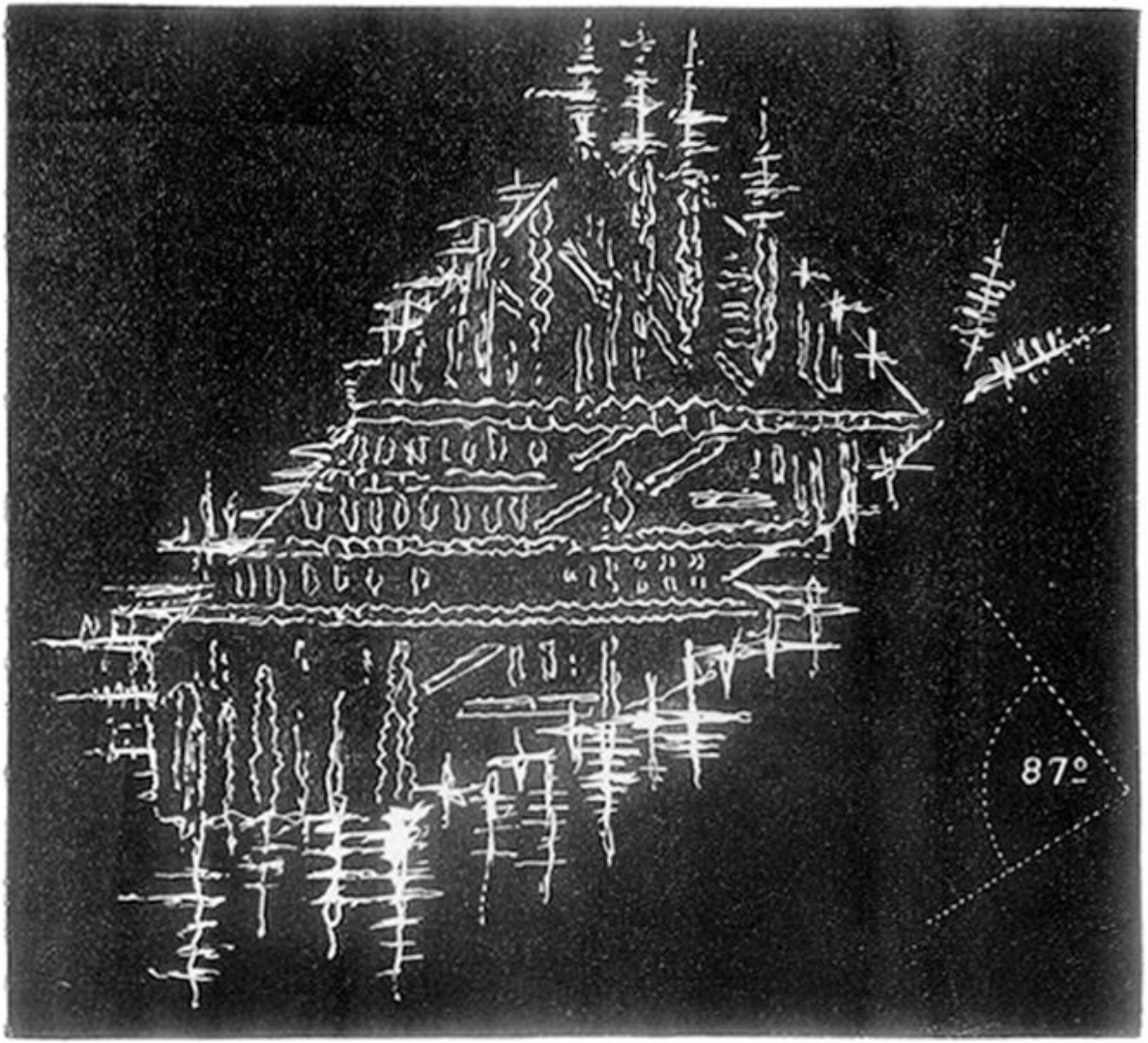


FIG. 3.

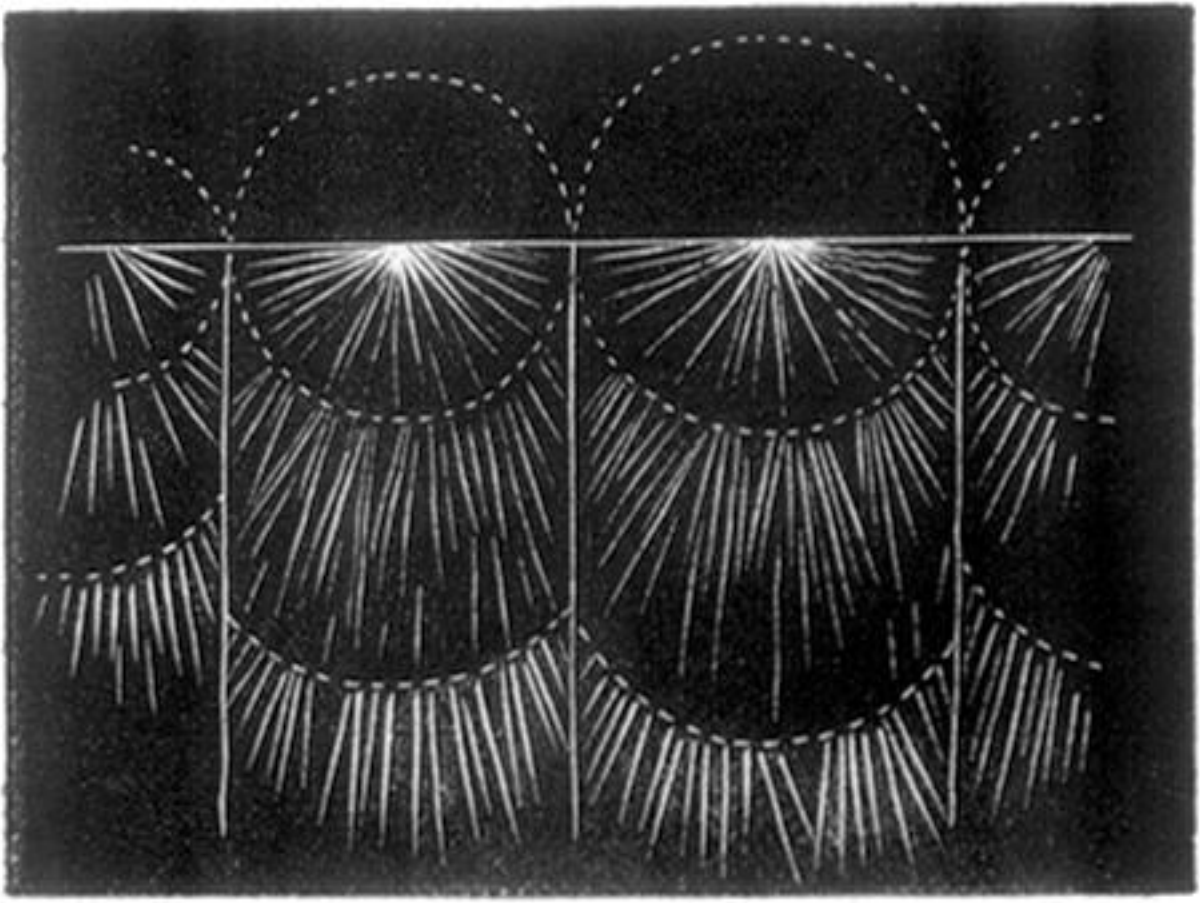
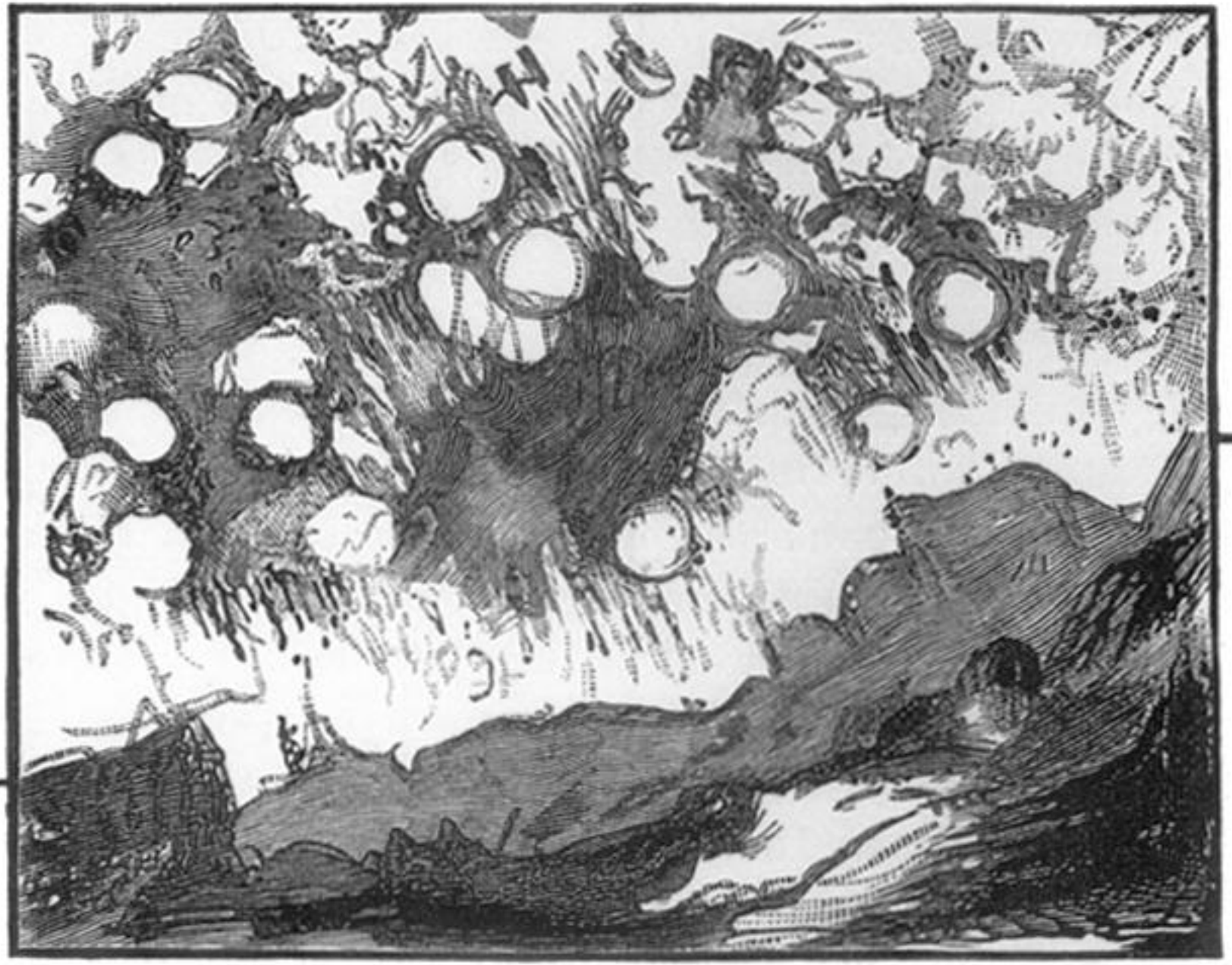
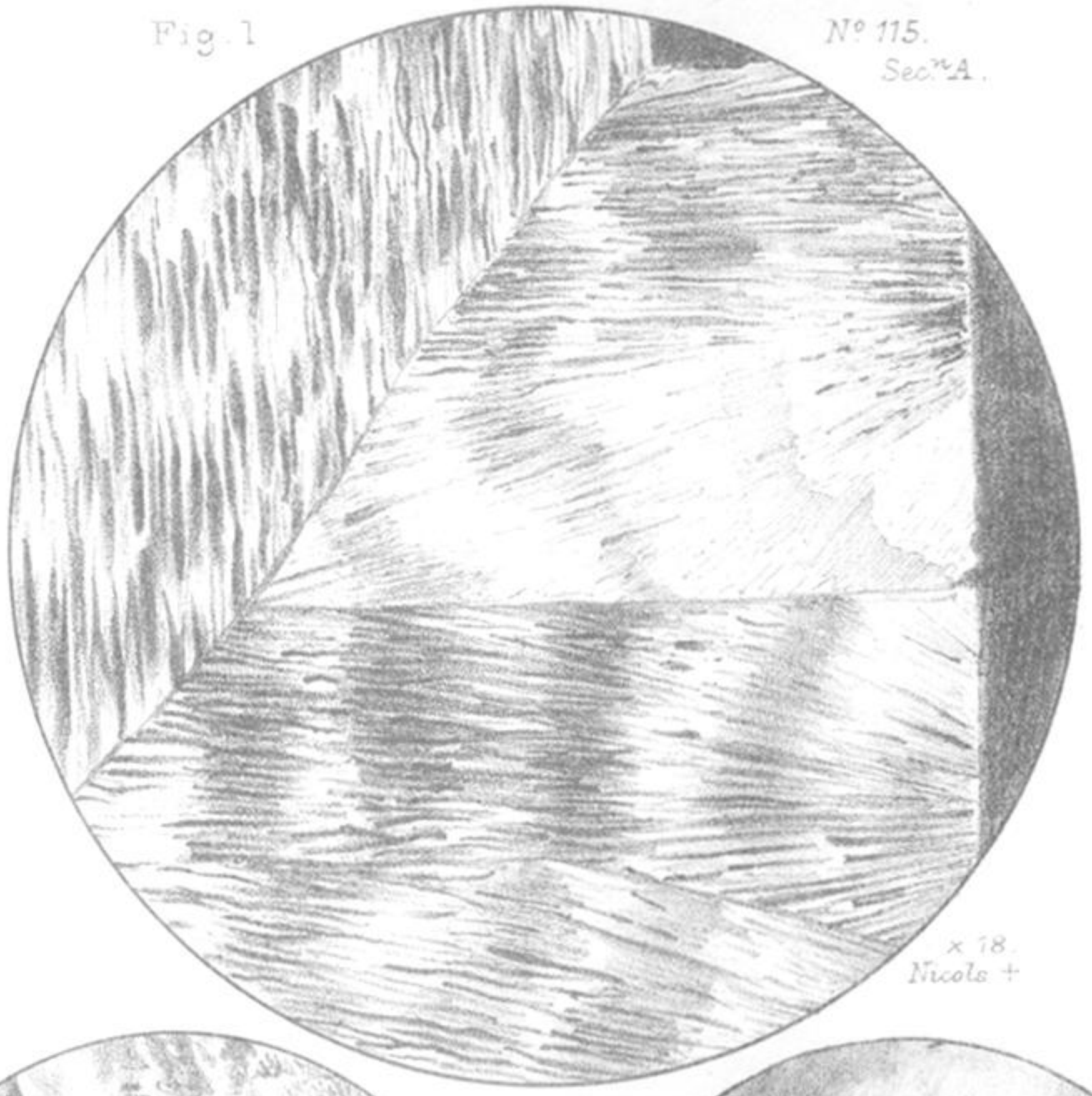


FIG. 4.



Part of large spherule in obsidian from Hot Springs, near Little Lake, California.

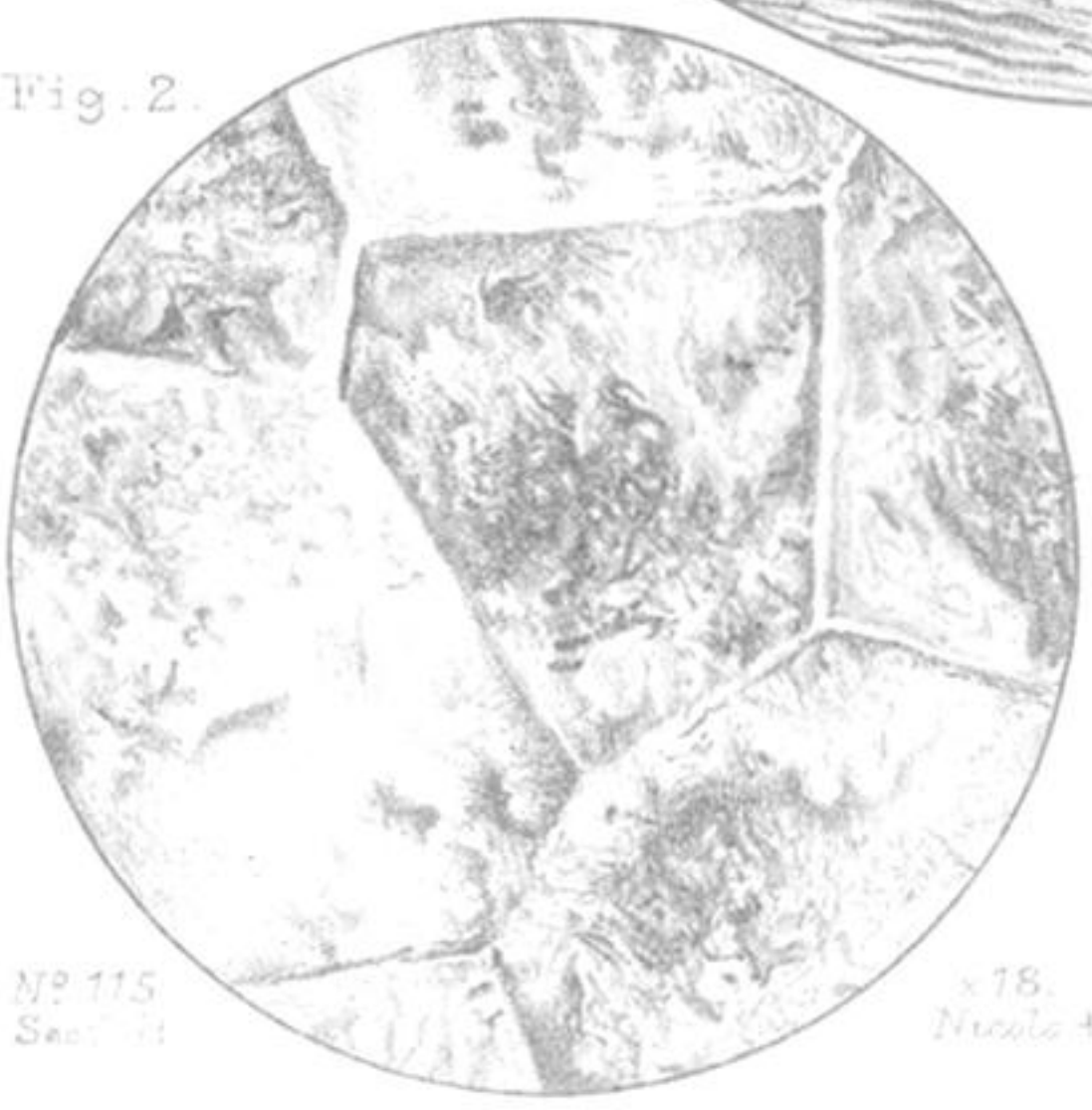
Fig. 1



N° 115.
Sec^n A.

x 18.
Nicols +

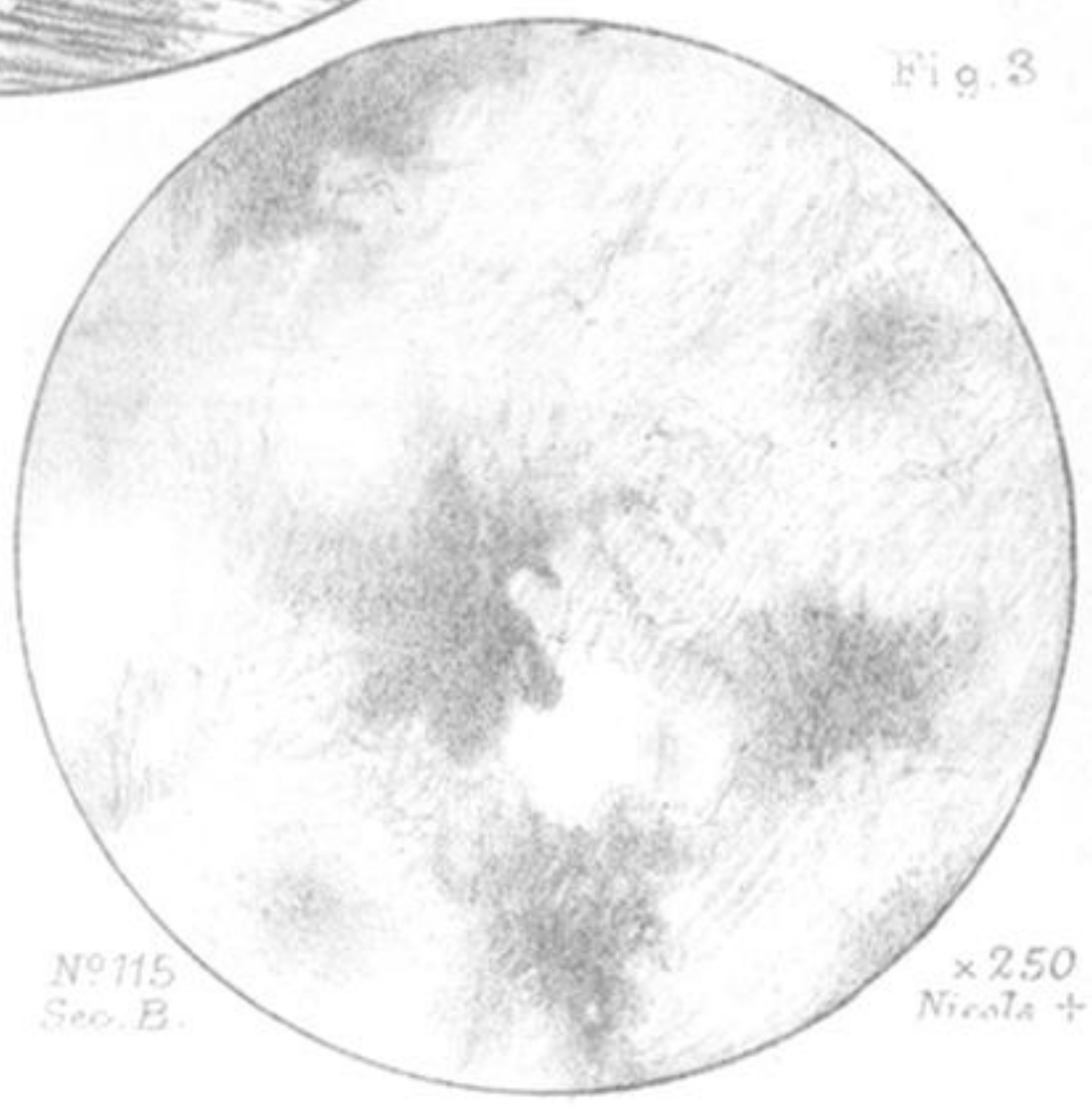
Fig. 2.



N° 115
Sec. A

x 18.
Nicols +

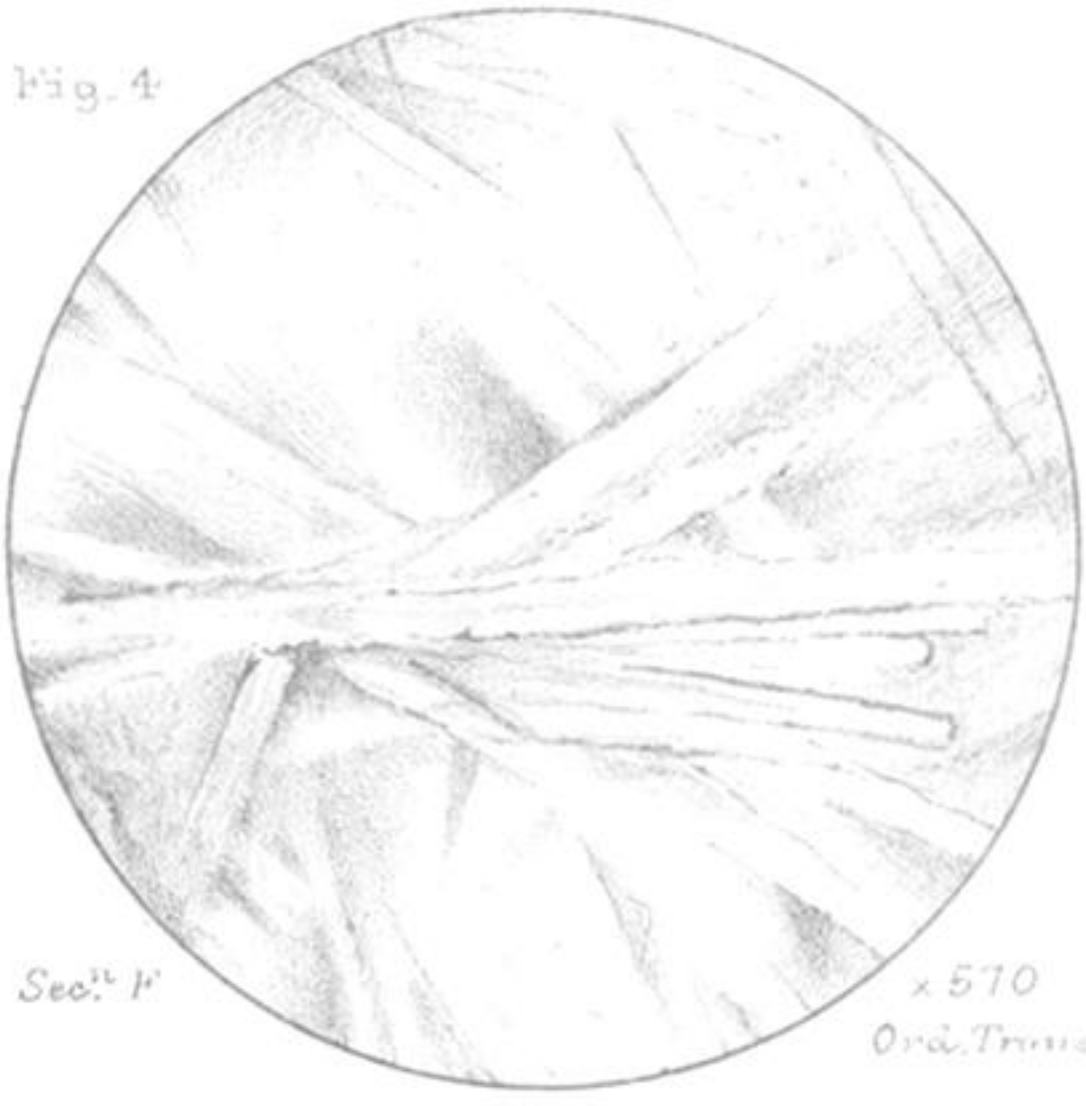
Fig. 3



N° 115
Sec. B.

x 250
Nicols +

Fig. 4



Sec^n F

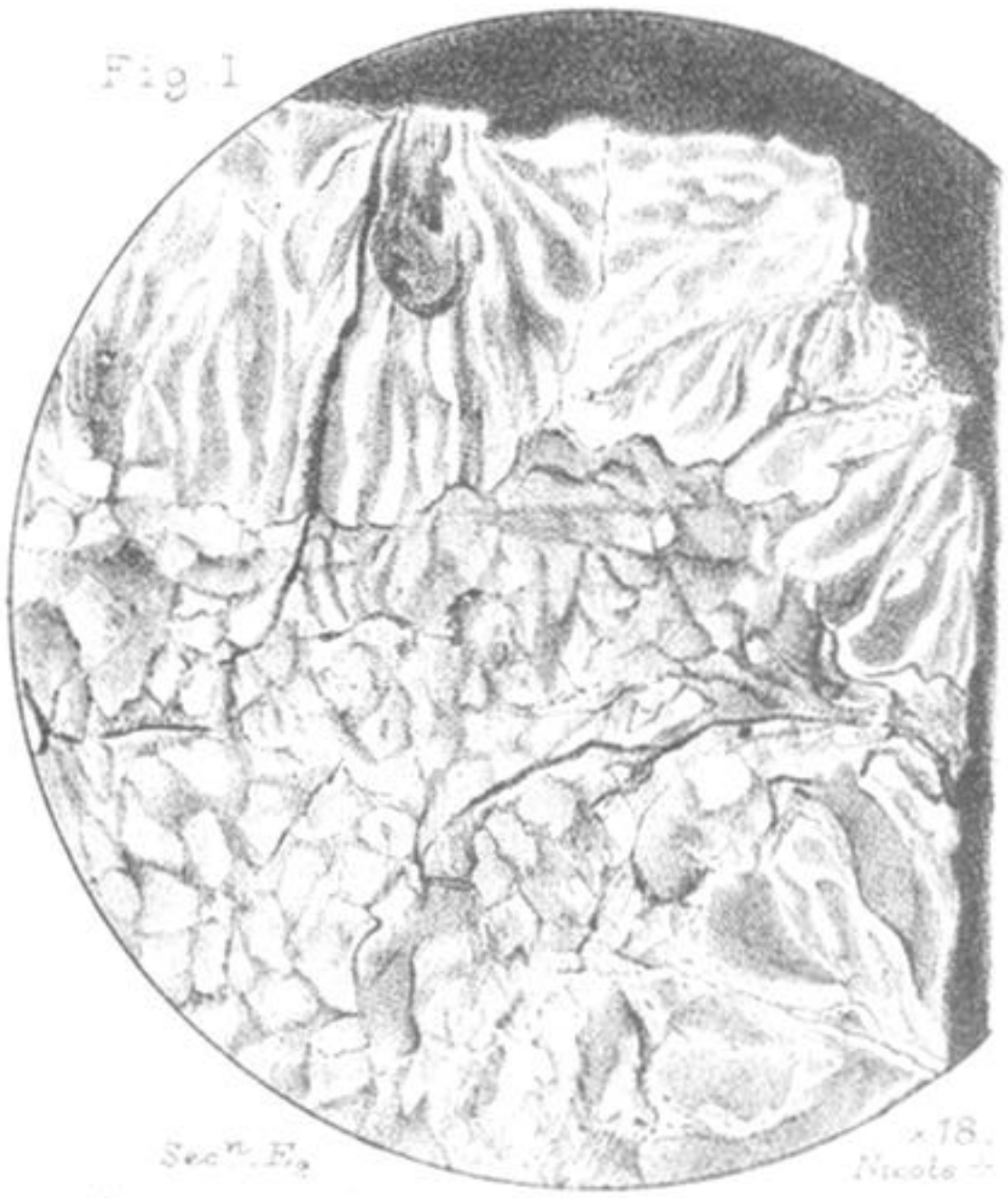
x 570
Ord. Trans. I.t.

Fig. 5.

Sec^n F.

x 18
Ord. Trans. I.t

Fig. 1

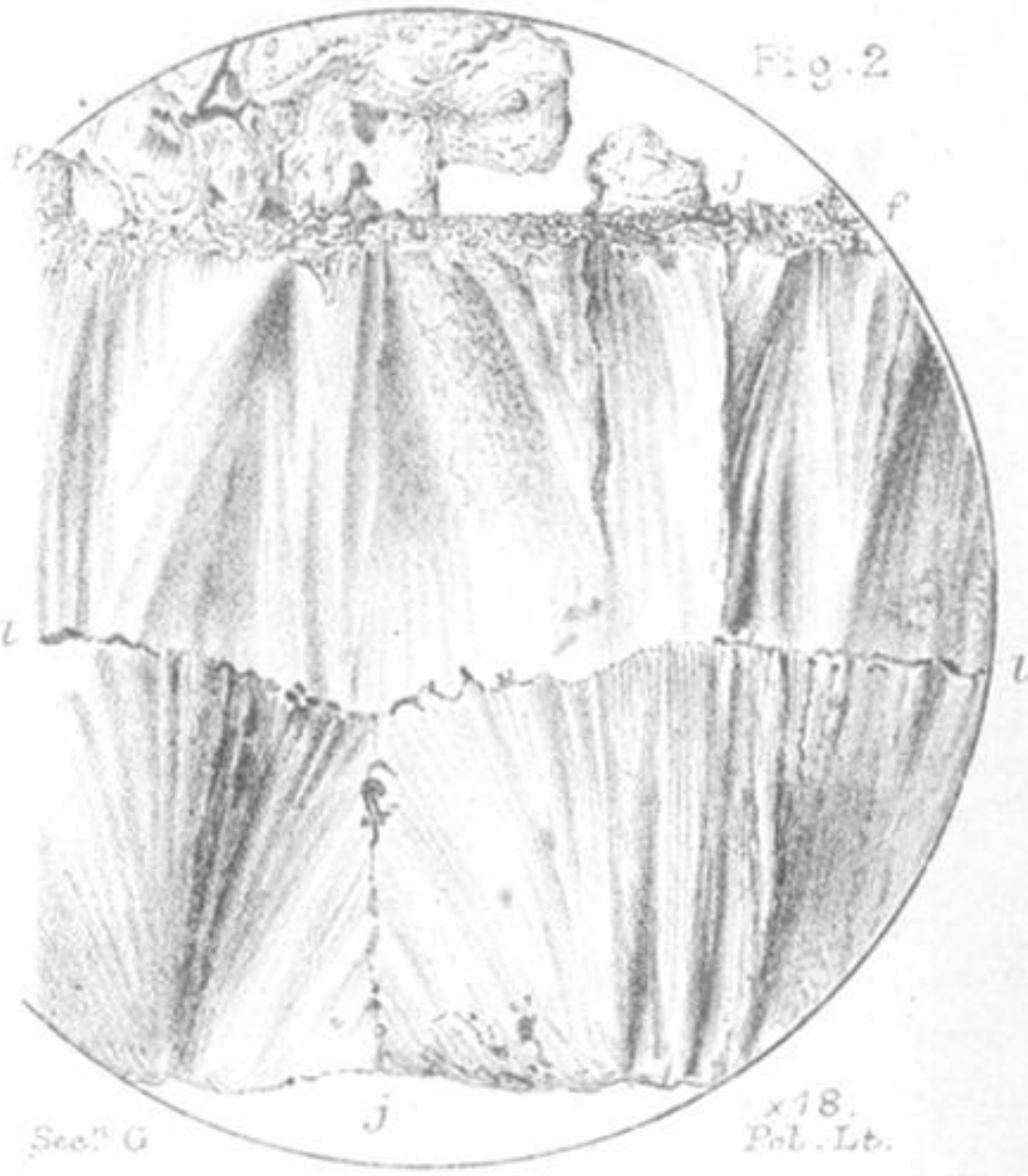


Sec.n E.

×18.

Nicols +

Fig. 2

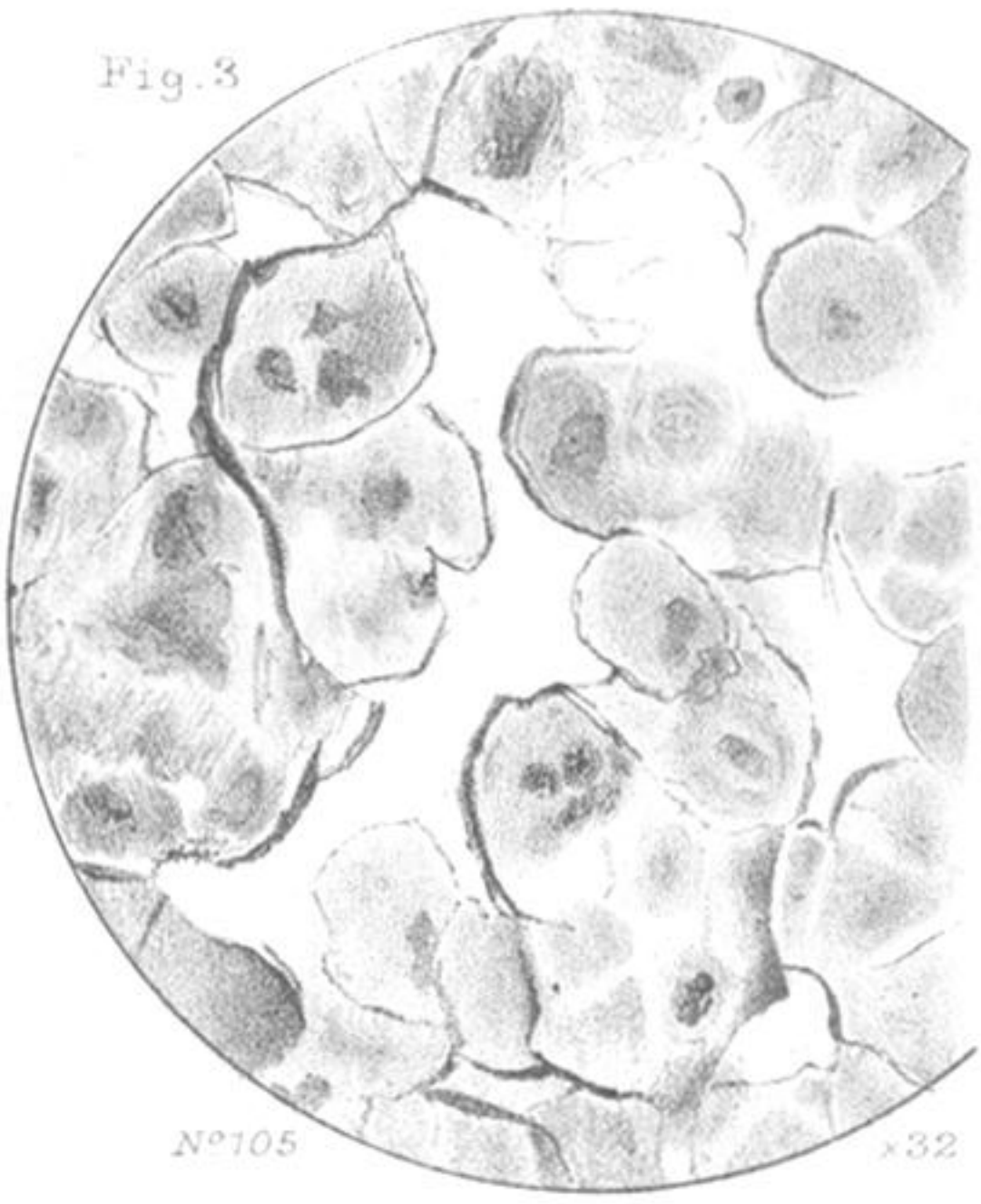


Sec.n G

×18.

Pol. Lt.

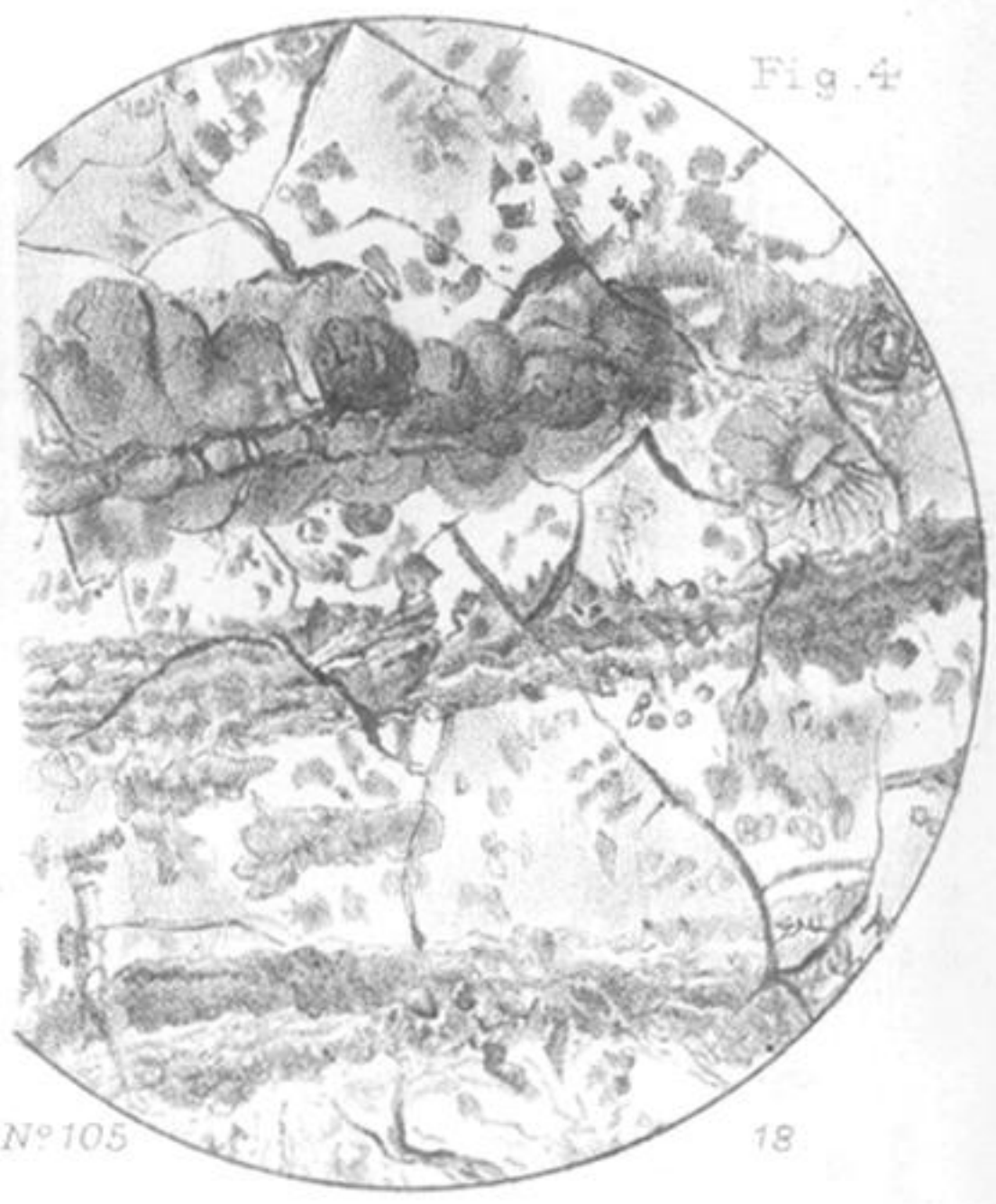
Fig. 3



N°105

×32

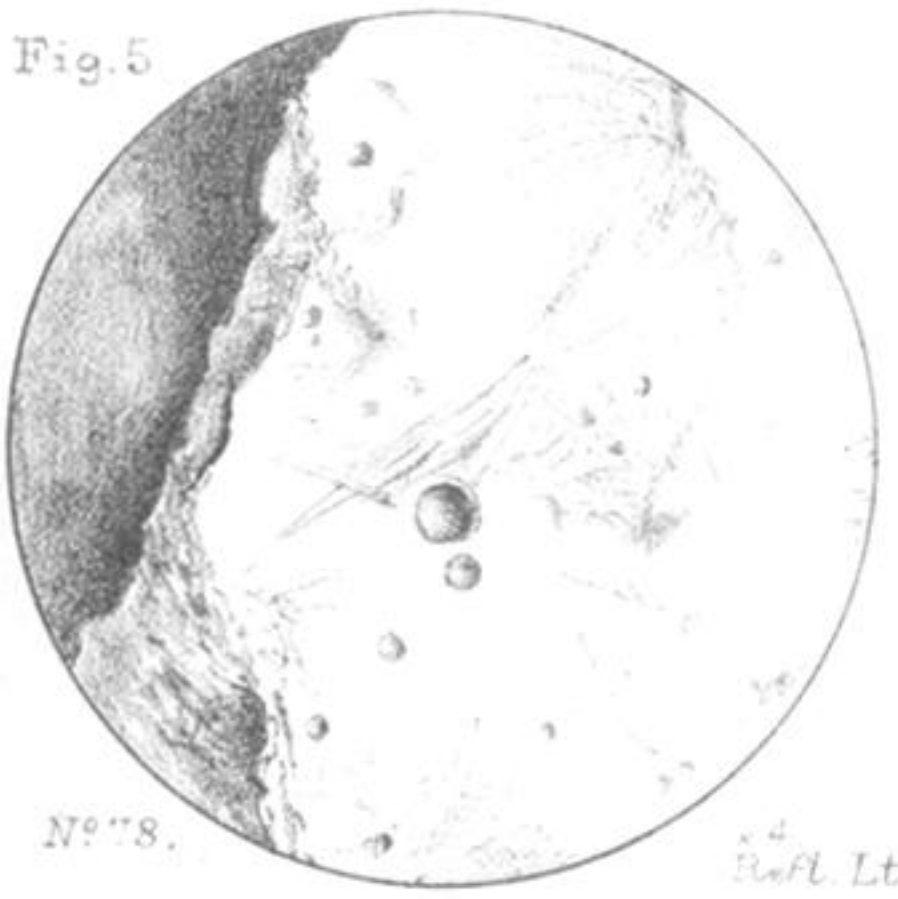
Fig. 4



N°105

18

Fig. 5



N°78.

Refl. Lt.

Fig. 6

Sec.n L.

× Or 250.

Ord. Trans. Lt.

Fig. 1.

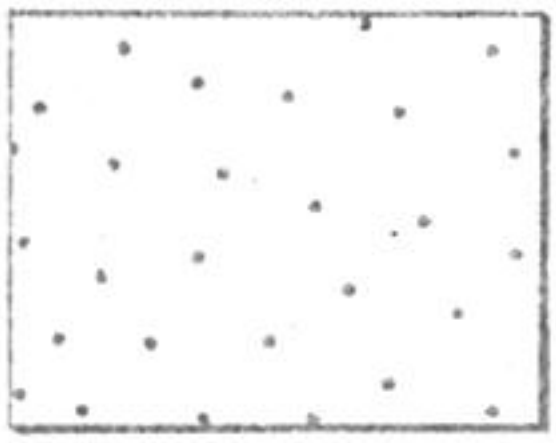
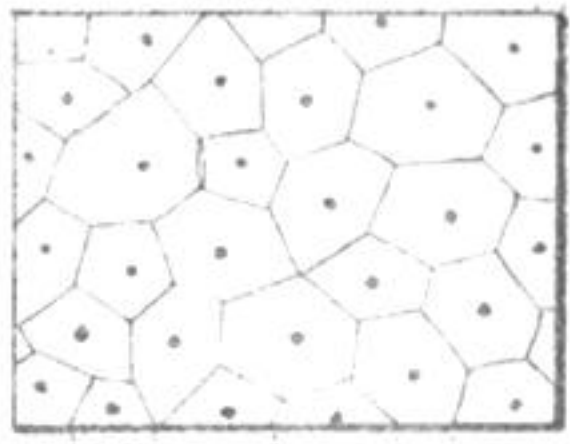
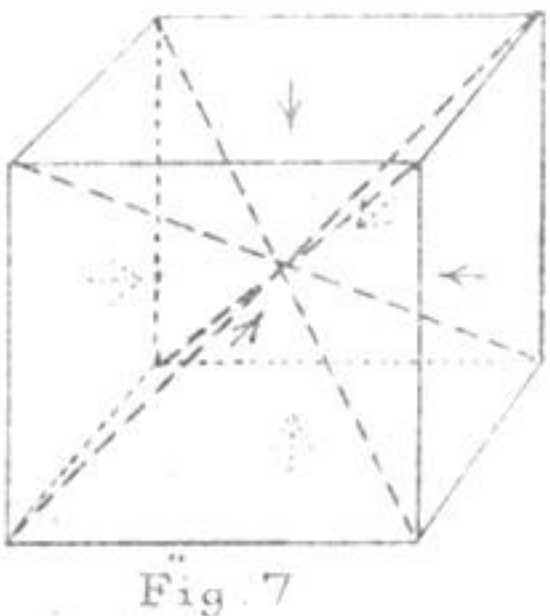


Fig. 2





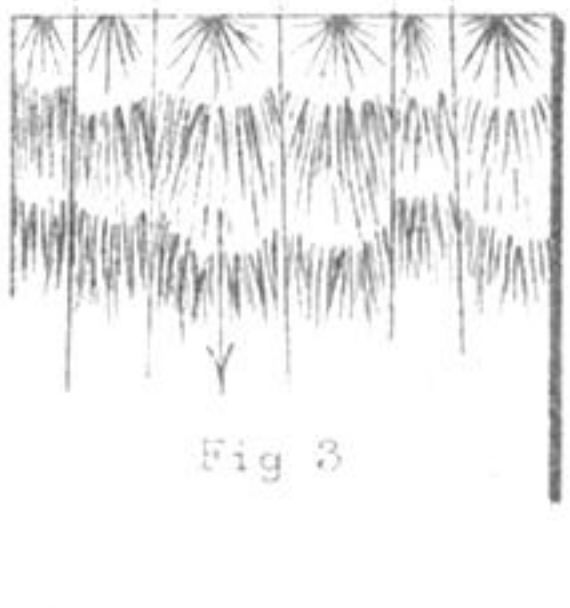
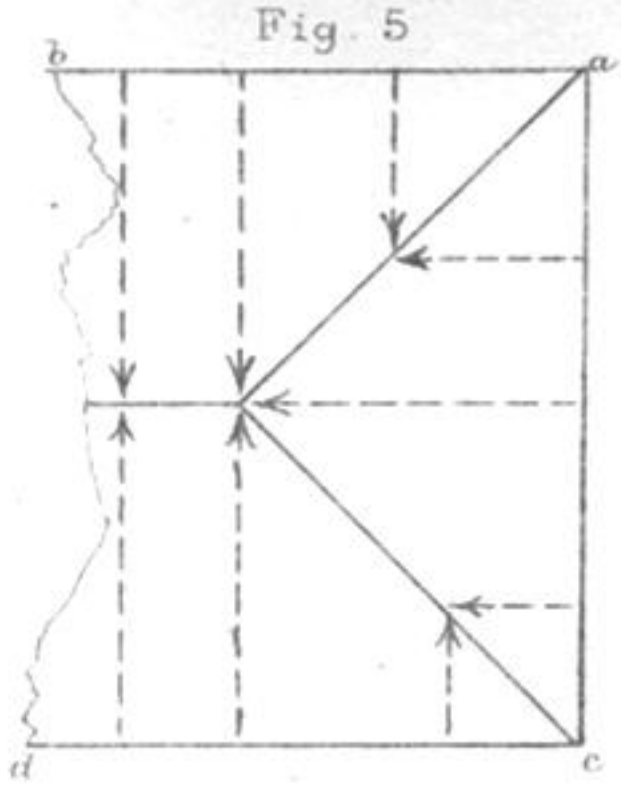


Fig 3

Fig. 5



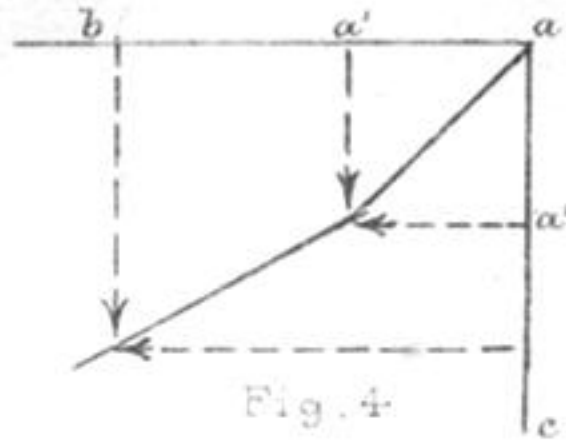


Fig. 4

Fig 6

Fig 7

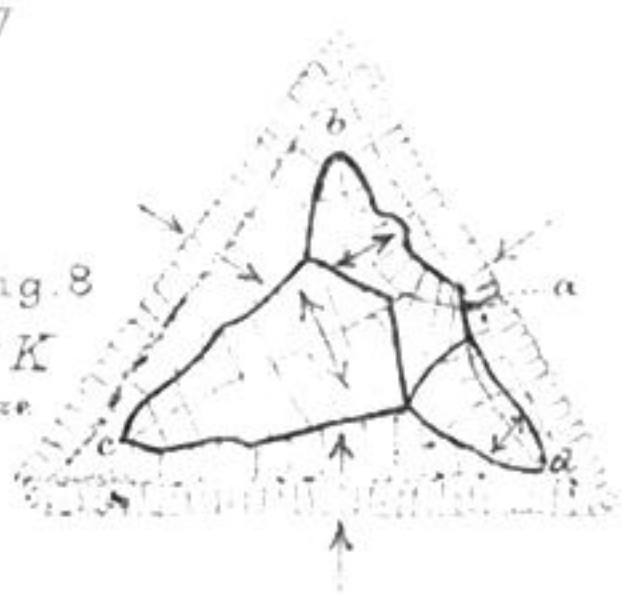


Fig. 8

Sec^n K

Nat size

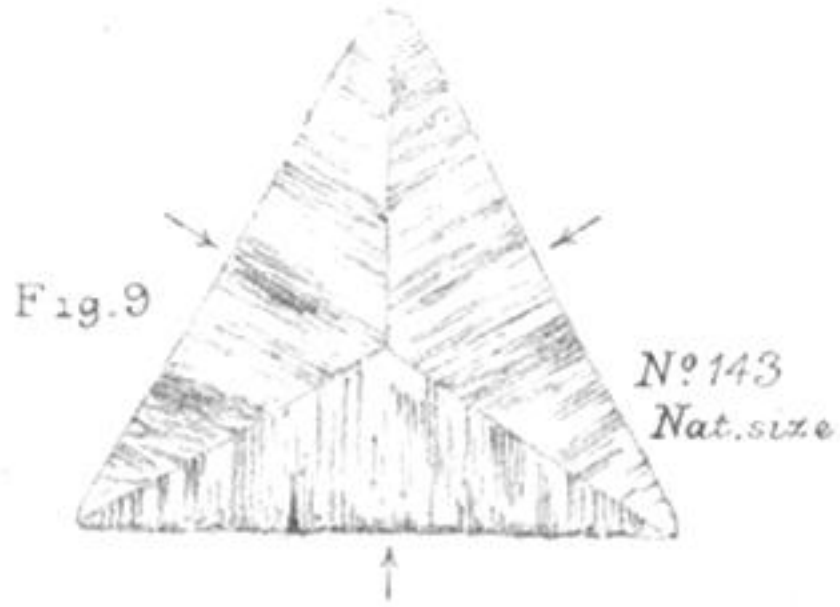
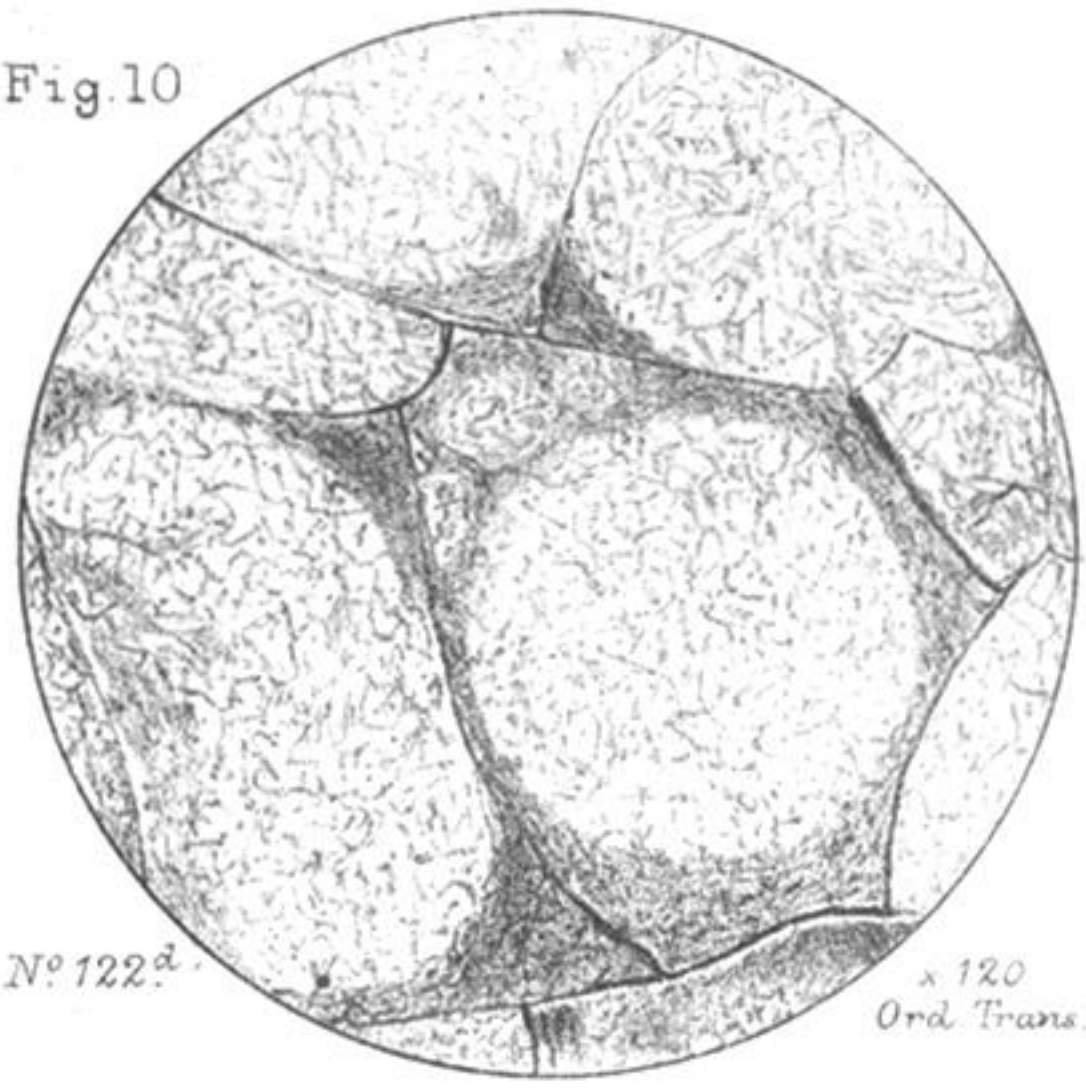


Fig. 9

Nº 143

Nat. size

Fig. 10

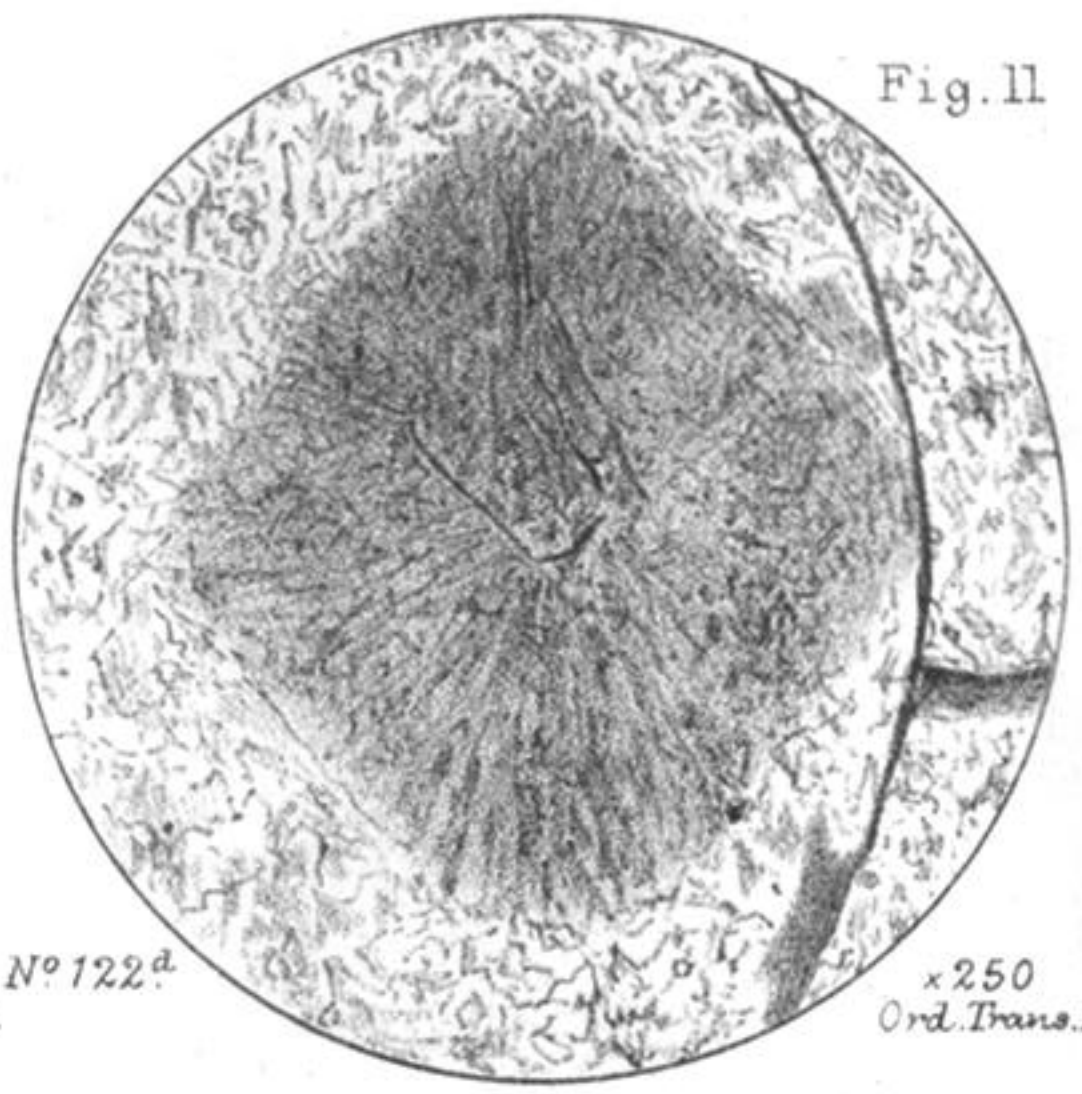


Nº 122d

x 120

Ord. Trans. Lt.

Fig. 11



Nº 122d

x 250

Ord. Trans. Lt.

Fig. 12

Nº 127

x 820

Fig. 13

Nº 126

x 820.

N° 147 Nat size.

Fig 1.

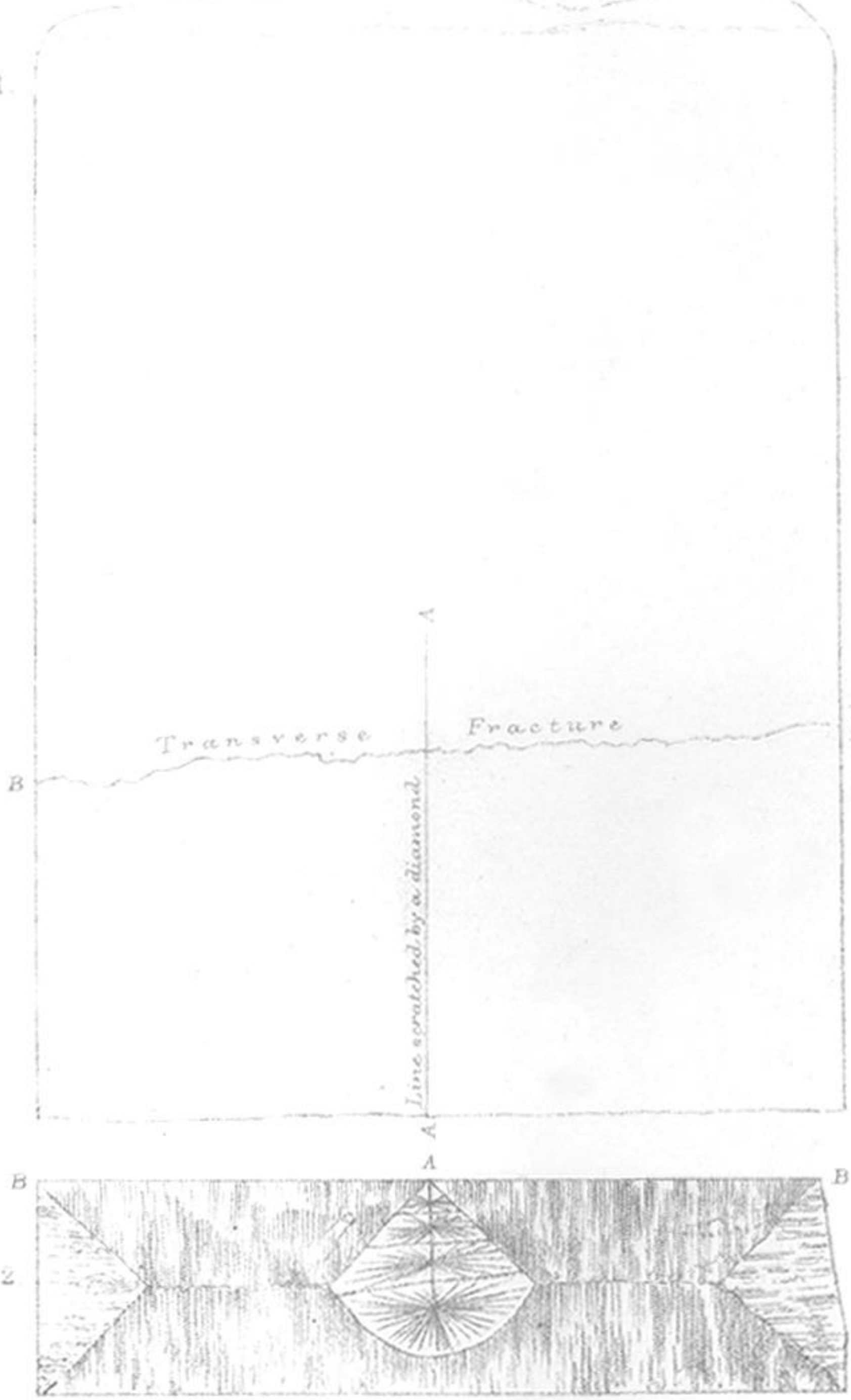


Fig 2

Fractured surface along the line B.B.

Fig 4.

Nat. size.

Fig. 5.

Fig. 3.

Nat. size.

Nat. size.