II.—*The Microscopical Features of Mechanical Strains in Timber and the Bearing of these on the Structure of the Cell-wall in Plants.*

By WILFRID ROBINSON, *D.Sc., Lecturer in Botany, University of Manchester.*

Communicated by Prof. W. H. LANG, *F.R.S.*

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[PLATES 1–4.]

INTRODUCTION.

When wood is subjected to increasing mechanical stress its component parts ultimately undergo changes resulting in permanent deformation or failure.* This paper deals with the minute microscopic changes upon which the permanent deformation of wood depends, and with the relationship between the microscopic structure of wood and some of its more important mechanical properties. The work has provided abundant material for a study of the structure of the walls of the cells of which wood is composed. Considerable light has been thrown on the structure and properties of the vegetable cell-wall in general, and it has been possible, from the facts for wood, to frame a hypothesis which seems to explain satisfactorily most of the properties of cell-walls.

The examination of the mode of failure in timber, which has led to the work described in this paper, was begun at the request of Lt.-Col. JENKIN, R.A.F. I am deeply indebted to him for the original suggestion of this line of work and for his continued interest during its course. I have derived great advantage throughout the work by discussing various engineering questions, as they have arisen, with Major ROBERTSON, R.A.F., and I desire to thank him for many helpful suggestions. I am further indebted to him for the supply of many fractured specimens of wood. The research has been carried out, in the course of more definitely applied work for the Air Ministry, in the Barker Cryptogamic Research Laboratory of the University of Manchester. I have to thank Prof. W. H. LANG, F.R.S., for encouraging me to attempt to relate the facts of the mechanical properties of wood to fundamental botanical questions bearing on the structure of cell-walls in plants.

The mechanical properties of a wood may depend on the microscopic or ultramicroscopic structure of the substance of the walls of the cells comprising it, on the form of these cellular elements, and also on their gross anatomical arrangement.

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* It is recognised that a long thin column of wood may undergo mechanical failure by elastic instability, but since the deformation in such cases occurs within the limits of elasticity and is not permanent, the failure is accompanied by no permanent microscopical changes in the cell-walls of the wood. In this paper it is the changes accompanying failure by permanent deformation which are being considered.

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In the present study it was found that the gross manner of failure in end-compression of some of the lighter coniferous woods differed in a striking way from that seen in many of the denser woods, both of Dicotyledons and of Conifers. It is probable that these gross differences are dependent on anatomical differences in the various woods, and are especially connected with the greater or smaller proportion of thick-walled elements, as well as with the form of the cells in the latter. On the other hand it is shown below that, underlying the gross differences in the manner of failure in end-compression in the various woods, there is a fundamental similarity in the method by which failure is initiated in the cell-walls of all woods. The earliest recognisable stages in the failure, due to the permanent deformation of the walls of the cells of the wood, are microscopic, and (requiring to some extent, special methods of demonstration) have not previously been described.

The macroscopic as well as some microscopic features of the failure of wood have been described by a number of investigators and brief reference must be made to the main results of their work.

THIL[*] (1900) described the anatomical structure of many woods in relation to their mechanical properties. He concluded that the form of the fracture depended on the medullary rays acting as places of less resistance and attempted to relate the course of the fracture to a spiral arrangement of the medullary rays.

JACCARD[†] (1910) investigated the anatomical structure of a large number of woods after compression. He studied the wood both of Dicotyledons and of Conifers and concluded that there is no specific type of rupture common to all woods and, contrary to THIL, that the fracture bears no relation to the medullary rays. The rupture is determined by points of least resistance in the wood, the pits in the walls of the tracheides and fibres forming such points of weakness. JACCARD described certain alterations in the folded cell-walls. He states that these show a longitudinal fibrillar structure which, in transverse sections, appears as a concentric layering in the walls. He attributes the appearances to the layers of the cell-walls having planes of less cohesion between them; under compression these planes behave as planes of cleavage and separation takes place along them. In the tracheides of the autumn wood of certain Conifers a fine transverse striation is referred to, but its significance is not discussed. Mention is also made of the similarity of some of the transverse folds he observed, to the dislocations described by VON HÖHNEL[‡] for flax and other fibres.

FULTON[§] (1912) studied the failure of Oak, Pitch Pine, Ash and Box, giving

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[*] THIL, A., "Constitution anatomique du Bois."—'Étude sur les Fractures des Bois dans les Essais de Résistance.' 'Études présentées au Congrès Internat. des Méthodes d'Essai des Matériaux de Construction,' Paris, 1900. (Seen summarised in 'Le Bois,' Beauverie, 1905.)

[†] JACCARD, P., "Étude anatomique des Bois comprimés," 'Mitt. d. Schw. Centralanstalt für d. Forst. Versuchwesen,' vol. 10, heft 1, pp. 53–101, Zurich, 1910.

[‡] HÖHNEL, VON, 'Jahrb. für Wiss. Bot.,' 1884, p. 311.

[§] FULTON, A. R., "Experiments to show how Failure under Stress occurs in Timber, its Cause, etc.," 'Trans. Roy. Soc. Edin.,' vol. 48, Part II, p. 21 (1912).

illustrations of the external and of some microscopic characters of the failures he obtained. The manner of failure of specimens fractured in compression, in tension, and by bending was investigated, and FULTON concluded that "the initial cause of failure in all timber lies in the medullary rays." This failure is attributed to an initial set caused by the natural sinuous displacement of the fibres in a tangential plane round the medullary rays, and by the lack of cohesion between the fibres and the medullary rays. No details of any internal microscopic changes in the substance of the woody walls are given.

BRUSH* (1913) investigated the behaviour of the fibres of ten species of wood, in compression, tension, longitudinal shearing and bending. He found that for end-compression the fibres behave as hollow tubes and either buckle sharply or bend gradually. Whether a fibre buckles or bends depends on the thickness of its walls and on the moisture-content. Apart from this distinction between buckling and bending,† no description is given of more minute changes in the structure of the walls. No reference is made to the part played by the pits nor is the effect of the medullary rays considered.

RECORD‡ has summarised the results obtained by JACCARD and BRUSH but adds nothing to their descriptions.

MATERIAL, METHODS, ETC.

Preliminary observations indicated that the problems involved in the mechanical failure of wood could be best elucidated by a detailed study of a few woods of different types. For the purpose of this investigation, therefore, the woods of Silver Spruce (*Picea sitchensis*), Ash (*Fraxinus excelsior*), and Pitch Pine (*Pinus palustris*) were selected. For the elucidation of special points and for the verification of the main conclusions of this paper a number of other woods including Mahogany, Swamp Cypress, Oregon Pine, Larch, Birch and also Andaman Padouk have been examined.

The mechanical stress which has been mainly considered is longitudinal compression, *i.e.*, compression applied endwise and therefore acting in the direction of the grain of the wood. In addition, longitudinal tension and longitudinal shearing, both in radial and tangential planes, were considered for comparative purposes. Short rectangular test-specimens were used in the earlier stages of the research, but for most of the work on the effect of longitudinal compression, small cylindrical test-specimens with expanded flanges at either end were prepared. These specimens measured 1 inch long by $\frac{1}{4}$ inch diameter at the narrowest portion. The end-compression was applied in a small testing machine designed and constructed for the purpose by Major

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* BRUSH, W. D., "A Microscopic Study of the Mechanical Failure of Wood," 'U.S. Depart. Agric. Review Forest Service,' vol. 2, pp. 33–38 (1913).

† In the present paper the terms "crinkling" and "buckling" are respectively equivalent to BRUSH'S "buckling" and "bending."

‡ RECORD, S. J., 'The Mechanical Properties of Wood,' New York, 1914.

Robertson, R.A.F., to whom I am also indebted for the design of the test-specimen. The shape of the test-piece ensured that failure should occur in a middle region.

The shape of the specimens fractured in tension and in longitudinal shear, and also the method of test adopted in the latter case, are dealt with in the sections of the paper concerned with tension and with longitudinal shear.

True radial and tangential longitudinal sections were cut through the pieces after failure, and prepared for microscopical examination in the usual way. In order to retain the tissues and cells of the wood in the condition in which they were on removing from the testing machine and to prevent, as much as possible, expansion and readjustments in the tissues and cell-walls, the use of water was in most cases entirely avoided. The sections were cut from specimens soaked in absolute alcohol and the stains used were applied in solution in absolute alcohol. In using reagents like chlor.-zinc-iodide such treatment was not possible, but, by comparison with sections which were never wetted with water, it was possible to make allowance for the swelling and readjustment which took place.

Gross Features of Compression Failure.

The gross appearances accompanying the compression failure in Spruce, Pitch Pine, and Ash will first be briefly described and then the detailed microscopic features of the failure will be dealt with for these woods.

In Spruce, after compression, a distinct zone of failure can be observed with the naked eye on both radial and tangential faces of a rectangular test-specimen. Plate 1, fig. 1, shows the appearance of the narrow zone of failure on the tangential face of such a compressed specimen. The zone is slightly inclined to the horizontal, its two edges are parallel, and there is no obvious displacement of the elements of the wood in the tangential direction as seen on this face. Plate 1, fig. 2, shows the zone of failure on the radial face of the same specimen. In this case the zone is practically horizontal, but its edges form a gently undulating outline. There is a most obvious displacement in the radial direction, this having been produced by the pushing over of the autumn wood of one year into the spring wood of the next. In some examples the displacement was so great that a separation of the tracheides took place at the annual rings (Plate 1, fig. 5*r*). The thin-walled tracheides of the spring wood in the zone of failure are crinkled and thrown into folds, whilst the thick-walled tracheides of the late wood are buckled more gradually. These differences, in the gross expression of the failure in the two kinds of tracheides, account for the undulating outline of the zone of failure which has been referred to above. In Spruce, there is no rupture between the medullary rays and the tracheides, nor indeed is any rupture visible on the tangential face of a compressed specimen. It will be seen later that Spruce differs in this particular from Pitch Pine, from Ash, and also from many of the woods, the failure of which has been described by the investigators referred to above.

In Pitch Pine, the zone of failure, as seen on a tangential face, is inclined at an angle of about 45° to the longitudinal axis of the specimen, the displacement of the elements of the wood having taken place in the tangential direction (Plate 1, fig. 3). The medullary rays are not of uniform size in Pitch Pine, and the separation takes place at the larger rays first (Plate 1, fig. 4). Owing to this separation at the medullary rays it is only possible to study the failure from tangential sections, since radial sections, except of specimens in very early stages of failure, separate completely into two parts. As in Spruce, the failure is manifested by buckling of the walls of the autumn wood and by crinkling of the walls of the spring wood. The proportion of thick-walled late wood, however, is much greater in Pitch Pine than in Spruce, and this probably accounts for the gross differences in the manner of failure.

In Ash, the gross features of the compression failure somewhat resemble those seen in Pitch Pine. The zone of failure is inclined at an angle, which may vary from 60° to 45°, to the longitudinal axis of the specimen. The failure manifests itself by the gradual buckling of the fibres, and this is accompanied by a displacement of the elements of the wood in the tangential direction (Plate 1, fig. 6). As in the failure of Pitch Pine, a separation of the elements ultimately occurs at the medullary rays. In Ash the fibres of the late wood comprise the main mechanical elements of the wood. When, therefore, a test specimen is compressed, the deformation of these fibres is responsible for the collapse of the specimen. As in Pitch Pine, the proportion of the thick-walled mechanical cells in the wood is very high when contrasted with a wood like Spruce.

These observations, on the grosser features of the failure of Pitch Pine and of Ash, confirm the descriptions given by FULTON for these two woods, but, as will be seen below, the present paper is not in agreement with his interpretation of the cause of failure. In Spruce, even the gross features of the failure are not in agreement with FULTON'S explanation, since the displacement is in the radial direction and separation never occurs at the medullary rays. It has been found that the actual causes of failure must be traced back to the initial stages of deformation which become manifest in the cell-walls of the tracheides, or fibres of the wood. This is the case, even though the final, grosser characteristics of the failure in woods like Pitch Pine and Ash, may partly be determined by the size and distribution of the medullary rays. From the results described below, it is likely that in all woods these initial stages of the failure and their relations to the minute structure of the woody walls are of primary importance.

That the initial stages of the permanent deformation have either been entirely overlooked, or that their significance has not previously been realised, may account for the diversity of the explanations of the manner of failure offered by different investigators. The grosser features of the failure of all three woods studied in detail, and of a large number of others examined more briefly, are secondary effects dependent on the anatomical structure of the particular wood. The initial failure, in all cases, depends on primary changes, in the substance of the cell-walls, which will be described below.

STAINING REACTIONS IN THE ZONE OF FAILURE.

Before describing the more minute changes associated with the permanent deformation, reference must be made to some unexpected results which were first obtained during the preliminary study of the grosser features of the zone of failure in compressed Spruce. Similar results were later obtained for Pitch Pine, for Ash, and for a large number of other woods. It was found that the zone of failure behaved differently, towards various stains and reagents, from the uninjured parts of the wood. Plate 1, figs. 7 and 8, taken from sections through specimens of compressed Spruce, illustrate this differential behaviour of the zone of failure when the reagent used is chlor.-zinc-iodide. The zone of failure appears as a deep blue band in contrast to the yellow stain given by the unaltered wood. The blue stain is similar to that usually obtained when chlor.-zinc-iodide acts on pure cellulose. Observation, by high powers of the microscope, shows that the blueness of the zone is due to transversely running bars as seen on the surface walls of the tracheides (Plate 2, figs. 15 and 16). These blue bars are separated by narrow yellowish areas ; within the actual zone of failure they are very numerous and close together, but they also are present in a more diffused manner for a considerable distance beyond the zone of failure (Plate 2, figs. 15 and 16). The blue reaction extends into the depth of the walls, and in the section of these the change is manifested by obliquely running bars of blue (Plate 2, fig. 15*x*).

An attempt was made, by using a variety of histological stains and reagents, to elucidate the nature of the change in the fractured region. Iodine and sulphuric acid give results parallel with, but even more striking, than those with chlor.-zinc-iodide. As before, the altered zone stands out in contrast to the normal parts of the wood. The deformed region gives a dark green colour rather than the blue which would have been expected if the zone consisted of pure cellulose. The rest of the wood, consisting of unaltered tracheides, gives the normal deep yellow colour. A close examination of the region of failure shows that the yellow lignin-reaction is present in the zone of failure, but that this yellow colour is largely overpowered by a blue colour in the portions which stand out blue with chlor.-zinc-iodide. The dark green stain is the result of the combination of the blue with the yellow of unchanged lignin.

Parallel results were obtained with a number of stains and reagents, and the effects of these are summarised in the following Table :—

Stain or Reagent.	Zone of failure.	Unaltered wood.	Remarks.
Chlor.-zinc-iodide	Blue	Yellow	
Iodine and H_2SO_4	Dark green	Yellow	
Aniline chloride	Yellow	Yellow	Normal lignin-reaction throughout.
Phloroglucinol and HCl	Pink	Pink	Normal lignin-reaction throughout.
Aniline chloride followed by aniline blue	Blue or bluish green	Yellow	
Cotton red (carthemin) followed by aniline blue	Blue	Red	
Safranin followed by hæmatoxylin	Blue	Red	Contrast less sharp than in other cases.

The results obtained, using aniline chloride alone, and also those with phloroglucinol, especially point to the presence of substances giving the lignin-reaction in the zone of failure, possibly in undiminished quantity. On the other hand, the behaviour of the walls of the fractured tracheides, especially towards chlor.-zinc-iodide, iodine and sulphuric acid, and such aniline stains as aniline blue, suggests that in some way the cellulose present in the lignified walls has been unmasked as a result of the mechanical strain. This change in the staining properties of the walls of compressed tracheides has obviously a fundamental bearing on the nature of the process of lignification of the cell-wall, and it will be further discussed in this connection after the minute details of the structure of the deformed walls have been described.

Apart from slight individual differences in the staining properties of the walls of the tracheides, fibres, and vessels of different woods, it was found that, broadly speaking, the changes in the behaviour towards reagents and stains just described for Spruce held for the zone of failure in such widely different woods as Pitch Pine, Ash, Birch, Andaman Padouk, Oregon Pine, and Swamp Cypress. Whenever failure in compression occurs in wood, it is possible to demonstrate the region of failure, however slight this may be, by making use of stains and reagents. The method has been particularly useful in demonstrating the very earliest stages in the deformation of the walls of the tracheides and fibres. It has thus been possible to trace the sequence of changes in compressed specimens from the initiation of deformation up to the stage when a clear zone of failure is visible on the faces of the specimen. This sequence of changes will first be described for Spruce.

INITIAL STAGES OF FAILURE IN SPRUCE.

Test specimens were carefully compressed so that only the first signs of failure (*i.e.*, that the elastic limit had been reached and that yielding was taking place) were evident from the behaviour of the testing machine. Sections from such specimens gave early stages in the development of the zone of failure. Plate 2, fig. 10, is the tangential view of such early stages as they appear in the relatively thin-walled spring wood. The walls of the tracheides are locally crinkled, and the crinkling extends in an approximately horizontal direction across the specimen from tracheide to tracheide. In the autumn wood, the walls of the tracheides buckle more gradually than the thinner walls of the spring wood, and are not thrown into abrupt folds like the latter.

Corresponding radial sections show the walls of the tracheides of the spring wood crinkled as in the tangential sections, and, as before, the series of local crinklings forms a horizontal band across the spring wood (Plate 2, fig. 11). The thicker walls of the tracheides of the late wood buckle gradually, and the line of the failure is usually inclined at about 45° to the length of the tracheides (Plate 1, fig. 6). Both in the tracheides of the autumn wood and in those of the spring wood, the pairs of walls of adjoining tracheides appear to behave as one, since they invariably buckle or crinkle, as the case may be, in the same direction. The ratios of the thickness of the cell-walls to the diameter of the cavities probably determines whether the crinkling seen in the spring wood, or the simple buckling seen in the autumn wood, will occur. In the passage from the spring wood to the autumn wood of the same year, the change in the thickness of the walls is a gradual one, and, in consequence, the transition from crinkling to buckling is also gradual.

The medullary rays in Spruce crinkle or buckle with the tracheides, but do not appear to form special places of weakness in the wood (Plate 2, fig. 10, *m.r.*). No separation between the tracheides and the medullary rays has ever been observed in Spruce.

The first lines of failure may pass through bordered pits as the former extend across the specimen, but no evidence was obtained that the pits form special places of weakness in the wood. Many very early stages in the failure were obtained, however, which prove conclusively that the yielding in the substance of the walls takes place, apart altogether from the presence or absence of pits. In Spruce, if the bordered pits formed special places of weakness in the woody walls, we should expect the radial walls, on which the bordered pits mostly occur, to be weaker than the tangential walls. The displacement of the elements of the wood should, on this supposition, take place in the tangential direction. It has, however, been shown above that this is not the case in Spruce, and it will be shown below that the fundamental changes that accompany the deformation of the cell-walls are not connected with the presence or with the distribution of pits. In this respect the present work is not in agreement with the conclusions of JACCARD, or with the statements of RECORD regarding the weakening effect of the pits.

Minuter Changes preceding Buckling and Crinkling.

The buckling and the crinkling of the walls of the tracheides of the autumn and spring wood respectively are preceded by local changes in the substance of the cell-walls. These changes can readily be observed in the radial and tangential sections of Spruce wood, showing initial failures. Somewhat thick radial longitudinal sections of Spruce show the thickness of the tangential walls of the tracheides in section and the radial walls in surface view. The changes which lead to deformation consist in the appearance of extremely fine, but sharply defined, crack-like lines in the walls of the tracheides.* In the sectional views both of the radial and tangential walls of autumn and spring wood, the lines are somewhat irregularly cross-hatched, and run obliquely through the secondary layers of the walls at inclinations greater than 45° to the edge of the wall (Plate 3, figs. 1, 2, and 4; Plate 2, figs. 17 and 18). It is clear, that where each line comes out to the surface, there is a step-like projection of the wall-substance (Plate 3, figs. 1 and 2). In most cases, the direction of the lines is common to the secondary layers of pairs of walls of adjoining tracheides, but no line has been observed crossing the middle lamella between adjoining tracheides. This probably signifies a difference in the elastic properties of the middle lamella (Plate 2, fig. 17, *ml.*).

In the surface view of the walls of the spring wood, corresponding to the sectional views just described, the lines run across the walls in an approximately horizontal or transverse direction (Plate 3, figs. 1 and 4). On the surface of the walls of the autumn wood they may be either transverse, or more or less inclined to the axis of the cell, often forming a system of fine cross hatchings (Plate 3, fig. 6). The inclination of the lines, as seen on the surface of the walls, is never the same as that of the slits of the pits on the walls of the tracheides. The appearances of the lines, in the sectional views of the cell-walls and also in the surface view of these, are consistent with an explanation which regards them as the traces of planes of displacement in the cell-wall substance. The boundaries between the step-like projections, seen in the sectional views, manifest themselves as one or more series of parallel, transverse or inclined lines on the surface of the walls (Plate 3, figs. 6 and 7).

When deformation begins in the cell-walls of the wood, parts of the substance of the walls are pushed over other parts so that regular planes of slipping are locally developed. That the lines which represent the boundaries between these planes of

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* It has been found that the mere mechanical effect of cutting sections, however good the knife may be, is sufficient to produce artificially a small number of these lines of slip, but tracing the appearances back from advanced to more initial failures leaves no doubt that the lines described are a direct result of the compression. In a number of instances sections were alternately cut from control uninjured specimens of wood and from the compressed specimens. The comparison of these afforded additional evidence of correctness of the interpretations given. Tracheides, isolated by maceration from a zone of failure, with practically no mechanical manipulation, show slip-lines in very large numbers in the buckled or crinkled walls, and only a few elsewhere.

slipping are sometimes inclined approximately at 45° to the axis of the cell, indicates that they are probably planes of shearing in the substance of the walls.

As the failure proceeds, the number of shearing or slipping planes rapidly increases, with the result that an extended region of the wall is affected, until finally the wall buckles or is thrown into a series of crinkles (Plate 3, figs. 3, 4, and 5). The walls, under the stress of end-compression, thus exhibit plasticity by the development of planes of slip or shear within their substance. It is by this microscopic, plastic deformation of the substance of the cell-walls that the failure is initiated. Whether buckling or crinkling subsequently occurs is determined by the relative thickness of the walls of the tracheides (Plate 3, figs. 3 and 5).

Very large numbers of early stages were observed in which slip-planes had developed before any visible buckling or crinkling had begun to take place (Plate 2, fig. 17 ; Plate 3, fig. 1). There is, therefore, no doubt that the primary mode of failure, or permanent deformation, is by the development of the microscopic planes of shear in the substance of the cell-walls. The buckling and the crinkling are subsequent developments.

After buckling and crinkling have taken place, the further development of the failure is then determined by the anatomical structure of the wood. In Spruce, as has already been pointed out, the relatively small proportion of autumn wood is probably one of the main factors in determining the ultimate and grosser characters of the failure.

The "slip-lines" or planes described here for the wood of Spruce present certain similarities to the slip-bands or gliding planes described by EWING and ROSENHAIN* for the crystals of metals under strain, and by REUSCH† and others at an earlier period for many crystalline substances. Since wood cannot be regarded as crystalline in the ordinary sense, the relationship between the phenomena in wood, on the one hand, and in the metals and crystals on the other, will be discussed below.

By careful illumination it is possible to observe the slip-lines described above, in unstained sections merely mounted in water. A more vivid demonstration of them, however, is obtained by staining compressed specimens with aniline chloride followed by aniline blue. These stains afford a means of demonstrating the lines even in the most initial stages of failure, before any buckling or crinkling has taken place, and before a zone of failure has developed. The lines and the wall-substance in their immediate vicinity hold the blue stain, whilst the rest of the wall remains yellow. Corresponding results are obtained with cotton red and aniline blue, and with chlor.-zinc-iodide solution. It has in fact been established that the remarkable differential staining of the zone of failure described above (pp. 54 and 55) is almost entirely due to the multiplicity of slip-planes in the substance of the cell-walls. The substance of

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* EWING and ROSENHAIN, 'Phil. Trans.,' A, vol. 193 (1900); ROSENHAIN, 'Introduction to Physical Metallurgy,' 1914.

† REUSCH, quoted in LEHMAN'S 'Molekulärphysik,' vol. 1, p. 64 *et seq.* (1888).

the walls in the immediate vicinity of these microscopic slipping planes holds the cellulose stains and reagents selectively.

The staining effect is thus clearly connected with the displacement of the particles of the cell-walls in the vicinity of the slip-planes and strongly suggests the possibility of a local chemical alteration of the lignified wall at these places. On the other hand, the modification in the staining properties may merely be the result of a physical alteration in the wall-substance. It is possible that the alteration is due to an actual transformation of the lignified wall into cellulose, in the immediate vicinity of the planes of slipping. It must be pointed out that many of the staining effects obtained with ordinary dyes on cell-walls, as well as the usual reactions for cellulose, can be explained as adsorption effects. BARGER* and his collaborators, for example, have shown that iodine forms blue adsorption compounds, with a large variety of organic chemical compounds in addition to that formed by the action on starch. He has also shown that the ability of an organic substance to form such blue adsorption compounds depends on the particles of the substance being in the colloidal state. The blue colour produced in the chlor.-zinc-iodide reaction for cellulose is probably due to the formation of such an adsorption compound with iodine in the presence of zinc chloride. Lignified cell-walls normally give no such blue compound with iodine in the presence of zinc chloride.

Botanists, since the time of NÄGELI, have regarded the lignification of the cell-wall as due to the passage of incrusting substances into the substance of the cellulose wall. Expressing this view of the nature of lignification in terms of the more modern conceptions of colloid chemistry and physics, the incrusting process would consist in the adsorption of lignone substances by the colloidal particles of cellulose in the wall. The formation of such adsorption compounds would lead to the complete obscuring of each particle of cellulose by a film of lignone substances. Such a compound would, therefore, be incapable of forming blue adsorption compounds with iodine.

It is possible to think of such adsorption compounds of cellulose with lignone substances in the cell-walls of wood, as being split up by mechanical stress and the cellulose being revealed as a consequence. Such a view would explain why, even in the region of failure, the ordinary lignin-reactions can be obtained as readily as in the normal wood, but side by side with a strong cellulose-reaction. According to this explanation the mechanical strain does not result in the destruction of the incrusting substances, but merely in their ultramicroscopic rearrangement in relation to the cellulose particles by which they can be regarded as being adsorbed in the unaltered lignified walls.

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* BARGER, C., and FIELD, 'Journn. Chem. Soc. Trans.,' 1912, p. 1394; BARGER, G., and STARLING, W., 'Journ. Chem. Soc. Proc.,' 1913, p. 128.

BEHAVIOUR OF COMPRESSED WOOD TOWARDS POLARISED LIGHT.

The facts regarding the nature of the deformations in the cell-walls of compressed specimens and the interpretations which have been outlined above, received striking confirmation by the use of the polariscope. It was found that the optical properties of the walls of the deformed tracheides had been altered in important respects.

Under low powers of the microscope, with crossed nicols, the zone of failure, both in radial and tangential sections, stands out as a very bright band across the unaltered parts of the section. The band corresponds exactly in form to similar bands brought out by staining methods in other specimens. On rotating the analyser to the parallel position, the illumination of the band reverses and stands out as a dark zone crossing a brightly illuminated section. Comparison with the behaviour of the uninjured parts of the wood shows that in addition to the illumination being reversed in the zone of failure, the degree of illumination is brighter than in the unaltered parts of the wood at their brightest.

The effect under polarised light is partly due to the folding of the cell-walls and consequent altered orientation of these, but examination of walls showing slip-lines without buckling or crinkling, shows that the folding is not the main cause of the altered anisotropy in the zone of failure. Under high magnifications the coarser slip lines are particularly well demonstrated and the parts of the wall substance in the immediate vicinity of the lines show greater anisotropy than the rest of the wall. This results in the lines standing out under crossed nicols as bright lines (often red) across the darker wall, and as dark lines in the parallel position.

The polariscope thus affords an even more effective means of demonstrating the slip-lines than when staining methods are used. Both methods give clear results for Spruce, to which the above descriptions apply, but, in some other woods like Ash the shearing lines are not so easily demonstrated by the methods of differential staining, owing to the unaltered walls taking up, to some extent, the cellulose stains and reagents. In such cases the polariscope has been particularly useful as a rapid and vivid means of demonstrating the existence of lines of slip.

SLIP-PLANES IN ASH.

In Ash the gross characteristics of the failure, briefly referred to in an earlier paragraph, are preceded by changes in the walls of the fibres which comprise the main mechanical elements of the wood. It has been pointed out that the fibres buckle gradually under compression and finally there is a separation of the tissues at the medullary rays. The buckling of the fibres is, however, invariably preceded by the initiation of microscopic planes of slipping in the substance of the cell-walls.

The multiplication of these slip-planes leads to the buckling of the fibres as in the autumn tracheides of Spruce (Plate 3, fig. 9). The slip-lines, in the sectional views of the walls, are often inclined at an angle of about 45° to the long axis of the fibre, but the angle, as in Spruce, may be considerably higher than this. Seen in the surface view of the walls the lines may cross transversely but are often inclined at a high angle to the longitudinal axis of the fibre; this inclination, however, is never that of the slits of the pits.

The first sign of failure, as in Spruce, is the development of these planes of shear in the cell-walls; as they increase in number and more fibres become involved the failure gradually passes over into buckling of the fibres to be followed by separation at the medullary rays. The whole process in Ash, however, is much more gradual than in Spruce, and a much greater area of fibres shows slip-lines before the buckling begins. This may be correlated with the greater plasticity of the wood of Ash than that of Spruce. Even in the autumn wood of Spruce the buckling is much sharper than is usual in Ash (Plate 1, *cf.* figs. 5 and 6).

SLIP-PLANES IN PITCH PINE.

In Pitch Pine the thin-walled cells of the spring wood are crinkled under compression, while the thick-walled tracheides of the late wood buckle like those of the autumn wood of Spruce. The crinkling or buckling of the tracheides in this wood is also preceded by the development of definite shearing planes in the substance of the cell-walls. These are particularly well demonstrated both by the method of differential staining and by the polariscope. The sequence of changes, leading to buckling or crinkling, is similar to that described for Spruce and for Ash (Plate 3, fig. 8). The much greater proportion of thick-walled tracheides probably largely determines the grosser characters of the failure already described.

For the three woods studied in detail, it is thus clear that the first stage in the failure under compression is the development of planes of shearing in the substance of the walls of the cells comprising the wood. The buckling or crinkling are secondary effects, depending probably on the thickness of the cell-walls. The still grosser appearances of the failures can be explained by such anatomical characters as the proportion of autumn to spring wood, and the size, nature, and distribution of the medullary rays. The main contribution of this paper, however, is the tracing of the original causes of failure back to the minute microscopic deformation of the substance of the cell-walls of wood, along planes more or less definitely orientated in relation to the direction of the stress. The general conclusions regarding the origin of failure in compression derived from the detailed study of Spruce, Pitch Pine, and Ash, have been extended to all the woods so far examined. These include Oregon Pine, Oak, Swamp Cypress, Birch, Larch, and Andaman Padouk.

THE EFFECT ON COMPRESSION FAILURES OF SOAKING TIMBER IN WATER.

In the work described above, the moisture-content of the test specimens was that of ordinary air-dried wood, *i.e.*, from 12 to 15 per cent. of the dry weight of the wood. It was found in a previous investigation that the compressive strength of Spruce is strikingly affected by the moisture-content of the specimen tested. For example, wood, which in the fibre-saturated condition (*i.e.*, about 30 per cent. moisture) yielded under a compressive stress of about 3000 lbs. per square inch, required about 8500 lbs. per square inch to produce failure when the moisture-content was reduced to 3 per cent. of the dry weight of the wood. It was of interest, therefore, to ascertain if this remarkable difference in the strength values at different conditions of moisture-content could be correlated in any way with differences in the microscopic characters of the strains. Some results from this point of view were obtained with specimens of Spruce soaked in water, to ensure complete fibre-saturation.

The soaked specimens were compressed in the testing machine until the indicator showed yielding had begun to take place. Sections from such specimens demonstrated that failure is initiated, as in air-dry wood, by the development of planes of slipping in the cell-walls. These slip-planes, however, are more diffused through the specimen than when dry wood is compressed. The zone of failure, which ultimately appears, is in consequence broader, and its limits are less sharply defined than before. All the appearances obtained in such soaked specimens suggest that the buckling and even the crinkling of the tracheides occur much more gradually since they are preceded by much more generalised slipping than when the Spruce is dry.

In Ash, the effect of soaking in water is even more striking than in Spruce. As before, the failure is initiated by the development of planes of slipping in the fibre walls. The initial failures so produced, however, occur in large numbers, evenly distributed through the length of the test-specimen (text-fig. 2). In Ash of ordinary moisture-content, *e.g.*, 15 per cent., the few initial failures which arise are confined to a middle region of the specimen, and lead to a zone of failure and displacement in this region (text-fig. 1). The form of the individual initial failures both in dry and in soaked Ash is the same, even though the number and distribution of these initial failures is so different.

The effect of soaking the wood of Ash and of Spruce in water is to lower considerably the value of the compressive strength of the wood, and to make it more plastic. This increased plasticity is manifested by the more ready occurrence of slipping in the substance of the cell-walls, and also by the more generalised distribution of the slip-lines in the test-specimen after failure.

In the employment of wood for certain purposes, the pieces are often shaped by bending, after soaking in warm water or steaming. The pieces are held in the bent position, and, on cooling and drying, retain the deformation given to them. This method is frequently employed in the case of Ash. It was therefore of interest to examine the microscopical effect of producing such permanent deformation by bending wood after soaking in warm water or steaming it.

Specimens of Spruce and of Ash, measuring 10 inches by $\frac{1}{4}$ inch by $\frac{1}{4}$ inch, were bent to various degrees, and held in the bent position until cold and dry. Sections through the middle of such bowed specimens showed that the permanent deformation had invariably been produced by the development of planes of slipping in the walls of the tracheides or fibres on the compression side of the specimen. These planes of slipping were regularly distributed through the deformed portion, being most abundant at the region of greatest deformation. In cases where extreme bending of the specimen was carried out, initial failures and buckling of the fibres and tracheides took place. Even where only the very slightest permanent bowing was produced, it was possible to demonstrate planes of slipping in the cell-walls in the middle part of the specimen. The facts for Ash and for Spruce, permanently deformed after soaking in warm water or steaming, are thus in entire agreement with those obtained in the compression failures of these woods in the air-dried condition.

Fractures in Longitudinal Tension.

The gross features of the tension fractures of a number of woods, including Oak and Ash, have been described and figured by Fulton (*loc. cit.*). He found that the slipping,* which resulted in fracture, invariably occurred along the planes of the medullary rays, so that the fracture had an irregular splintery character, as seen on the tangential face, and was manifested on the radial face, as a straight break across the specimen. The results obtained for the tension fractures of Spruce, Ash, and Pitch Pine, in the present work, are not in agreement with those of Fulton, even for the gross form of the fractures. As in the failures in compression, the initiation of the fracture has been traced back to the behaviour of the substance of the walls of the individual tracheides or fibres of the wood.

The fractured specimens, which were supplied me by Major Robertson, R.A.F., were cylindrical in form with expanded ends, the central portion of the specimen being much narrower in diameter than the ends which had been held in the grips of the machine.

The gross features of the fractures may be briefly summarised. In Spruce, the fracture is normally of a splintery character, as seen both from the radial and the tangential faces, but the planes of slipping for the main splinters are generally parallel to the annual rings, and the gross slip often takes place in the spring wood in the near vicinity of these rings (text-fig. 3). A certain amount of slipping also occurs in planes at right angles to the annual rings, and this explains the splintery character, as seen in the tangential view of the fractured specimen (text-fig. 3). The history of the development of the broad picture of the fracture is probably as follows. The initial effect of the tension stress is to cause local isolated ruptures in the specimen; these ruptures result in the production of longitudinal shearing

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* The slipping referred to by Fulton is a gross slipping of the tissues of the wood and not the more microscopic slipping in the substance of the walls, described in this paper.

stresses, and the rest of the material fails by longitudinal shearing. The microscopic characters of the fractured surfaces, *e.g.*, at S (text-fig. 3), are identical with those obtained in specimens of Spruce fractured by longitudinal shearing, and are therefore consistent with the explanation given.* The microscopic characters of the initial local ruptures will be described below.

In Ash the fracture is more abrupt than in Spruce, but the gross slipping in this wood also takes place along planes parallel to the annual rings, particularly in the spring wood (text-fig. 4). As in Spruce, there is also some slip in the tangential planes, but this is not so obvious in the specimens I have examined as that in the planes parallel to the annual rings. Plate 4, fig. 15, shows that the form of the fracture is not affected by the medullary rays.

In Pitch Pine the tension fracture is usually extremely short and is transverse in character, but even here the bigger irregularities follow the planes of the annual rings rather than those of the medullary rays (text-fig. 5). Owing, however, to the normally brittle character of Pitch Pine, it is not so suitable for the consideration of the questions under discussion.

The more microscopic characters of the fractures produced by longitudinal tension may now be described. In tangential sections of the fractures of Spruce, Ash, and Pitch Pine, there is no evidence that the medullary rays form special places of weakness for pure tension stresses in the longitudinal direction. The medullary rays are so abundant that it seems unlikely that fractures could occur without involving some of them; but the specimens examined conclusively showed that the initiation of slipping could not in any way be specially related to the rays (Plate 4, fig. 18).

Normal specimens of Spruce in the air-dried condition give breaks of the tracheides similar to those shown in Plate 3, figs. 10 and 11. The walls of the tracheides, both of the autumn and spring wood, are ruptured along planes which have exactly the inclination of the slits of the pits. Plate 3, fig. 11, shows a complete fracture in a spring tracheide while at (S.) slipping, which has not yet led to actual rupture, is taking place. The planes of slipping in the walls and also the ruptures in these are confined to the vicinity of the pits, although the inclination of the slip-planes is the same as that of the slits of the latter. In tension failures, unlike compression failures, the initial rupture rapidly follows upon the development of planes of slipping in the substance of the walls; rupture is, therefore, preceded by the appearance of relatively few slip-lines. It is noteworthy, however, that the fractured ends of the tracheides, as well as the few slip-lines that appear, behave selectively towards stains and reagents just as do the slip-lines in the compression failures.

The slip-lines in the sectional view are generally obliquely inclined to the edge of the walls. From the general microscopic appearance of the fractured tracheides, however, there is no doubt that most of the slipping takes place in tangential planes (*i.e.*, at right angles to the surface) in the walls. Text-fig. 6 illustrates the direction

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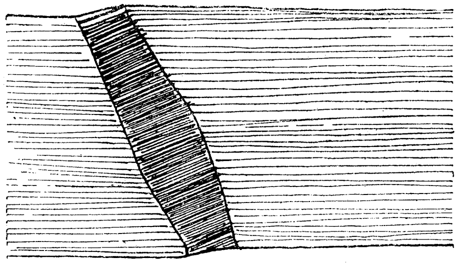
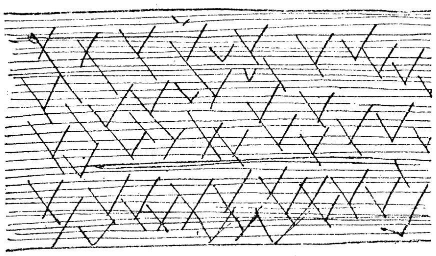
* See pp. 67–69 below.

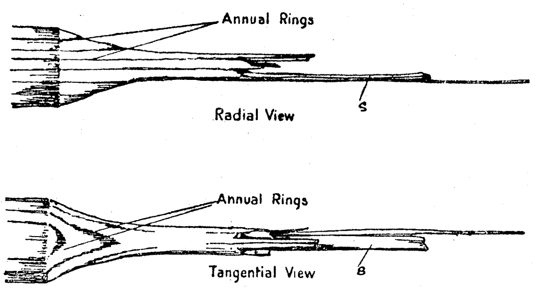


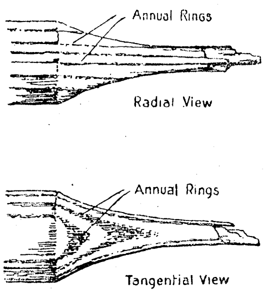


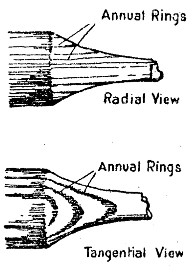
TEXT-FIG. 1. TEXT-FIG. 2.

TEXT-FIG. 1.—Diagram of zone of failure in air-dry Ash (15 per cent. moisture). × 4.

TEXT-FIG. 2.—Diagram of lines of failure in similar piece of Ash to that in fig. 1, after soaking in water. × 4.





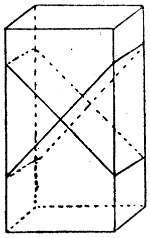


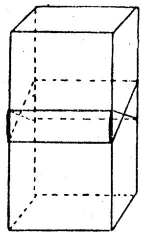
TEXT-FIG. 3. TEXT-FIG. 4. TEXT-FIG. 5.

TEXT-FIG. 3.—Specimen of Spruce fractured in tension, showing appearance of fracture from the radial and tangential views. (Half actual size.)

TEXT-FIG. 4.—Similar specimen of Ash to that in text-fig. 1, fractured in tension. (Half actual size.)

TEXT-FIG. 5.—Similar specimen of Pitch Pine, fractured in tension. (Half actual size.)

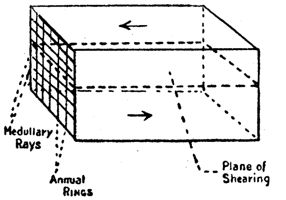


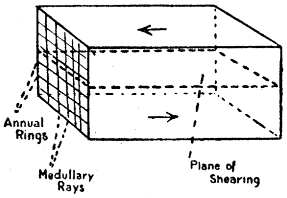


TEXT-FIG. 6. TEXT-FIG. 7.

TEXT-FIG. 6.—Diagram illustrating planes of shear in the cell-walls in tension specimens of Spruce.

TEXT-FIG. 7.—Diagram illustrating the direction of the planes of shear in the cell-walls of compression specimens of Spruce.





TEXT-FIG. 8. TEXT-FIG. 9.

TEXT-FIG. 8.—Diagram to illustrate the direction of longitudinal shearing along a radial plane.

TEXT-FIG. 9.—Diagram to illustrate direction of longitudinal shearing along a tangential plane.

of the planes of slipping in such cases. This differs from the slipping in the radial direction in the walls (*i.e.*, parallel to the surface), which is most frequently observed in the compression failures of Spruce (text-fig. 7). In tension fractures the displacement of the wall-substance is thus in the tangential direction in the individual walls, whilst in compression failures the movement is usually in the radial direction.

For normal Spruce the substance of the cell-walls behaves differently towards tension and compressive stresses. In both cases the failure occurs by shearing in the wall-substance, but this is much less plastic in tension than in compression, since, in the former case, very few planes of slipping arise before rupture occurs. While in tension the special planes of weakness generally have the same inclination as the slits of the pits, in compression, slipping never occurs along these planes, but along planes orientated at right angles to them (*cf.* Plate 3, figs. 10 and 6).

Striking deviations from the form of tension fracture just described, were obtained for brittle samples of Spruce and also for the normal tension fracture of a number of the harder woods. In these cases the lines of fracture do not follow the inclination of the slits of the pits, but, on the contrary, the walls are broken across transversely, *i.e.*, at right angles or at a high angle to the long axis of the tracheide or fibre (Plate 4, figs. 13, 14, and 17). In the portion of the wall seen in section, it is clear that the break occurs along radial planes in the individual cell-wall, inclined at 45° or rather more to the long axis of the cell. This tension fracture of brittle wood thus occurs along planes of slipping, similarly orientated to those already described for compression specimens. Some early stages in such tension failures of a brittle sample of Spruce were obtained, and these indicated that even in this case the actual rupture was preceded by the formation of a very small number of planes of slipping in the walls of the tracheides. These planes of slipping rapidly connected up across the specimen, which then fractured (Plate 4, figs. 13 and 14).

The results obtained from tension fractures of brittle Spruce appear to indicate that the brittle qualities are associated with a greater resistance to slip along tangential planes, having the same inclination as the slits of the pits, than along radial planes in the individual walls. In normal Spruce, on the other hand, there is more resistance to slipping on radial planes than on tangential planes in the individual walls; this leads to the more splintery appearance of the fractured ends of the cells (*cf.* Plate 3, fig. 10, and Plate 4, fig. 14).

In Ash, the fibres are roughly circular in transverse section, and not, as in the tracheides of Spruce, rectangular in section. The slipping which takes place in the walls as a result of tension, occurs along oblique planes which seldom have the same inclination as the slits of the pits (Plate 4, fig. 15). As in Spruce, the tension failure occurs by slipping in the substance of the walls of the fibres, and rupture takes place before very many planes of slipping have developed. Some slight indications were obtained that more slip-planes appear in Ash before rupture than in Spruce, but it would not at present be safe to draw conclusions from this.

In Pitch Pine, the fractured tracheides present very close similarities to those seen in the brittle specimens of Spruce. The abrupt break shown in text-fig. 5 is accompanied by transverse breaks as seen on the surface of the walls of the tracheides (Plate 4, fig. 16). In this case, also, the sectional view of the walls shows slip-lines inclined at about 45° to the edge of the wall. The failure, therefore, occurs by slipping along radial planes in the substance of the cell-walls, but extremely few slip-planes are developed in any one tracheide, prior to rupture taking place (Plate 4, fig. 16).

The facts for the tension failures of Spruce, Ash, and Pitch Pine are in harmony with those already described for the compression failures of these woods. Failure takes place, both in tension and compression, by the development of planes of slipping or shearing in the substance of the cell-walls. In tension failures of brittle samples of Spruce, of normal Pitch Pine and generally of normal Ash, the planes of slip are identical with those obtained in compression. In normal Spruce and occasionally in Ash, the planes of shearing for tension failures have the same inclination as the slits of the pits. Most of the examples of failure in tension studied have shown only a very localised distribution of slip-lines in the vicinity of the fracture.

Longitudinal Shearing.

The behaviour of wood subjected to longitudinal shearing can be correlated with the behaviour in longitudinal tension. Specimens of Spruce were fractured by longitudinal shearing both in the tangential and in the radial directions. Small rectangular pieces measuring about ½ inch long by ¼ inch by ¼ inch were broken by pushing one part of the specimen over the other by striking a blow on the specimen held firmly in a vice. The fractures obtained by this simple method corresponded exactly in their gross and microscopic characters to those exhibited by larger specimens tested in longitudinal shearing by Major Robertson, R.A.F. It was found advantageous to use this simple method of applying the stress, since it was then possible to make microscopical observations on a large number of specimens. It was also possible to trace earlier stages in the failure than could possibly have been obtained in specimens from a testing machine.

Text-figs. 8 and 9 illustrate the directions in which the specimens were cut, and the arrows indicate the direction of the shearing. When Spruce is subjected to shearing along a tangential plane the failure always occurs in the spring wood and at rupture the fractured surfaces are finely hairy. Microscopical examination shows that the fracture occurs in the substance of the cell-walls of the tracheides and not by a separation of the tracheides from one another. Radial longitudinal sections through the fracture show that the substance of the cell-walls has been torn into a series of oblique shreds (Plate 2, fig. 12); these shreds give rise to the hairy appearance mentioned above.

The shearing stress in the tangential plane has resulted in the separation of the substance of the walls along planes which are usually inclined at an acute angle to the long axis of the cells (Plate 2, fig. 12). Early stages in the failure are characterised by the appearance, at fairly regular intervals, of steeply-inclined, oblique splits in the walls (Plate 4, fig. 19). These splits gradually widen and as the shearing continues the tangential walls of the fractured cells become separated, the shreds produced elongating by stretching (Plate 2, fig. 12, Plate 4, fig. 19). This stretching of the shreds is accompanied by the appearance on them of fine parallel lines which are inclined to the direction of the original splits.* The shearing in the substance of the walls of the tracheides usually takes place independently of the bordered pits and is often confined to a very narrow zone of the wall near to the corner of the tracheides. The bordered pits remain intact, and instead of forming places of weakness in relation to the longitudinal shearing, appear rather to be a source of strength to the walls. It seemed possible that the shreds seen in the specimens fractured in the tangential direction might be derived in part from the tangential walls of the tracheides as well as from the radial walls shown in Plate 2, fig. 12, and Plate 4, fig. 19. Transverse sections of fractured specimens, however, proved conclusively that when the shearing takes place in the tangential plane, only the radial walls of the tracheides are shredded, and the tangential walls are not visibly affected by the stress (Plate 2, fig. 14).

When the wood of Spruce is subjected to longitudinal shearing along a radial plane (text-fig. 8), the stress operates both on the autumn and spring wood and affects each differently. In the spring wood, as before, the fracture occurs by a regular shredding of the walls along steeply inclined planes (Plate 2, fig. 13). Slight splits which are steeply inclined appear at fairly regular intervals; these gradually widen giving rise to shreds which elongate by stretching. This elongation of the shreds is accompanied, as before, by the appearance of fine parallel lines which are differently inclined from the splits (Plate 4, fig. 20).

In the autumn wood the fracture occurs by an abrupt separation of the radial walls at the middle lamella of the tracheides and at the medullary rays (Plate 4, fig. 21). There is, therefore, no shredding evident where the fracture passes through the autumn wood. The different appearances of the fracture, in the region of the autumn and spring wood respectively, are best seen in transverse sections through the fracture (Plate 4, figs. 21 and 22). The difference in the behaviour of the autumn wood is probably related to the greater thickness of the secondary layers of the cell-walls causing these to offer greater resistance to shearing than the middle lamella and the walls of the cells of the medullary rays.

The staining effect, obtained with chlor.-zinc-iodide in the case of compression failures, was also obtained in these shear failures. The shreds of the walls give the

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* These fine parallel lines have all the appearances of the striations described by NÄGELI, CORRENS, etc., for the walls of fibres and other plant cells, but as is pointed out below, no such striations have ever been observed in the present work on wood, except in relation to mechanical injury and in the wood near branches.

blue colour similar to that obtained in the zone of failure in compression, and the striæ on the shreds appear as dark lines of a deeper blue colour. The mechanical stress of longitudinal shearing, therefore, produces the same sort of fundamental change in the staining properties of the cell-walls which has already been described for compression failures.

In addition to this staining effect the fractures in longitudinal shearing show features which can be further correlated with the characteristic method by which failure is initiated in compression. The longitudinal shearing stresses, operating on the wall of a tracheide (if this were isotropic), would tend to produce separation along two systems of planes inclined approximately at 45° to the direction of stress. The actual result on the thin-walled tracheides is consistent with this expectation except for the inclination of the planes. The oblique splits represent the direction of one of the series of planes of separation, while the fine striæ on the shreds are slip-lines due to the stretching. In some few instances splits occur simultaneously in both series of planes of separation giving an irregular fracture such as is seen in Plate 4, fig. 23. Much more often the splits are confined to one of the series of planes of separation and shreds are produced which show striæ or slip-lines. The anisotropy of the cell-wall probably explains the fact that the inclination of the planes of separation, as manifested by the splits and the striæ on the shreds, is not 45° to the direction of the stress.

The inclination of the planes of separation as seen on the surfaces of the walls, unlike that of the gliding planes, which have been decribed above, for compression failures, is similar to, or identical with, that of the slits of the pits. This correspondence between the inclination of the splits and that of the pit-slits, as well as the possible nature and effect of the natural anisotropy of the cell-wall will, be discussed below, in connection with the general questions bearing on the internal structure of the woody cell-walls.

Discussion of Results and Theoretical Considerations.

The discovery that the permanent deformation of wood under mechanical stress takes place by the development of planes of slipping in the walls of the cells of which it is composed, has led to fundamental conclusions regarding the ultimate mechanical properties of wood. The properties depend primarily on the behaviour of the substance of the cell-walls, and only secondarily on the arrangement of the individual cells and tissues in the wood. In this sense wood is a mechanical structure the qualities of which depend even more on the material of construction, that is the cell-wall substance, than on the distribution of material in the structure.

The behaviour of the cell-wall substance towards mechanical stresses in the development of planes of slipping, presents striking similarities to the mechanical properties of other substances. Reusch (*loc. cit.*), in 1867, described the production of gliding planes in the crystals of many ordinary salts as a result of compression. His observations have been extended by many other investigators, and the gliding planes are now recognised as localised planes of slipping which may form planes of cleavage for the crystals. More recently EWING and ROSENHAIN (*loc. cit.*) have shown that the plastic deformation of metals is due to the development of gliding planes within the crystals of which the metals consist. They hold that plastic deformation can only take place by gliding on the slip-planes of true crystals, and that the plasticity of metals is bound up with their crystalline structure. The slip-planes arise in directions which bear a definite relationship to the crystallographic axes, but as far as I am aware no relation has been traced between the directions of stress and those of the slip-planes in the individual crystals of the metals.

The well-known LÜDER'S lines which often appear on strained specimens of certain metals have, however, according to HARTMANN[*] and also to GULLIVER,[†] inclinations which approximate to those expected of planes of maximum shearing, *i.e.*, 45° to the direction of the stress. It is also generally recognised that LÜDER'S lines are outward manifestations of large numbers of the microscopic gliding planes in the crystals of the metal. The general direction of the slip follows the plane of least resistance in the substance of the metal, since it is reasonable to suppose that the minute size of the heterogeneous crystalline components allows the metal to behave as an isotropic substance.

The substance of the cell-walls of wood is probably, most correctly, regarded as of a colloidal nature, but at the same time it must be pointed out that the cell-walls show many important resemblances to crystals. These resemblances must be taken into account in the consideration of the nature of the planes of slipping which arise in wood under mechanical stress.

NÄGELI[‡] was the first to attempt to relate the properties of cell-walls to conceptions of molecular physics. He studied the double refraction of cell-walls, their swelling properties and the visible microscopic structure, and was led from his observations over a wide field to propose the micellar hypothesis of the structure of cell-walls and other organised substances. According to this hypothesis the cell-wall consists of crystalline molecular aggregates or micellæ, arranged in a definite manner to build up micellar complexes. The micellar complexes are orientated in rows, and the fine spiral striations seen on the walls of many elongated cells represent alternating micellar rows having respectively greater or less water-content. The inclination of the striations, when present, is the same as the inclination of the slits of the pits, and even where striæ are not readily visible the direction of the micellar rows

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[*] GULLIVER, "Some Phenomena of the Permanent Deformation of Metals," 'Proc. Inst. Mech. Engineers,' 1905, p. 141; 1907, p. 579.

[†] HARTMANN, 'Distribution des Déformations dans les Métaux, etc.,' Paris, 1876.

[‡] NÄGELI, 'Bot. Mitth.,' vol. 1, "Die Anwendung des Polarisation apparates auf die Unters. des vegetabilischen Elementartheile," 1862, p. 183; 'Bot. Mitth.,' vol. 2, "Über den innern Bau der vegetabilischen Zellenmembranen," 1864, pp. 1–102; 'Theorie der Gährung,' 1879.

has been inferred by NÄGELI and later investigators from the slits of the pits. NÄGELI found that the directions of greatest swelling and of greatest optical elasticity were connected with the direction of inclination of the striæ. In the elongated cells of wood the axis of greatest swelling is in a radial direction in the wall, that is at right angles to the surface. The axis of least swelling lies in the tangential plane, that is parallel to the surface of the wall, and is inclined in the spiral course of the striæ or pit-slits. An intermediate amount of swelling takes place along a tangential axis at right angles to this. The axes of optical elasticity are the inverse of these, the least in the radial direction, the greatest along the spirals of the striæ, and the intermediate one at right angles to these.

The main trend of botanical opinion has favoured, more or less completely, the micellar hypothesis of NÄGELI; it is a remarkable tribute to the hypothesis that even quite recently some workers with colloids, such as BACHMANN,* VON WEIMARN,† and BRADFORD‡ should have made use of some of the main conceptions of NÄGELI, in explaining the structural properties of gels. It has, however, been frequently pointed out that many of the facts, on which the micellar hypothesis was based, are incorrect. These facts need not be referred to in detail, but NÄGELI'S conception of essentially crystalline character of the cell-wall in plants must be considered in relation to the present work on wood. To-day, the substance of the cell-wall is usually regarded as an emulsoid gel. It is, therefore, probably non-crystalline in structure for, according to WO. OSTWALD§ and to BACHMANN, no emulsoid gel has been proved to be crystalline. VON WEIMARN, however, regards many gels as possessing crystallinity, and BRADFORD has recently extended VON WIEMARN'S theory to certain of the organic gels. Alternative explanations to the micellar hypothesis have been proposed, but, with the possible exception of STRASBURGER'S|| molecular-net hypothesis, none of them has attempted to explain more than one or two of the sets of properties first studied (in this connection) by NÄGELI. PFEFFER¶ has pointed out that the properties of elasticity and rigidity have not been investigated in connection with the molecular structure of organised bodies, and I am not aware of any previous work from this point of view. The bearing of the behaviour of the cell-wall substance of wood towards mechanical stress, on hypotheses of the structure of cell-walls must, therefore, be dealt with at some length.

Striations of the nature of those described by NÄGELI (*loc. cit.*), CORRENS,** DIPPEL,††

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* BACHMANN, "Unters. u. die ultramikros. Struktur von Gallerten," 'Zeit. für Anorgan. Chem.,' vol. 73, p. 128 (1912).

† WEIMARN, VON, 'Koll. Zeitschr.,' vol. 4, p. 317 (1908); vol. 5, p. 62 (1909); vol. 6, p. 32 (1910).

‡ BRADFORD, S. C., 'Biochem. Jl.,' vol. 11, 1917; vol. 12, 1918; 'Science Prog.,' vol. 12, 1917.

§ OSTWALD, WO., 'Colloid Chemistry' (Eng. Ed.), 1915, pp. 56–65, etc.

|| STRASBURGER, 'U. d. Bau Wachstum d. Zellhäute,' 1882; 'Histologische Beiträge,' vol. 2 (1889).

¶ PFEFFER, 'Plant Physiology,' vol. 2, pp. 70–83.

** CORRENS, 'Jahrb. für Wiss. Bot.,' 1892, p. 254; 1894, p. 587.

†† DIPPEL, 'Das Mikroskop,' 1898.

KRIEG* and others have not been observed in the woods here investigated when in the uninjured condition. But this is not surprising, since the descriptions referred to are for the most part from wood obtained in the vicinity of branches or from fibres which had been subjected to chemical or mechanical treatment. In the specimens used in the present work, there was little possibility of any of the pieces consisting of wood from the neighbourhood of branches.

Although, however, striæ have not been met with, spirally inclined slits of pits have been observed continually on the walls of the tracheides and fibres (Plate 1, fig. 9). It has been mentioned above that the inclination of these slits has usually been regarded as a good indication of the direction of the micellar rows.

It has been shown in the above study of the failure in longitudinal compression of Spruce, Ash, and Pitch Pine, that the planes of slipping are always inclined differently from the planes of inclination of the slits of the pits, and generally form a high angle with them. In Spruce, for example, the slits of the pits are steeply inclined, and only form a small angle with the axis of the cell, as seen in surface view. The slip-lines run transversely across the surface of the walls of the thin-walled cells or are inclined at a high angle (more than 45°) in the thick-walled cells. In both cases the lines run obliquely in the section of the wall, but at an angle of more than 45°, to the long axis of the cell.

The displacement for compression failures is thus never along the planes of the slits of the pits, and, except for the fact that the inclination of the slip-planes to the direction of stress is always greater than 45°, the behaviour of the material of the walls is such as might be expected from an isotropic substance.

The anisotropy of the cell-walls, as regards their mechanical properties, is more striking in connection with the different behaviour in tension and compression. It is well known that the strength of wood is much greater in longitudinal tension than in end-compression. The different microscopical characters of the fractures can be correlated with this difference. It has been seen that increasing stress in end-compression leads to the development of increasing numbers of slip-planes in the substance of the walls, but that actual rupture rarely, if ever, occurs along these, failure being finally manifested by buckling and crinkling of the fibres. In tension there is a greater resistance to the development of slip-planes, and very few of these appear, but slipping along them is followed by rupture almost immediately. The microscopic facts, therefore, indicate that the gradual plastic yielding of the substance of the cell-walls, which occurs in compression, does not take place to anything like the same extent in tension. The fact that, in Spruce, after the initial ruptures have occurred in tension, the rest of the material fails by longitudinal shearing, does not affect this conclusion. If the substance of the cell-walls were isotropic, it seems

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* KRIEG, 'Beihefte zum Bot. Centralb.,' vol. 21 (1907).

reasonable to suppose plastic yielding would be manifested both in tension and compression in a similar manner.

In tension the inclination of the planes of slipping differs for different woods, but two main types have been observed. These are illustrated by normal Spruce on the one hand, and by Pitch Pine, brittle specimens of Spruce, and by Ash on the other. In the first of these types the slip-planes follow the same inclination as the slits of the pits. The hypothetical micellar rows, therefore, form planes of weakness for longitudinal tension in the cell-walls of normal Spruce and Ash. In the second type* (*e.g.*, Pitch Pine, brittle Spruce, and Ash) the slip-planes are orientated in the same manner as in the compression failure, and, consequently, in these cases, the planes parallel to the slits of the pits do *not* form planes of less resistance than the rest of the wall. In the first type there seems to be less cohesion, for tension stress, between the particles of wall-substance along the planes of the slits, than in any other direction. In the second type there is no such obvious difference between the cohesion in any one direction and in any other,† and the fracture therefore approximates more closely to planes of maximum shear in the cell-walls. It is perhaps noteworthy in this connection that brittle specimens of Spruce often give strength-values in tension tests which are not so widely different from the values in compression tests as are those of normal Spruce.‡

The failure of Spruce in longitudinal shearing is initiated by the appearance of obliquely-inclined splits, on the surface of the walls, which stand at right angles to the plane of shearing. The natural anisotropy of the cell-wall causes the splits usually to follow the inclination of the slits of the pits ; the shreds produced, elongate by slipping, along planes inclined to these. The slip-lines on the shreds present all the characters of the spiral striations described by NÄGELI and his followers for the walls of many elongated cells.

When longitudinal shearing stresses operate on thick-walled cells, *e.g.*, in the autumn wood of Spruce, or in the fibres of hard woods, separation occurs in the middle lamella between adjoining cells. The middle lamella offers less resistance to the shearing stresses than the other layers of the thick wall. This mechanical weakness of the middle lamella is not manifested in the tension and compression failures since the stress is mainly taken by the other layers of the wall in these cases.

It would be possible to use, to some extent, the facts described above in support of the micellar hypothesis of NÄGELI. It has been shown that, in regard to their mechanical properties, the cell-walls of wood manifest an anisotropy closely parallel to that shown in regard to such other physical properties as double refraction and swelling. In terms of the micellar hypothesis, the axes of greatest optical elasticity,

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* Andaman Padouk and Swamp Cypress also conform to this type.

† The different degrees to which plastic yielding by slipping occurs in tension and compression, respectively, of course holds for both types.

‡ I am indebted to Major ROBERTSON, R.A.F., for this information.

of greatest mechanical rigidity, and of least swelling on the one hand, and the axes of greatest swelling, of least mechanical rigidity, and of least optical elasticity on the other, would be identical. This would be in general agreement with the facts derived from the microscopic appearances of the cell-walls of wood after failure in compression, in tension and in shearing in a longitudinal direction respectively. It has already been pointed out, however, that the conception of crystalline micellæ as the ultimate particles of cell-wall substance is not in accord with many modern views regarding the structure of colloid gels (p. 71). Neither is the micellar conception necessary to explain the facts described above for wood. It seems to me that a mechanical hypothesis of the structure and properties of the colloidal cell-wall explains all the known facts.

The salient points of the alternative hypothesis of cell-wall structure, which I have been led to propose from this study of the minute mechanical properties of the cell-walls of wood, will now be outlined. The cell-wall in plants has usually been regarded as a secretion product of the protoplasm. On the basis of modern views of surface energy and adsorption, it is conceivable, however, that the membrane in vegetable cells arises, first, by the accumulation of pectic substances, and then of cellulose, at the surface bounding the protoplasm. This accumulation at the surface would occur passively, as the substances arose in the protoplasm by reason of their capacity to reduce the surface energy of the protoplasm according to the GIBBS-THOMPSON law. The cellulose, thus accumulating at the protoplasmic boundaries in the growth of the membrane, will be in the condition of a highly viscous fluid, but, as the membrane grows, the viscosity increases, and finally the membrane attains the qualities of a rigid gel.

In the flow of mobile liquids, the displacements of the particles in relation to one another are uniform, in other words, such liquids under mechanical stress exhibit homogeneous shearing. EWING and ROSENHAIN (*loc. cit.*) have further pointed out that even viscous fluids may manifest homogeneous shearing. KUNDT,* however, has shown that, when even dilute sols of gum, collodium, etc., are subjected to mechanical deformation by rapidly rotating layers between two glass surfaces, a transitory double refraction is observed. The shearing produced in such cases must be heterogeneous, but, since no microscopic change is visible, an ultramicroscopic heterogeneity of shear must be thought of in this case. If, however, a membrane possessed even a small amount of rigidity, the shearing produced under mechanical deformation might be permanent, and yet ultramicroscopic, and thus only manifested by the development of double refraction. On the other hand, the permanent deformation of a more rigid membrane would give rise to a more gross heterogeneous shearing along microscopic planes of shear, the traces of which would be visible in the membrane. In other words, in the shearing of mobile, viscous, semi-viscous, and rigid substances, there must be every transition possible, from a condition

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* KUNDT, 'Wied. Ann.,' vol. 3, p. 110 (1881).

of absolutely uniform or homogeneous shearing of the particles, through a permanent ultramicroscopically heterogeneous shearing, to a grosser heterogeneity of shearing in rigid substances. In such rigid substances, the individual planes of shear are separated by apparently homogeneous layers, with no visible manifestation of shearing.

From the above theoretical considerations, it follows that the anisotropy of the cell-wall can be explained as due to strains* produced by the operation of mechanical stress on the semi-rigid substance of the cell-wall in its developmental history. In other words, in the growth and solidification of the cell-wall, large numbers of minute slip-planes develop, and this causes the wall to become anisotropous. These planes are either wholly ultramicroscopic, or also microscopic in character; in the one case they are manifested only by the double refraction of the cell-wall, and in the other also by the striations and the slits of the pits. It is perhaps not without significance, in relation to this hypothesis, that the young cell-wall, *e.g.*, of cambium cells, is not doubly refractive, but only becomes so later. BUTSCHLI† has shown that it is possible, by applying tension to hardened threads of gelatine, to produce markings which present extraordinary similarity to the fine striations of bast fibres. Although BUTSCHLI did not apply a mechanical significance to these markings, which I also have observed, it seems to me there is no doubt that they represent planes of slipping in the threads. It is further noteworthy that it is quite easy to produce striations in cell-walls, artificially, by mechanical treatment, and the conclusions of NÄGELI and others are open to criticism on this account. Such artificial "striations" have been described above in connection with the failure of the wood of Spruce in longitudinal shearing. NÄGELI regarded his mechanical treatment as merely revealing the predetermined inner structure of the wall. In my view, many of the striations were created by this mechanical treatment, and really represent microscopic planes of slipping in the wall-substance.

Little is known of the forces available in the growing cells of plants to account for the permanent deformations postulated above. It is, however, well known that in the development of tracheides and fibres from cambium cells considerable extension both in length and in diameter of the cells takes place. It is true that NÄGELI and SCHWENDENER‡ have maintained that this extension takes place by growth and not merely by stretching, but STRASBURGER,§ KRABBE‖ and others have shown that plastic stretching often occurs. The mechanism by which such plastic stretching could

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* The strains, thought of, are real strains in the mechanical sense, and not the internal tensions or stresses postulated by VON HÖHNEL and STRASBURGER, and recently revived by HARRISON ('Roy. Soc. Proc.,' A, vol. 94, 1918) to explain the double refraction of textile fibres.

† BUTSCHLI, "Unters. über Strukturen, u.s.w.," 'Verh. Nat.-Hist. Verein Heidelberg,' vol. 4 (1896).

‡ NÄGELI and SCHWENDENER, 'Das Mikroskop,' 1877, 2nd Aufl.

§ STRASBURGER, *loc. cit.*

‖ KRABBE, "Beitrag zur Kenntnis der Struktur u. des Wachstums Veg. Zellhäute," 'Jahrb. Wiss. Bot.,' vol. 18, pp. 346–424 (1887).

take place would be the development of the ultramicroscopic or microscopic slipping conceived of above.

In the present work it has been shown that permanent deformation in the cell-walls of wood takes place by the development of planes of slipping in the substance. This conception is now being carried back to the developmental history of such cell-walls and the peculiarities of the natural walls are regarded as manifestations of mechanical forces which have operated on them during the course of their development. In this connection it is perhaps significant that in the vast majority of the cases where striations have been observed the cells have an elongated form. It is further possible that some of the mechanical forces acting on the cell-wall in the course of its development arise as the hardening membrane contracts by loss of water in its fixed position.

In wood the greater resistance to plastic deformation by slipping in tension than in compression would receive some explanation on the view that tensile strain in the previous history of the cell-walls had rendered them less susceptible to further plastic deformation in tension. It is conceivable that further slipping in tension is not possible because all the available planes of slip have been utilised for the developmental straining. ROSENHAIN (*loc. cit.*), BEILBY,[*] and others have described similar phenomena for metals. These often show hardening and enhanced resistance to plastic deformation in tension after having undergone tensile strain. In some such cases the strain-hardened metal is more easily deformed in compression than in tension : that is, the strain hardening is uni-directional. This mechanical anisotropy in strain-hardened metals is somewhat analogous to that seen in wood.

The analogy, with the essentially crystalline metals, must not be pressed too far for wood, which, on the the views already expressed is not truly crystalline in nature ; but the resemblances may not be wholly without significance. In the case of wood it is held that the planes of slipping are not orientated in relation to any real crystallographic axes, but that they approximate to the planes of maximum shearing according to the direction of the stress. The orientation of these planes, however, is never 45°, as for isotropic substances, but is modified for particular stresses by the previous plastic deformations the wall-substance has undergone in the developmental history of the cell-walls. The above explanation of the mechanical anisotropy of the cell-walls of wood in my view, also satisfactorily explains the anisotropy in regard to their other main physical properties. The hypothesis that the mechanical anisotropy, as well as the double refraction and visible structure of the cell-walls may be explained as a result of mechanical causes operating on the substance of the cell-wall in the course of its development from a highly viscous fluid to a more rigid condition, has been framed almost solely in relation to facts derived from the study of the mechanical properties of wood. Further detailed investigation of the properties of the cell-wall

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[*] BEILBY, 'Roy. Soc. Proc.,' A, vol. 72 (1903); vol. 76 (1905); vol. 79 (1907); vol. 82 (1909).

in plants over a wider and more varied field will show whether the hypothesis can have a more generalised application.

SUMMARY.

1. The initial phenomenon of the permanent deformation of wood under end-compression, longitudinal tension, and longitudinal shearing, is the development of microscopic planes of slipping in the substance of the cell-walls of the wood.

2. The gross characteristics of failure in compression are described for Spruce, Ash, and Pitch Pine. The broad results for Ash and Pitch Pine confirm those of previous investigators, but Spruce shows important differences. It is shown that the gross characters of the failure in different woods are probably determined by the anatomical structure of the wood, but that primary changes due to the development of planes of slipping in the cell-walls precede the secondary effects described by previous investigators. The microscopic planes of slipping have not previously been recognised in wood.

3. The development of the slip-planes in the cell-walls is accompanied by profound changes in the behaviour of these towards many stains and reagents. The altered parts of the cell-walls behave as if free cellulose were present there. This effect is discussed in relation to its possible bearing on the process of lignification of cell-walls.

4. The gross and microscopic features of the failure of Spruce, Ash, and Pitch Pine in longitudinal tension are described. In all cases failure is preceded by the development of slip-planes, but only relatively few of these arise, and rupture occurs along some of them much more quickly than in compression failures.

5. The failure in longitudinal shearing is described for Spruce, and it is shown that the manner of failure is to some extent affected by the relative thickness of the cell-walls under stress. Failure takes place by the development of slip-planes, if the walls are relatively thin, and by separation at the middle lamella if the walls are thicker.

6. An attempt has been made to correlate the microscopic effects of the various forms of stress with the visible structure of the cell-walls, and with the double refraction of these. It has been found that the slip-planes developed in compression failures are not inclined similarly to the planes of the slits of the pits on the cell-walls. The failure in tension of normal Spruce, and also in longitudinal shearing of the spring wood of Spruce, occurs along planes having the same inclination as the slits of the pits, and therefore the same as that of the hypothetical micellar rows of NÄGELI. In many other woods, the failure in tension occurs along slip-planes similarly orientated to those obtained in compression failures.

7. The general behaviour of the cell-walls of wood is discussed in relation to the micellar hypothesis of cell-wall structure. The microscopic characters, accompanying the permanent deformation of wood by tensile and compressive stresses respectively, are different. The differences, which consist in the much smaller amount of slipping

which precedes rupture in tension than in compression in all the woods studied, and in the different inclinations of the planes of slipping in some of the woods, can be correlated with the differences in the numerical values, obtained for the strength under these stresses. It is pointed out that this mechanical anisotropy of the cell-walls is not wholly inconsistent with the micellar hypothesis of NÄGELI, which was framed to explain the anisotropy in other properties of cell-walls. Since, however, fundamental portions of NÄGELI'S hypothesis, such as the postulating of crystalline ultimate particles, are not necessary to explain the facts, an alternative hypothesis of cell-wall structure is proposed.

8. In the hypothesis, it is suggested that the mechanical anisotropy, as well as the double refraction and visible structure of cell-walls, may be explained as a result of mechanical causes operating on the substance of the cell-wall in the course of its development from a highly viscous fluid to a more rigid condition.

DESCRIPTION OF PLATES.

PLATE 1 (Photographs).

s., spring wood; *m.r.*, medullary ray; *r.*, place of rupture; *x.*, slip lines; *a.*, autumn wood; *f.*, zone of failure; *m.l.*, middle lamella; *p.s.*, pit-slits.

Fig. 1.—Compressed piece of Spruce, showing the zone of failure as seen on the tangential face. × $5\frac{1}{4}$.

Fig. 2.—The same piece of Spruce as in fig. 1, showing the zone of failure as seen on the radial face. × $5\frac{1}{4}$.

There is marked displacement in the radial direction; the displacement is most apparent at the limits of the annual rings, *i.e.*, where the autumn wood of one year abuts on the spring wood of the next year. There is no such evident displacement on the tangential face (fig. 1).

Fig. 3.—Tangential longitudinal section of a compressed piece of Pitch pine, showing the steeply inclined zone of failure. The displacement in the tangential direction is very marked, and an incipient zone of failure is seen in addition to the main zone. × 28.

Fig. 4.—Portion of the zone of incipient failure from the same section as fig. 3, showing the separation between the tracheides and the medullary rays. × 67.

Fig. 5.—Radial longitudinal section of compressed Spruce. A portion of a zone of failure is seen, showing the crinkling and buckling of the tracheides of the spring and of the autumn wood respectively. The radial displacement is obvious, and some separation of the elements has taken place at the annual ring. × 67.

Fig. 6.—Tangential longitudinal section of a compressed piece of Ash, showing the inclined zone of failure. The displacement in the tangential direction and the separation between the fibres and the medullary rays are clearly seen. × 28.

Fig. 7.—Tangential longitudinal section passing through the zone of failure in Spruce. × 9.

This has been stained by chlor.-zinc-iodide, and the reagent has swollen the zone of failure and straightened the tracheides. It shows the remarkable alteration in the staining properties of the zone of failure.

Fig. 8.—Radial longitudinal section passing through the zone of failure in Spruce. × 9.

This section was similarly treated to that in fig. 7, and shows equally clearly the change in the staining properties of the zone of failure. The reagent has swollen the zone and straightened the tracheides so that the displacement in the radial direction is not obvious, but the staining brings out the peculiar outline of the zone of failure in relation to the annual rings.

Fig. 9.—Portion of radial longitudinal section through compressed Spruce, showing the early stages in the development of the zone of failure. The bands of failure appear light on the darker background.

The crinkling of the spring tracheides is seen and also the early stages which lead to buckling in the thicker-walled autumn wood. The inclined slits of the bordered pits are seen in the photograph. × 67.

Plate 2 (Photographs).

Fig. 10.—Tangential longitudinal section of a compressed piece of Spruce, showing early stage in failure by crinkling of the walls of the tracheides. × 67.

Fig. 11.—Radial longitudinal section of a compressed piece of Spruce, showing slightly later stage in failure by crinkling of the walls of the tracheides. × 67.

Fig. 12.—Radial longitudinal section of a specimen of Spruce, fractured by longitudinal shear in a tangential plane. × 67.

The shearing has occurred in the walls of tracheides of the spring wood, and the wall substance has been stretched out into obliquely running shreds. (See also Plate 4, fig. 19.)

Fig. 13.—Tangential longitudinal section of a specimen of Spruce, fractured by longitudinal shear in a radial plane. The shearing has taken place in the walls of the tracheides, and the incipient production of shreds is seen. × 67.

Fig. 14.—Transverse section of similar piece, fractured by longitudinal shear in a tangential plane, to that shown in fig. 12. × 67.

The drawing out into shreds is seen to be confined to the substance of the radial walls of the tracheides.

Fig. 15.—Portion of radial longitudinal section passing through marginal portion of zone of failure in Spruce treated with chlor.-zinc-iodide. × 67.

The deep stain within the zone of failure is seen to be due to the multiplicity of bars of wall-substance which have stained selectively. These bars extend beyond the actual zone of failure, but are much less frequent, being separated by considerable zones of unaltered cell-walls.

Fig. 16.—Portion of tangential longitudinal section similar to the tangential section shown in fig. 15. × 67.

Again the presence of the deeply staining bars is seen, even outside the actual zone of failure.

Fig. 17.—Walls of tracheides of autumn wood of Spruce, in radial longitudinal section, showing commencement of permanent deformation by the development of oblique planes of slipping in the secondary layers of the wall-substance. No slip lines are evident in the middle lamella.

Photographed by polarised light with crossed nicols. × 350.

Fig. 18.—Similar photograph to fig. 17, showing the multiplication of slipping planes leading to crinkling of the cell-walls. × 350.

Plate 3 (Drawings).

(Figs. 1 to 7 of Spruce.)

Fig. 1.—The walls of the autumn tracheides of Spruce seen in tangential longitudinal section, showing very early stages in the development of slip planes. No bending has yet occurred. × 900.

Fig. 2.—Walls of two adjoining tracheides of autumn wood similar to those in fig. 1, showing later stages in the slipping. The number of planes ot slipping has greatly multiplied, and buckling is about to occur. The step-like projections of the substance of the wall are shown. × 900.

Fig. 3.—Walls of tracheides of autumn wood of Spruce, showing still later stage than in figs. 1 and 2. Buckling has now taken place as a result of the great multiplication of lines of slipping. × 600.

Fig. 4.—Walls of tracheides of spring wood of Spruce in radial section, showing early stage in the development of slip-planes, and in this case rapidly leading to crinkling. × 900.

Fig. 5.—Walls of tracheides of spring wood of Spruce at slightly later stage than in fig. 4, showing crinkling due to the multiplication of slipping planes. × 900. (*Cf.* Plate 2, fig. 11.)

Fig. 6.—Walls of tracheides of Spruce in radial section, showing oblique slipping lines both in the thickness of the tracheides and on the surface of the walls. The lines on the latter are not inclined at the same angle as the slits of the pits. × 275.

Fig. 7.—Walls of tracheides of spring wood of Spruce from same radial section as fig. 6, showing obliquity of slip-planes in the thickness of the walls and the horizontal character on the surface of the walls. × 275.

Fig. 8.—Walls of the tracheides of autumn wood of Pitch Pine in tangential longitudinal section, showing multiplicity of shearing planes leading to buckling. × 600.

Fig. 9.—Walls of fibres of Ash, showing multiplicity of shearing planes leading to buckling. × 900.

Fig. 10.—Walls of autumn tracheides of Spruce, fractured in tension, showing fibrous character of the break owing to shearing having occurred both in the radial and tangential walls. The inclination of the planes of fracture is approximately that of the slits of the pits. × 600.

Fig. 11.—Walls of tracheides of spring wood of Spruce in same specimen as fig. 10, showing similar oblique planes of fracture. An incipient fracture is also seen developing along similarly inclined planes at S. × 600.

Plate 4 (Drawings).

Fig. 12.—Walls of tracheides of autumn and spring wood of a brittle piece of Spruce, showing tension fracture spreading across them. × 80.

Fig. 13.—A few of the walls shown in fig. 12. Rupture has occurred in the spring tracheides, and the development of a very few slip-lines is seen in the autumn tracheides. × 275.

Fig. 14.—Walls of tracheides of autumn wood of Spruce, showing the horizontal break on surface of wall and oblique break in the thickness of the wall along slip-planes. The inclination of the slits of the pits is indicated. × 600.

Fig. 15.—Fractured ends of fibres of Ash. The break is along the oblique slip-planes, which are not inclined at the same angle as the pits. × 275.

Fig. 16.—Tracheides of Pitch Pine, fractured in tension. The break has occurred along slip-lines which are developed also in the vicinity of the rupture. × 600.

Fig. 17.—Walls of tracheides in fractured tension specimen of Pitch Pine, showing slip-lines. A bordered pit is shown, and this clearly has not proved a source of weakness. × 600.

Fig. 18.—Tension fracture of Ash (somewhat diagrammatic). The break has had no obvious relation to the medullary rays. × 80.

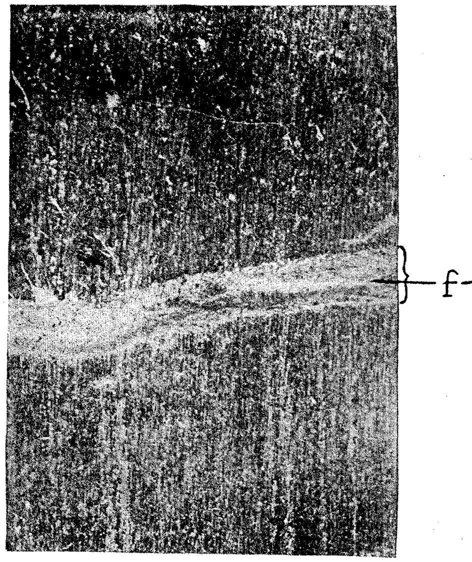
Fig. 19.—Radial longitudinal section of a specimen of Spruce, fractured by shearing along a tangential plane. The shredding of the walls is seen and also the fine slip-lines on some of the shreds. The bordered pits are intact, and only a narrow zone of the wall is stretched out—*cf.* width with that of the adjoining tracheide. × 275. (*Cf.* with Plate 3, fig. 11.)

Fig. 20.—Walls of tracheide from fractured region of a specimen sheared in the radial plane. Stretching of the wall has occurred with incipient shredding and the development of fine lines of slipping. × 275.

Fig. 21.—Transverse section through autumn wood of fractured specimen sheared in radial plane. The separation has occurred at the middle lamella. × 275.

Fig. 22.—Transverse section through the spring wood of the same specimen as in fig. 21, showing the drawing out of the tangential walls into shreds. × 275.

Fig. 23.—Walls of tracheide from fractured region of specimen sheared in the tangential plane. Separation is taking place along two series of obliquely inclined planes. × 275.



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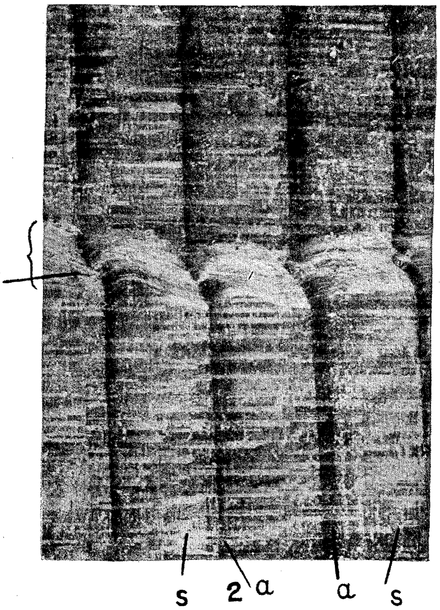

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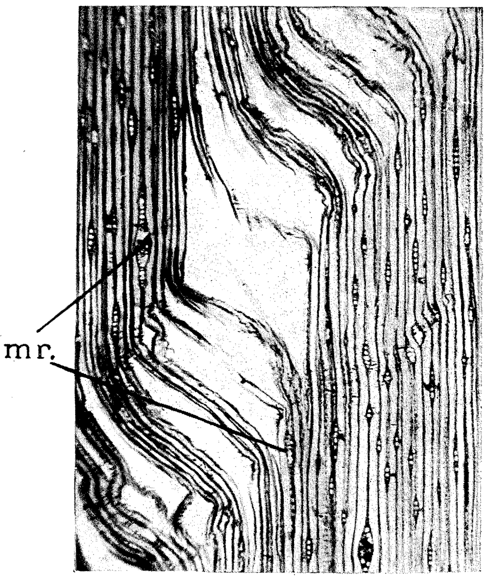

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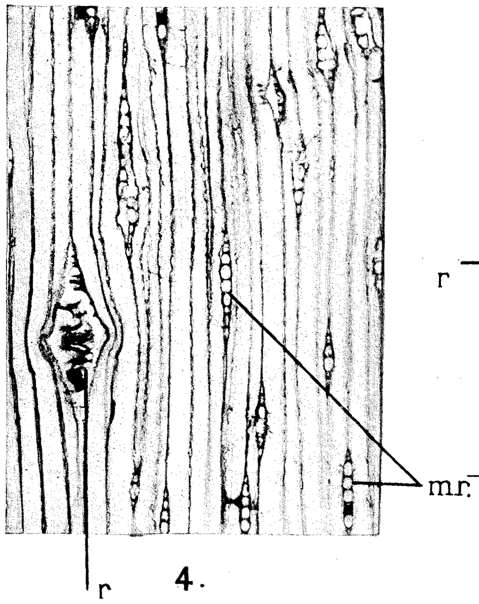

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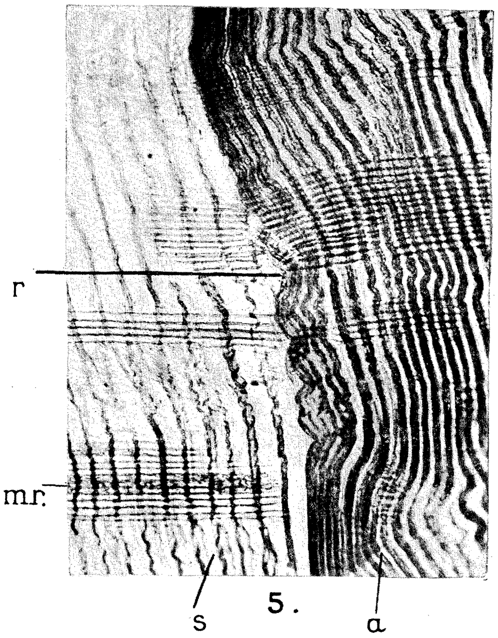

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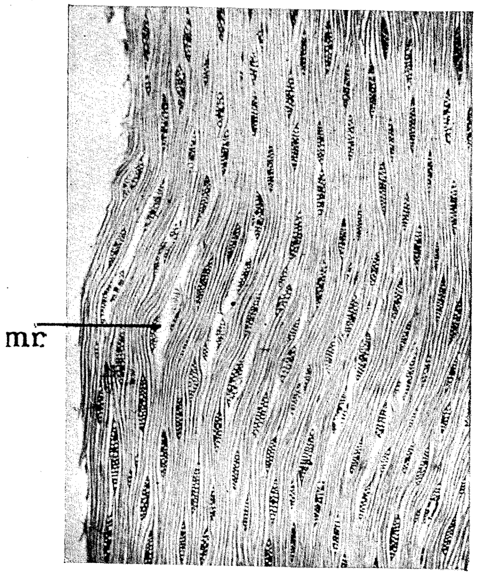

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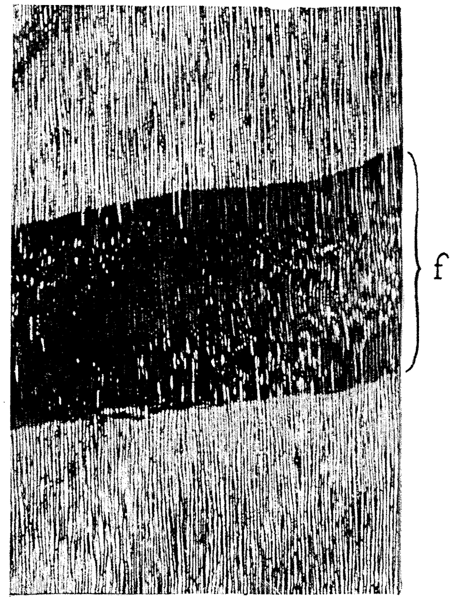

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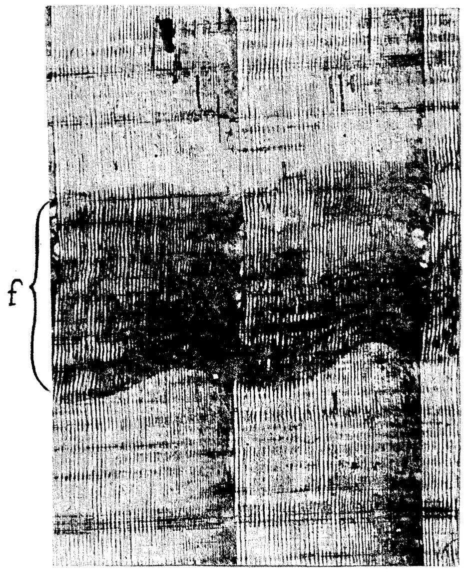

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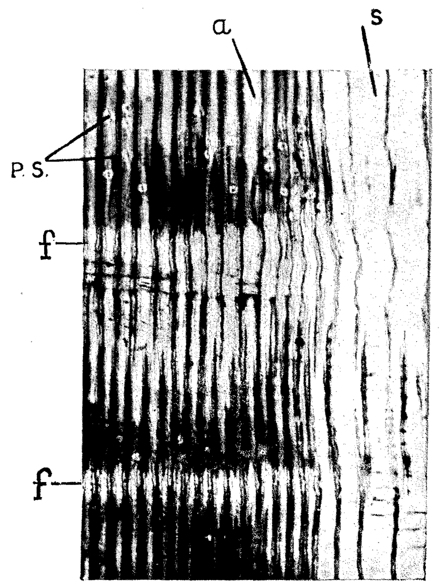

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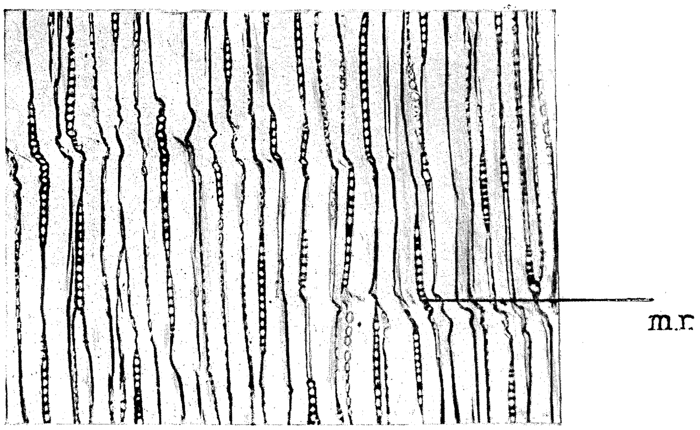

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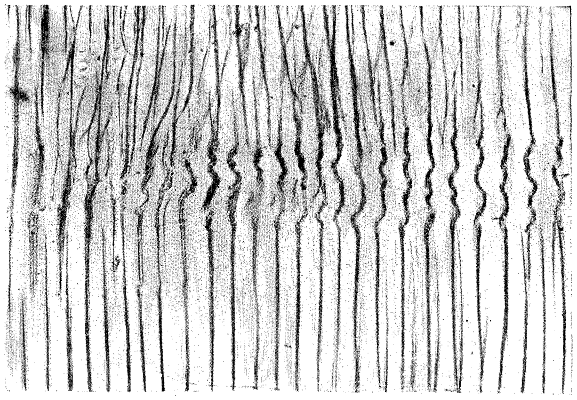

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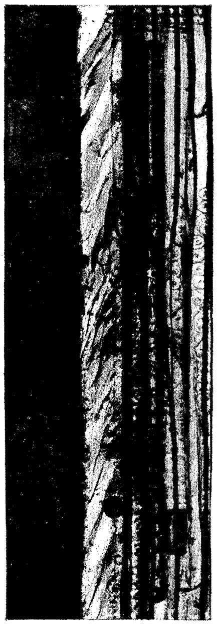

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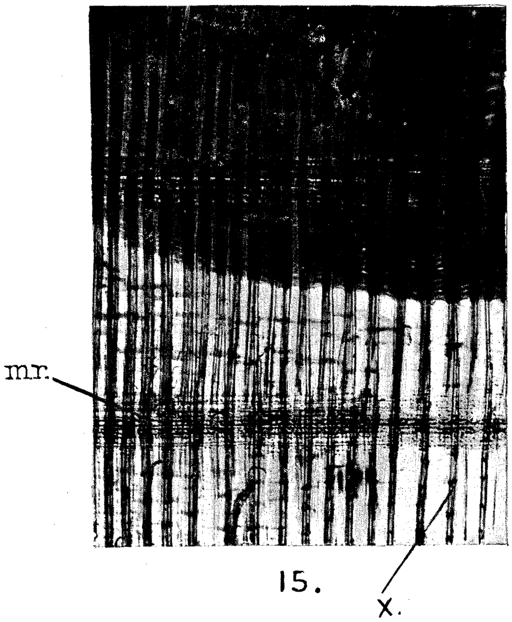

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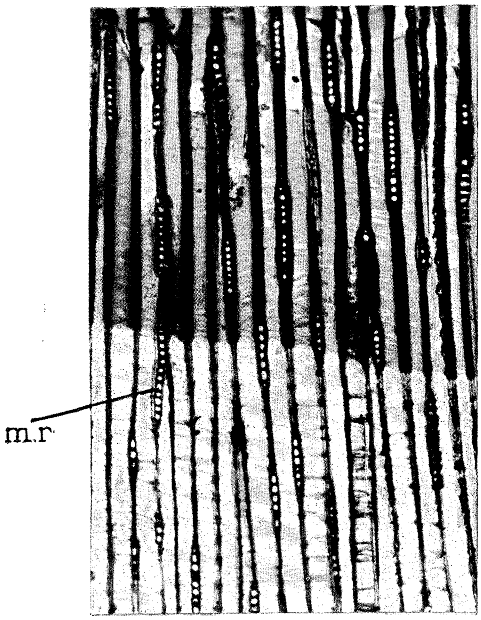

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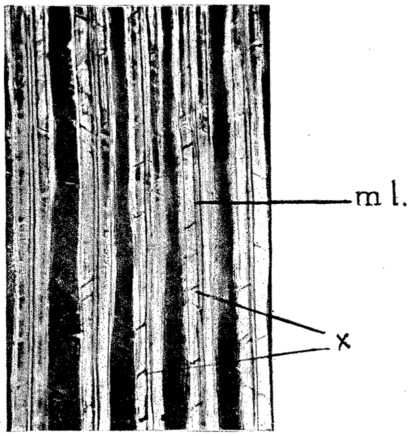

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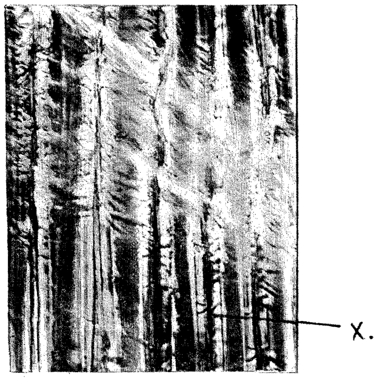

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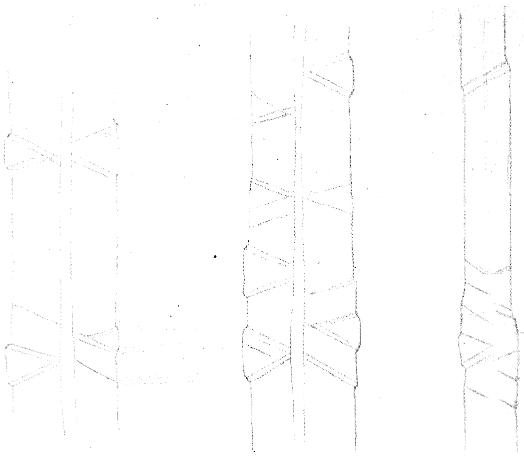

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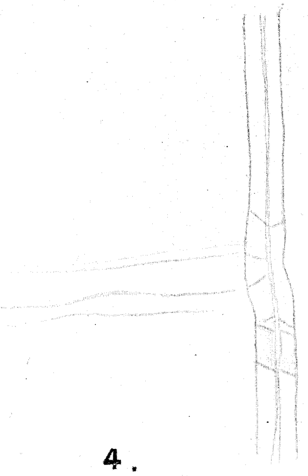

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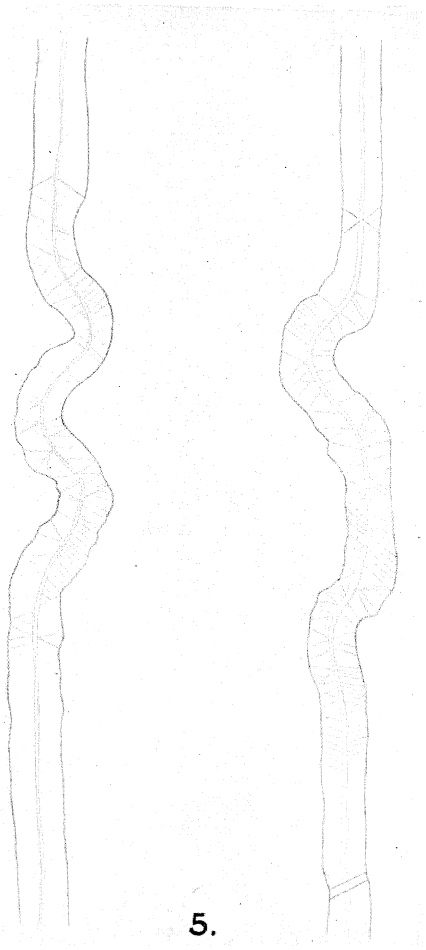

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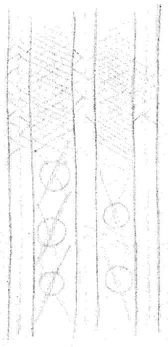

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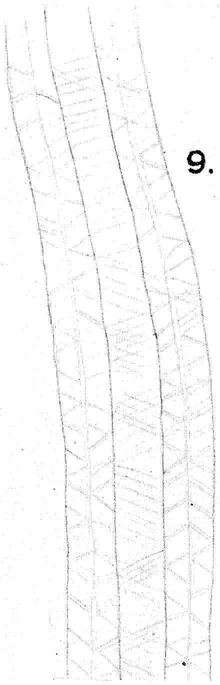

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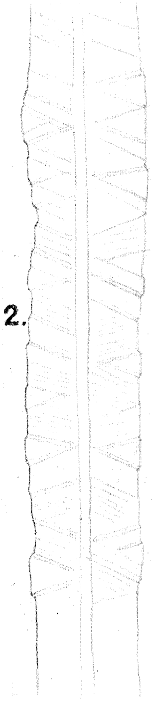

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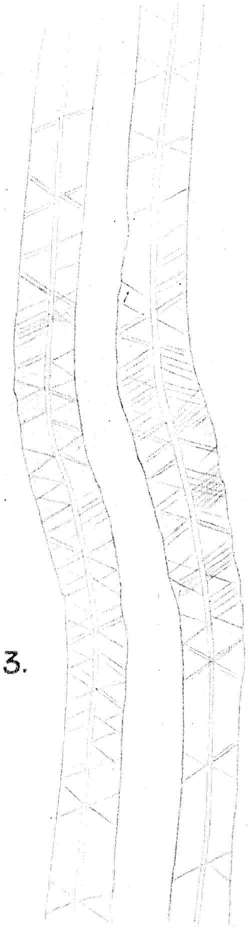

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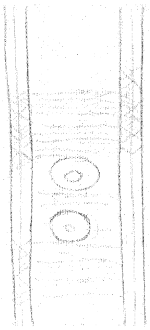

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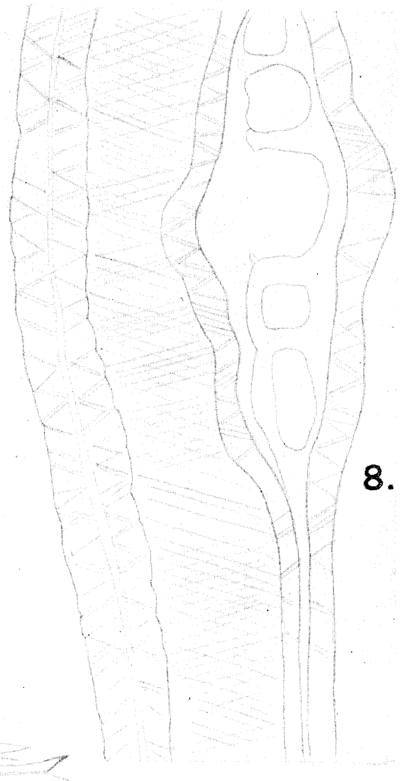

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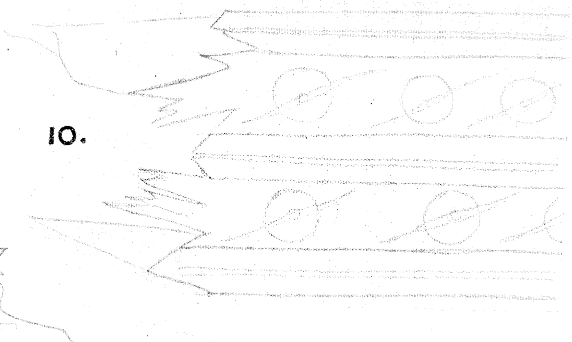

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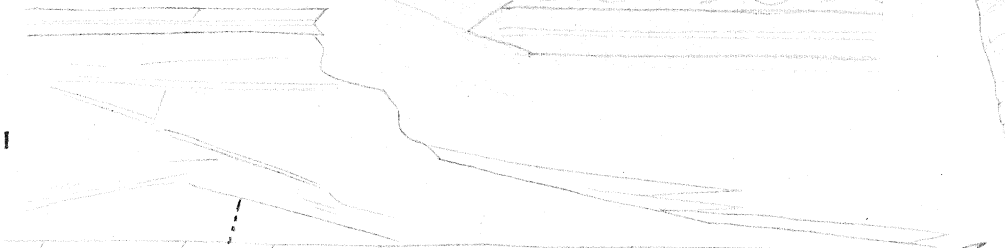

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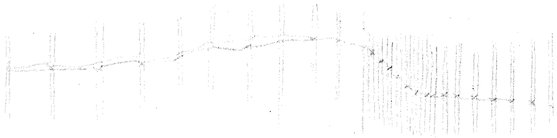

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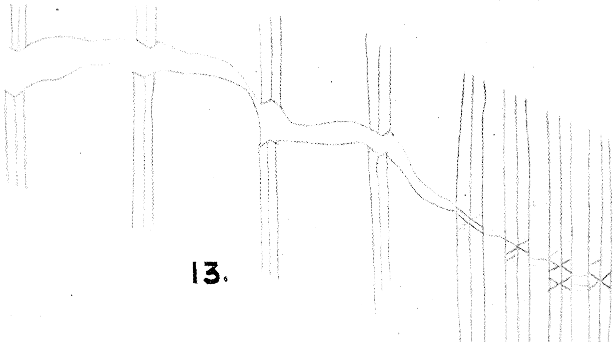

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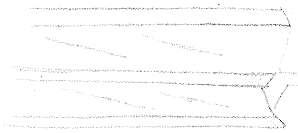

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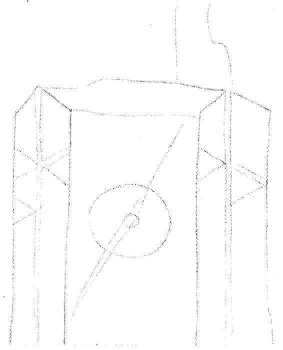

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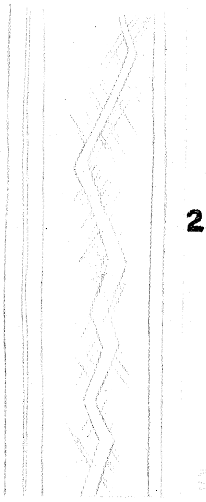

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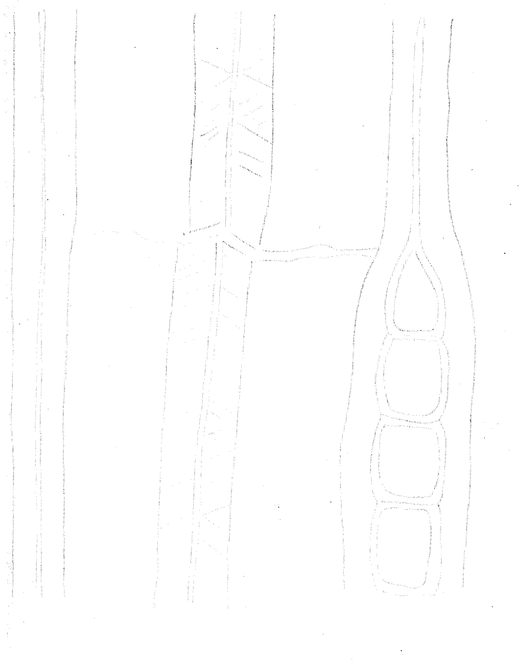

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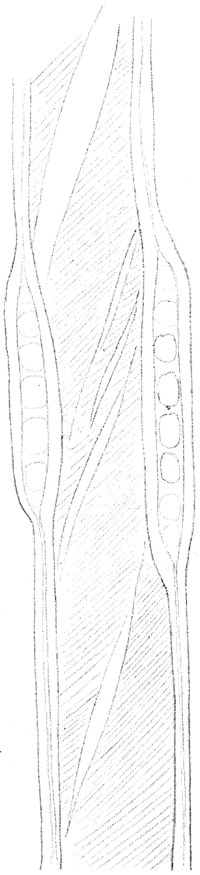

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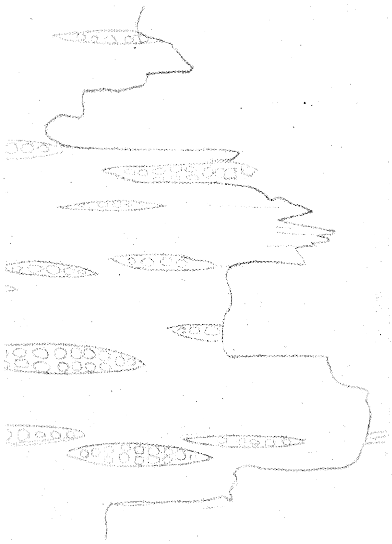

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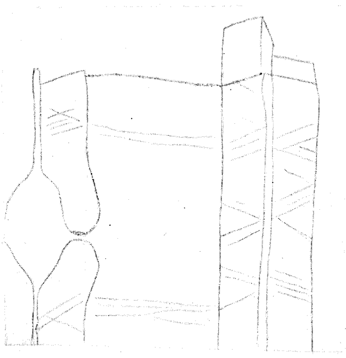

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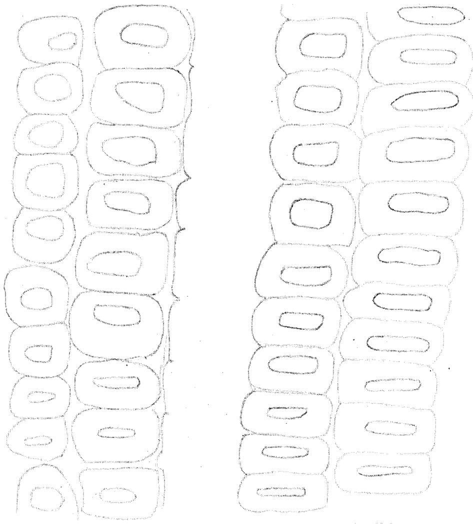

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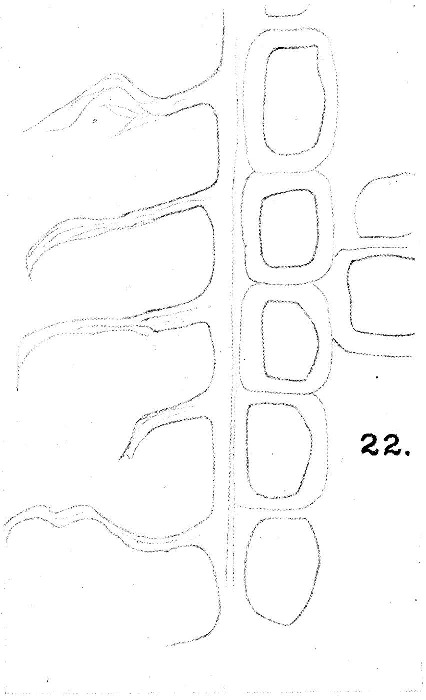

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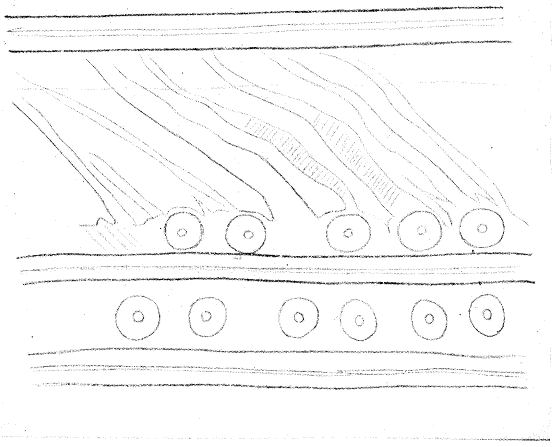

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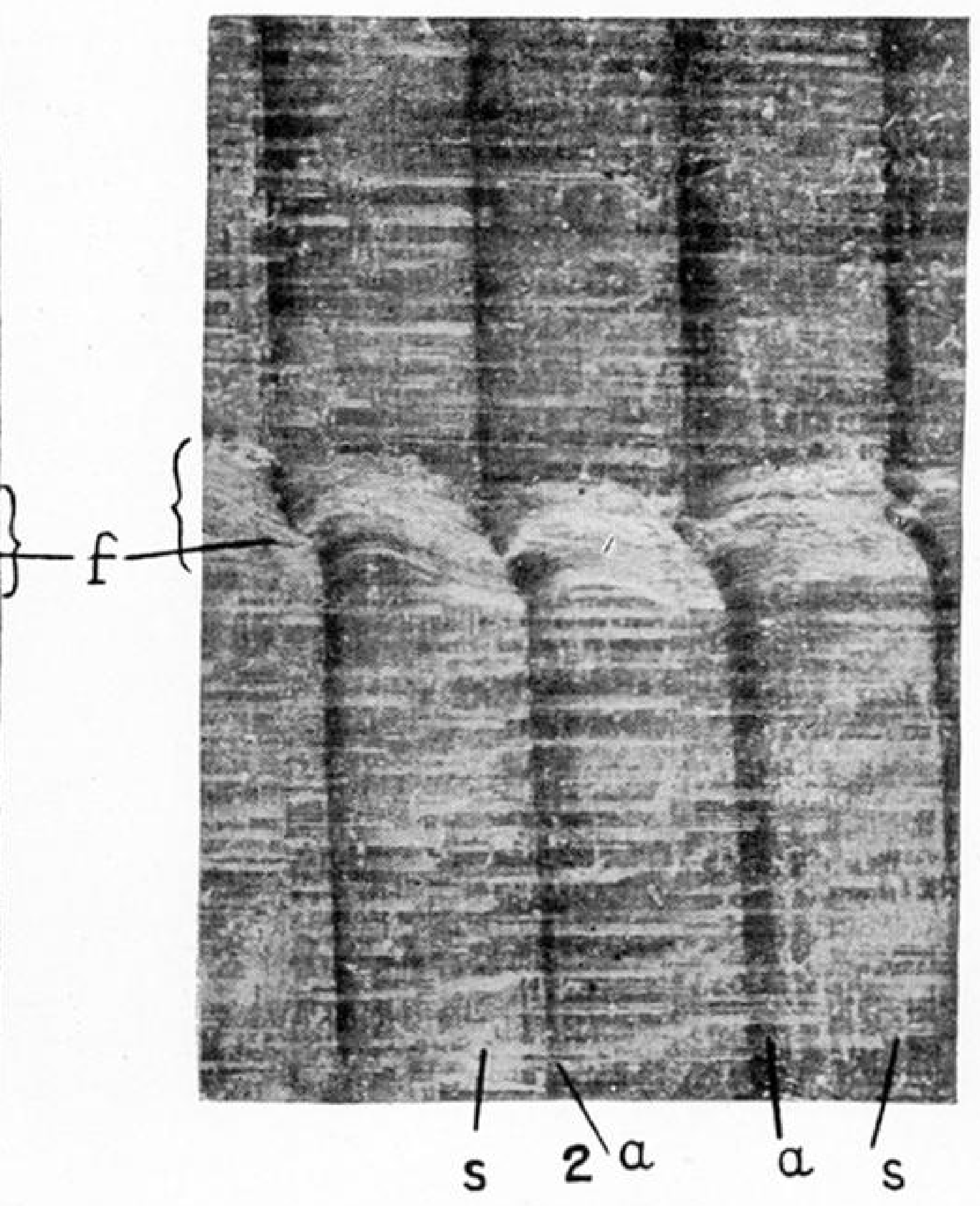

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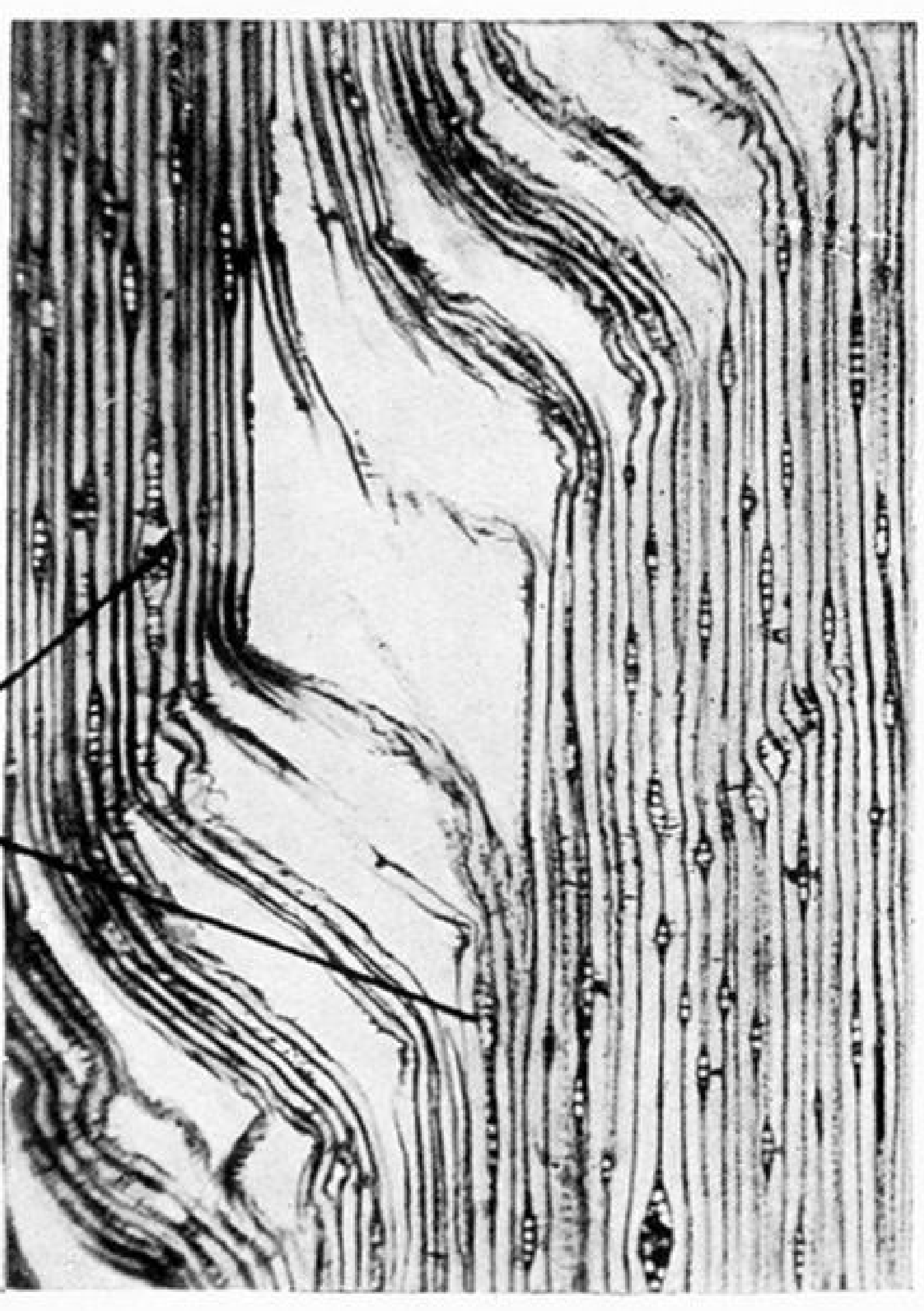

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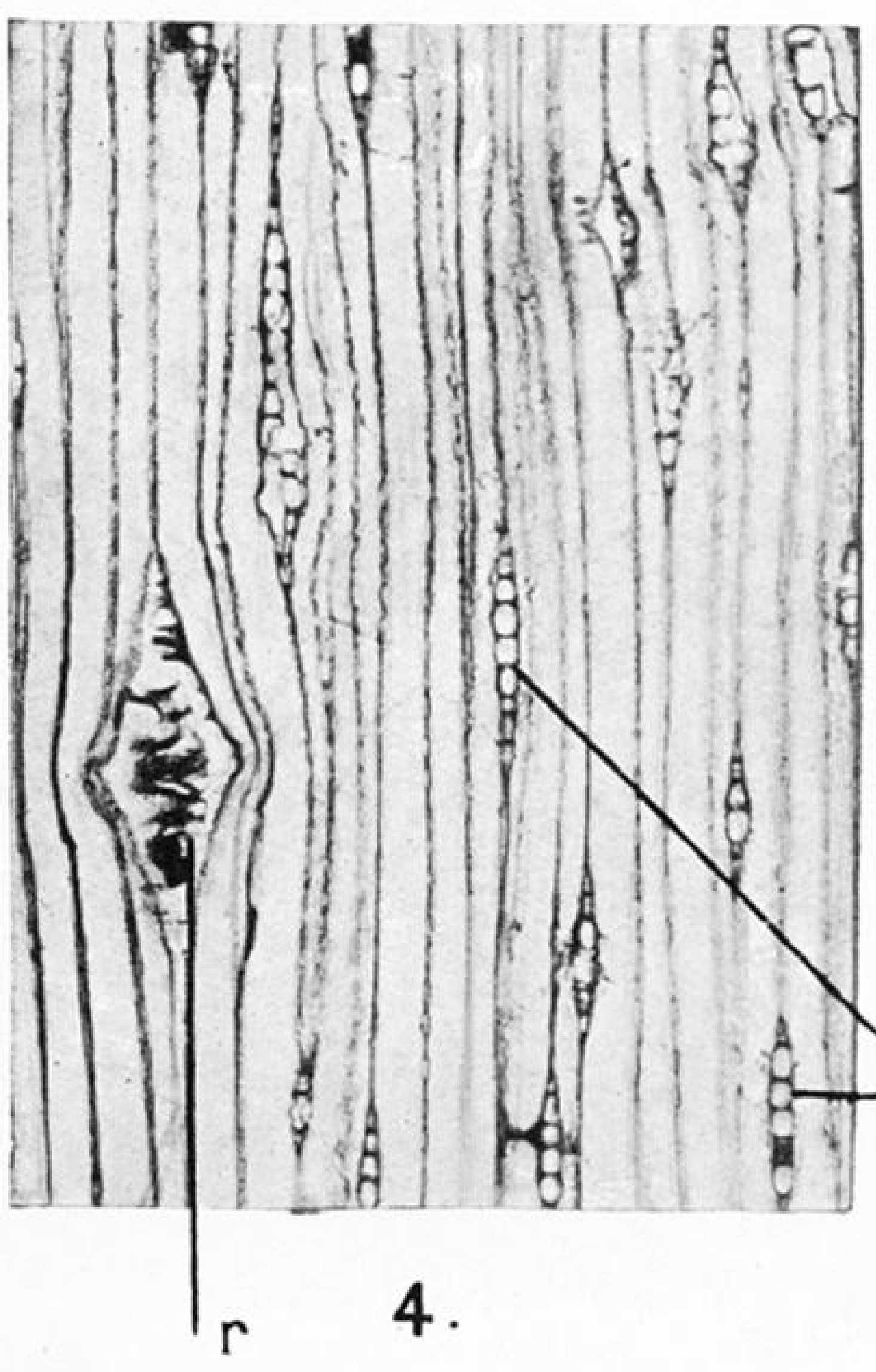

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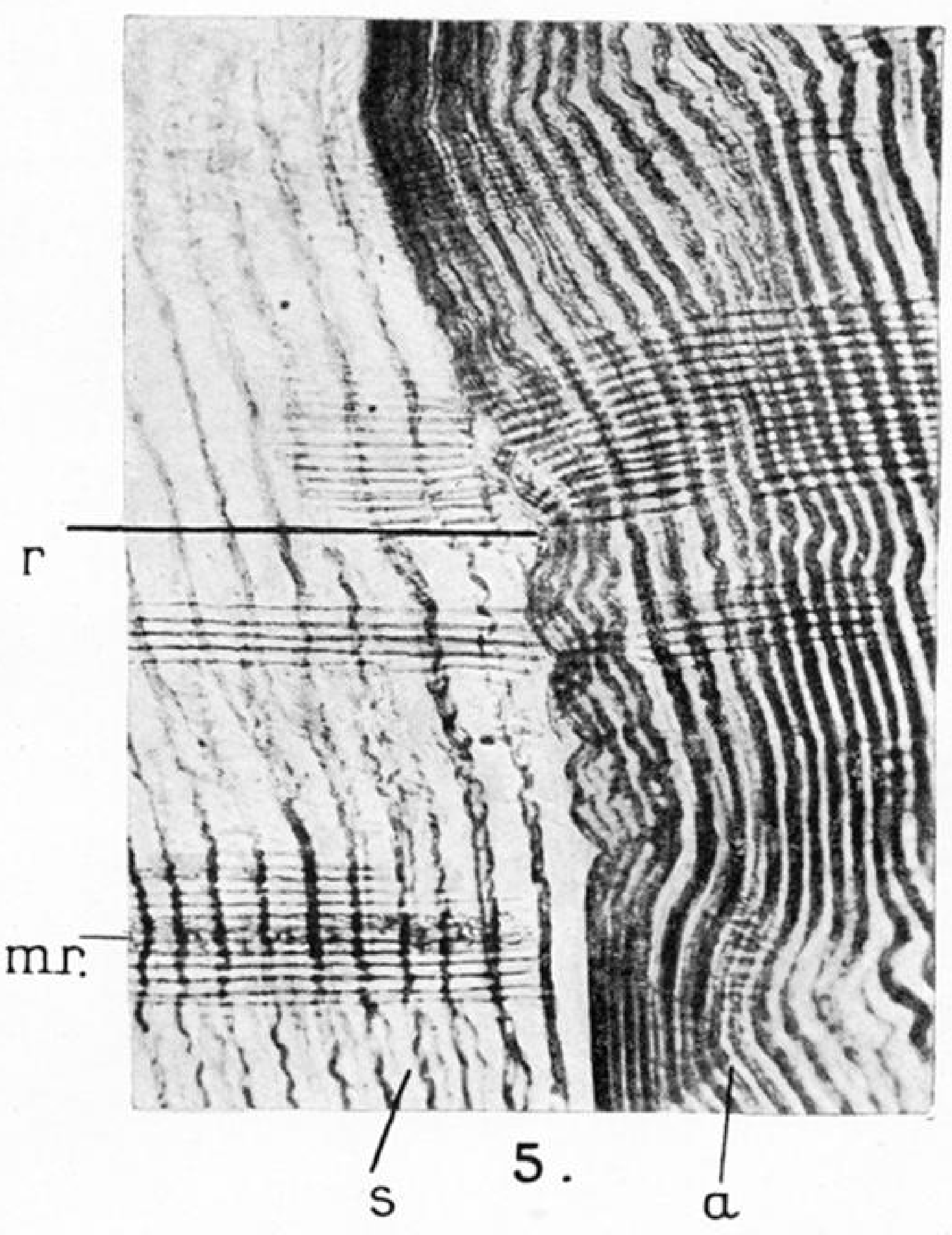

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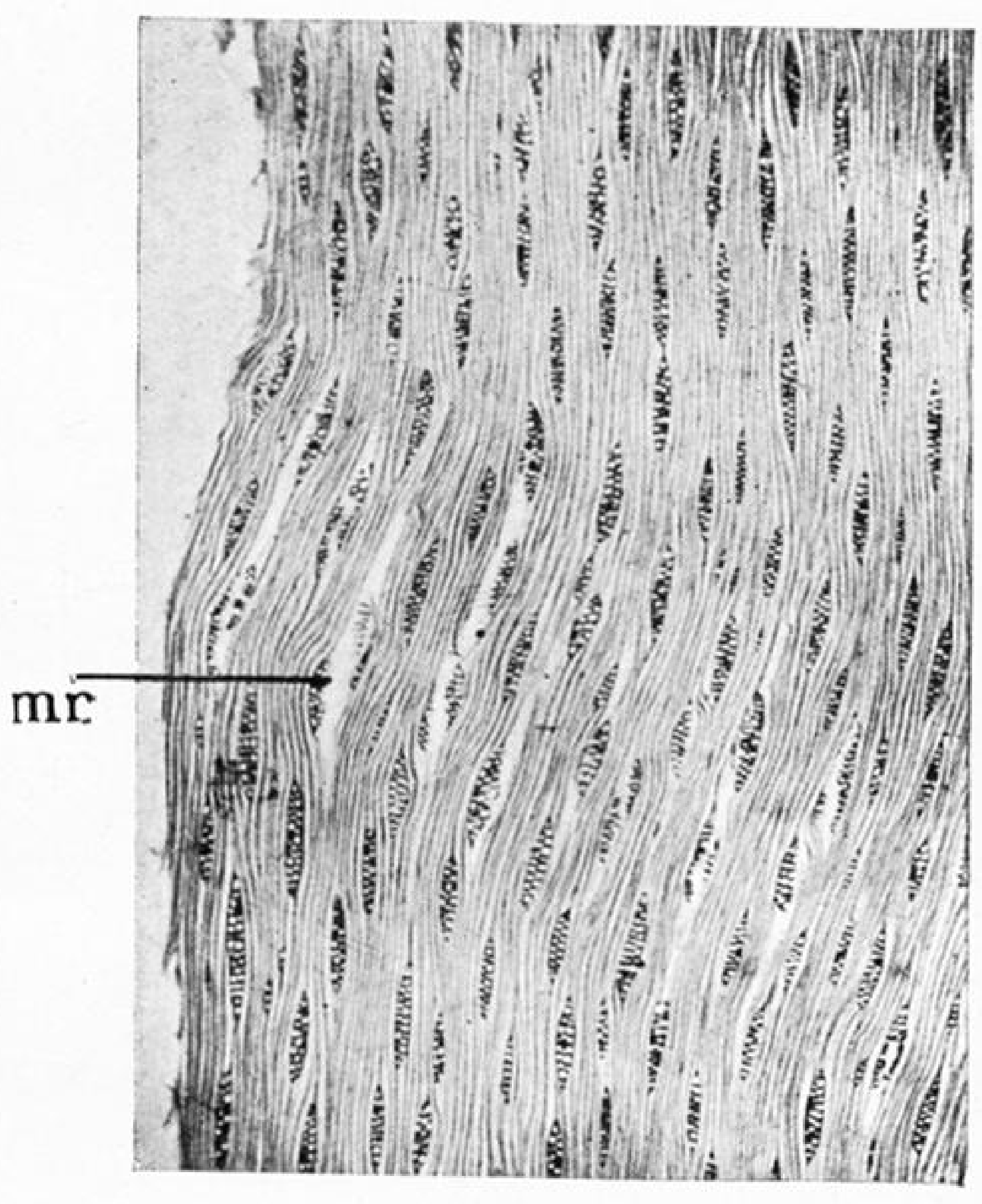

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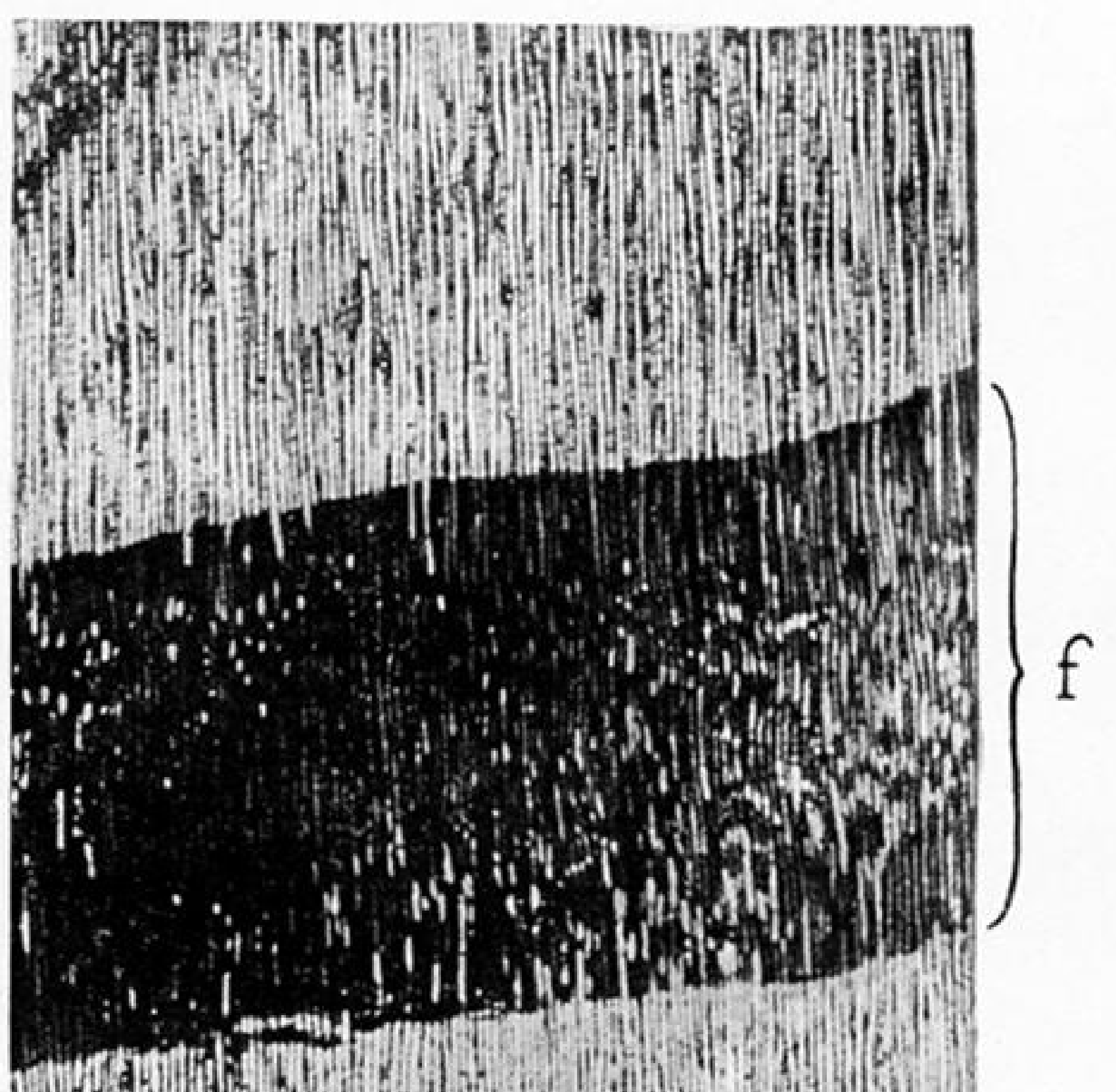

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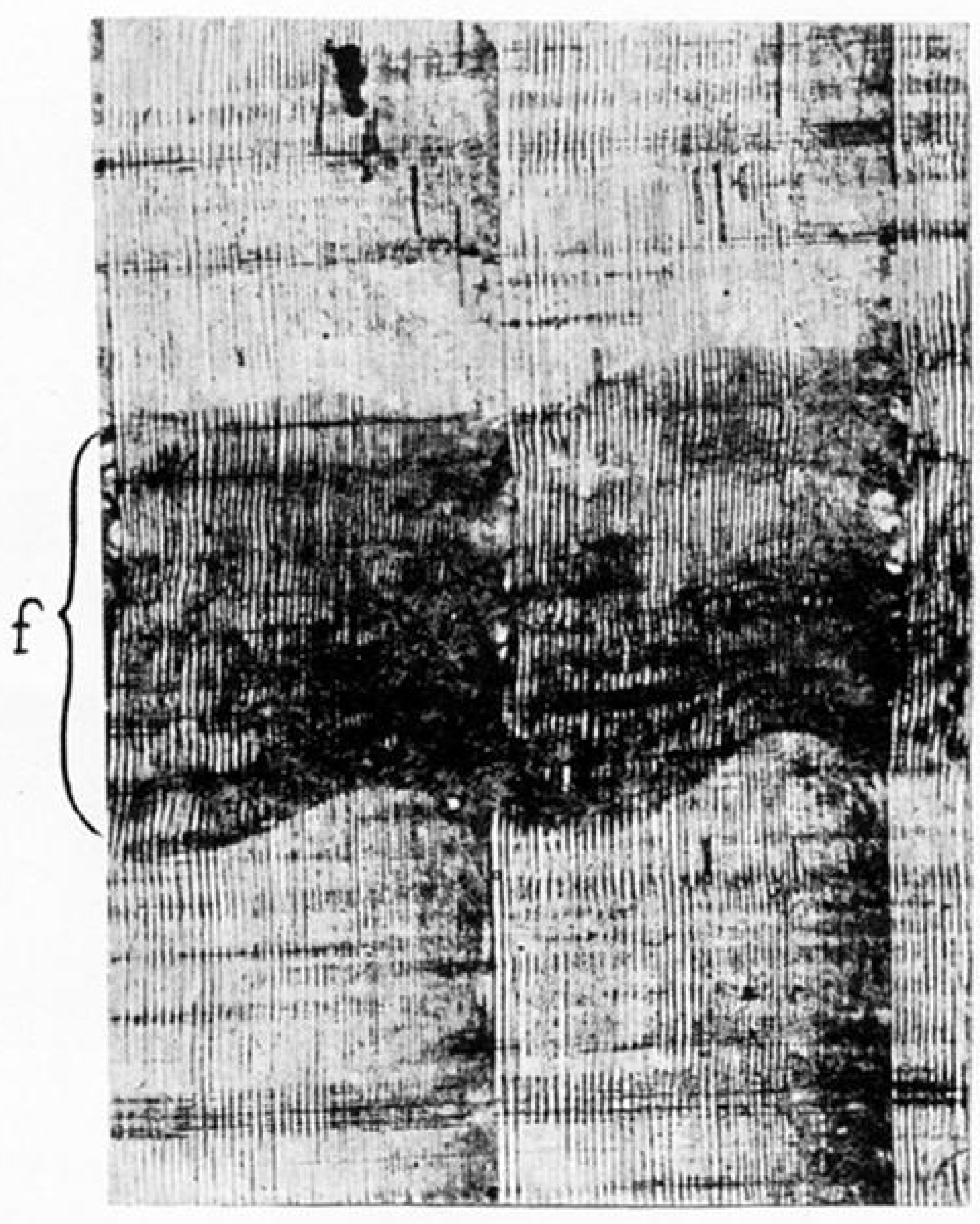

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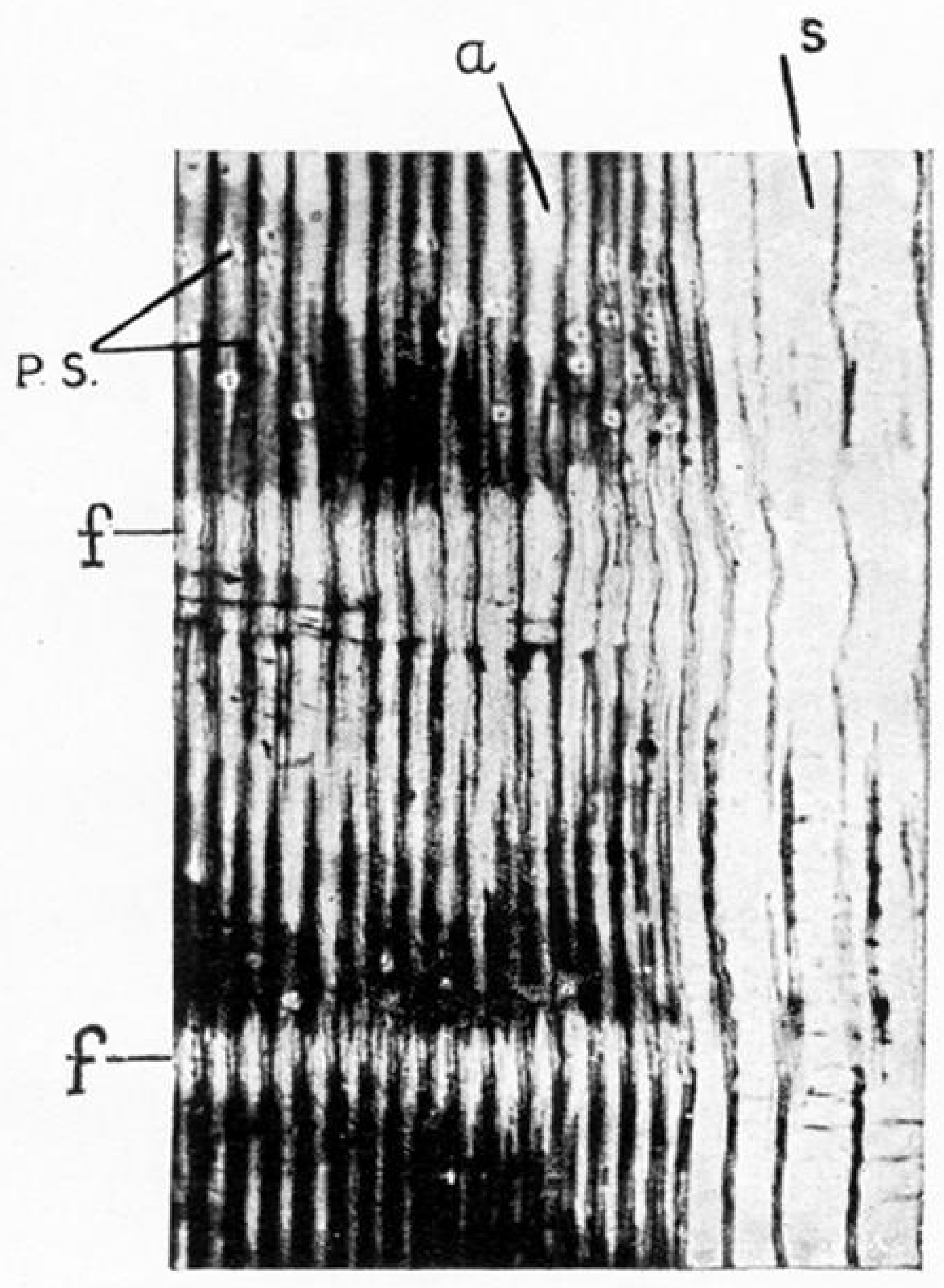


9.

PLATE 1 (Photographs).

s., spring wood; *m.r.*, medullary ray; *r.*, place of rupture; *x.*, slip lines; *a.*, autumn wood; *f.*, zone of failure; *m.l.*, middle lamella; *p.s.*, pit-slits.

Fig. 1.—Compressed piece of Spruce, showing the zone of failure as seen on the tangential face. × $5\frac{1}{4}$.

Fig. 2.—The same piece of Spruce as in fig. 1, showing the zone of failure as seen on the radial face. × $5\frac{1}{4}$.

There is marked displacement in the radial direction; the displacement is most apparent at the limits of the annual rings, *i.e.*, where the autumn wood of one year abuts on the spring wood of the next year. There is no such evident displacement on the tangential face (fig. 1).

Fig. 3.—Tangential longitudinal section of a compressed piece of Pitch pine, showing the steeply inclined zone of failure. The displacement in the tangential direction is very marked, and an incipient zone of failure is seen in addition to the main zone. × 28.

Fig. 4.—Portion of the zone of incipient failure from the same section as fig. 3, showing the separation between the tracheides and the medullary rays. × 67.

Fig. 5.—Radial longitudinal section of compressed Spruce. A portion of a zone of failure is seen, showing the crinkling and buckling of the tracheides of the spring and of the autumn wood respectively. The radial displacement is obvious, and some separation of the elements has taken place at the annual ring. × 67.

Fig. 6.—Tangential longitudinal section of a compressed piece of Ash, showing the inclined zone of failure. The displacement in the tangential direction and the separation between the fibres and the medullary rays are clearly seen. × 28.

Fig. 7.—Tangential longitudinal section passing through the zone of failure in Spruce. × 9.

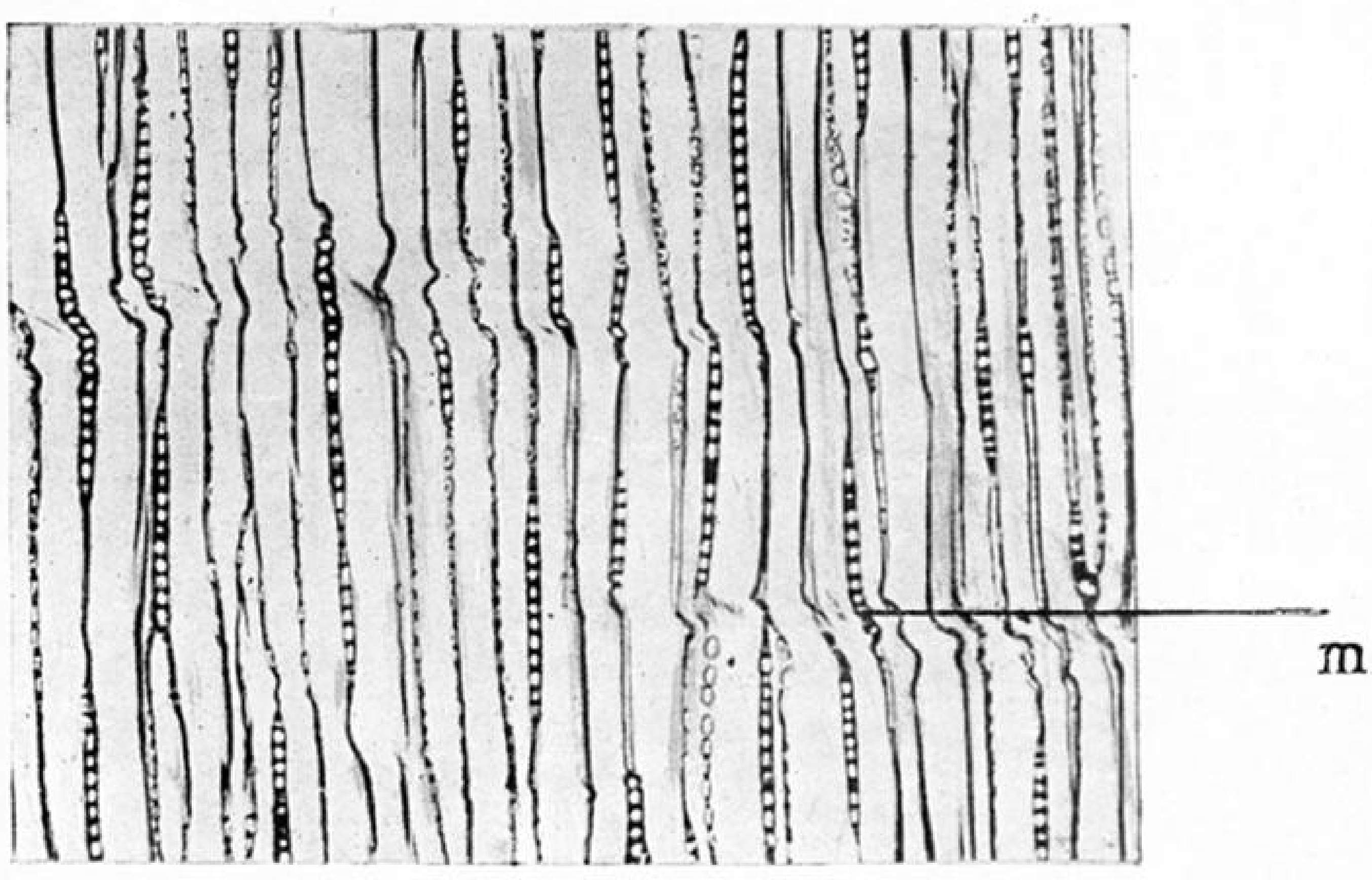
This has been stained by chlor.-zinc-iodide, and the reagent has swollen the zone of failure and straightened the tracheides. It shows the remarkable alteration in the staining properties of the zone of failure.

Fig. 8.—Radial longitudinal section passing through the zone of failure in Spruce. × 9.

This section was similarly treated to that in fig. 7, and shows equally clearly the change in the staining properties of the zone of failure. The reagent has swollen the zone and straightened the tracheides so that the displacement in the radial direction is not obvious, but the staining brings out the peculiar outline of the zone of failure in relation to the annual rings.

Fig. 9.—Portion of radial longitudinal section through compressed Spruce, showing the early stages in the development of the zone of failure. The bands of failure appear light on the darker background.

The crinkling of the spring tracheides is seen and also the early stages which lead to buckling in the thicker-walled autumn wood. The inclined slits of the bordered pits are seen in the photograph. × 67.



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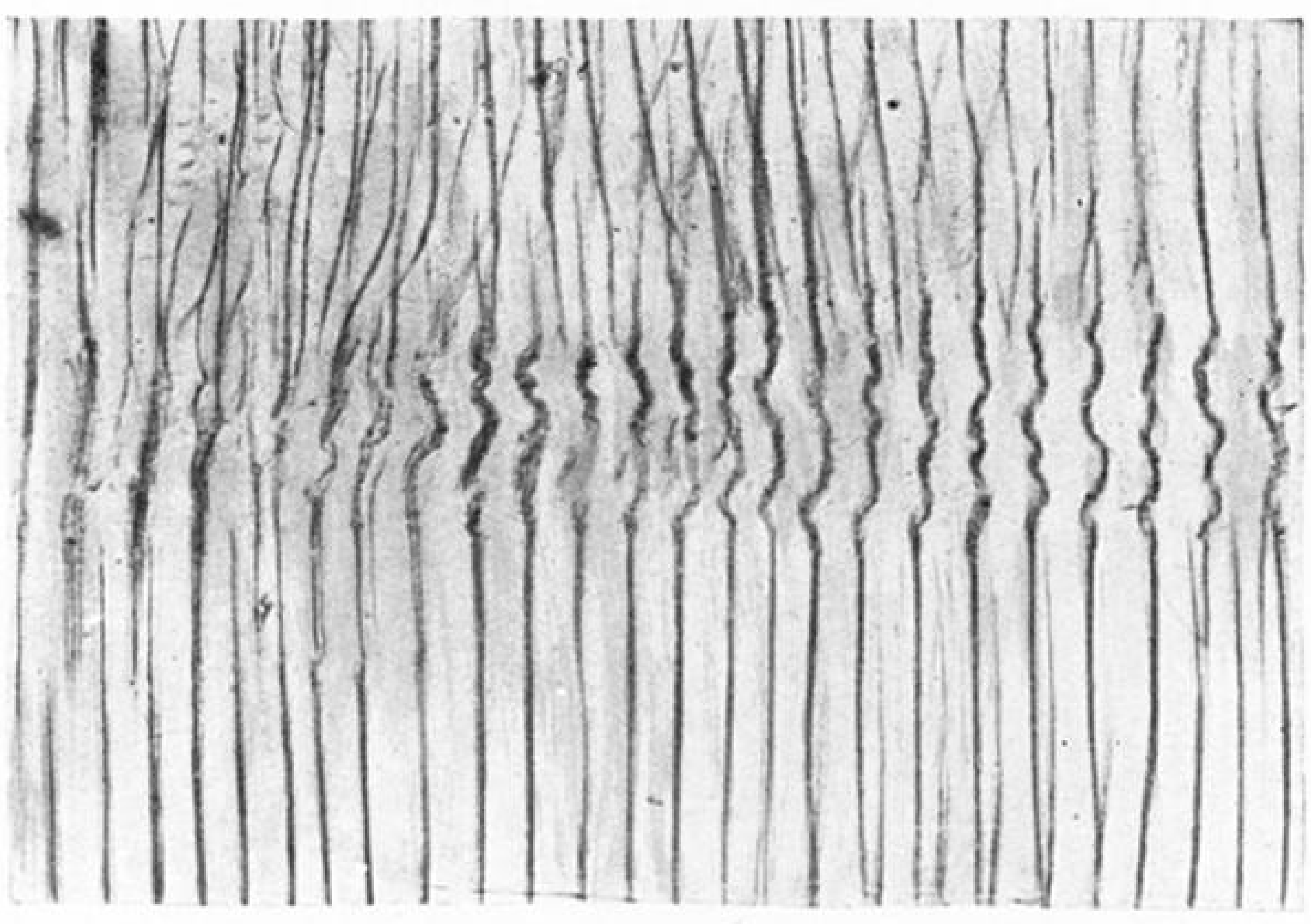

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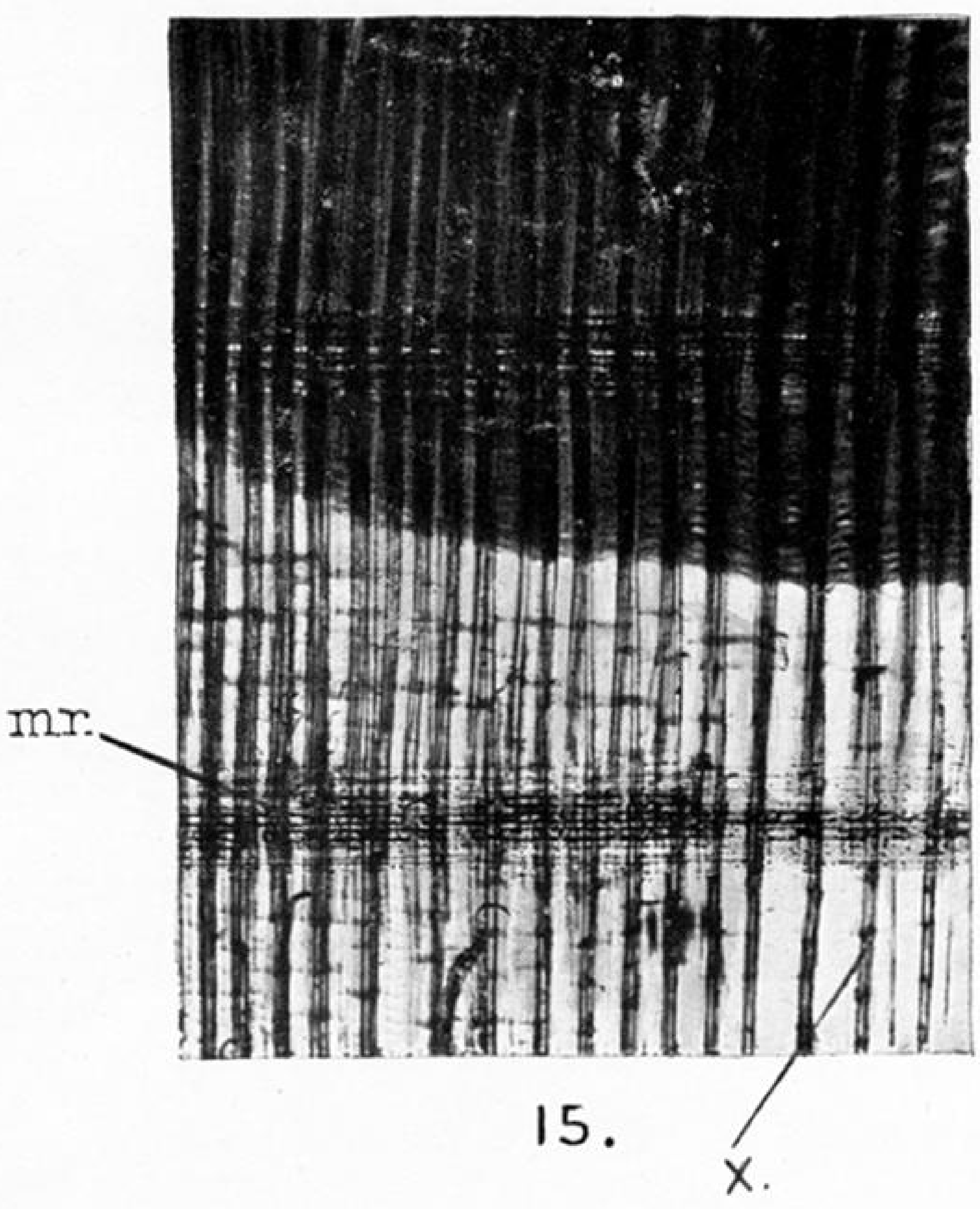

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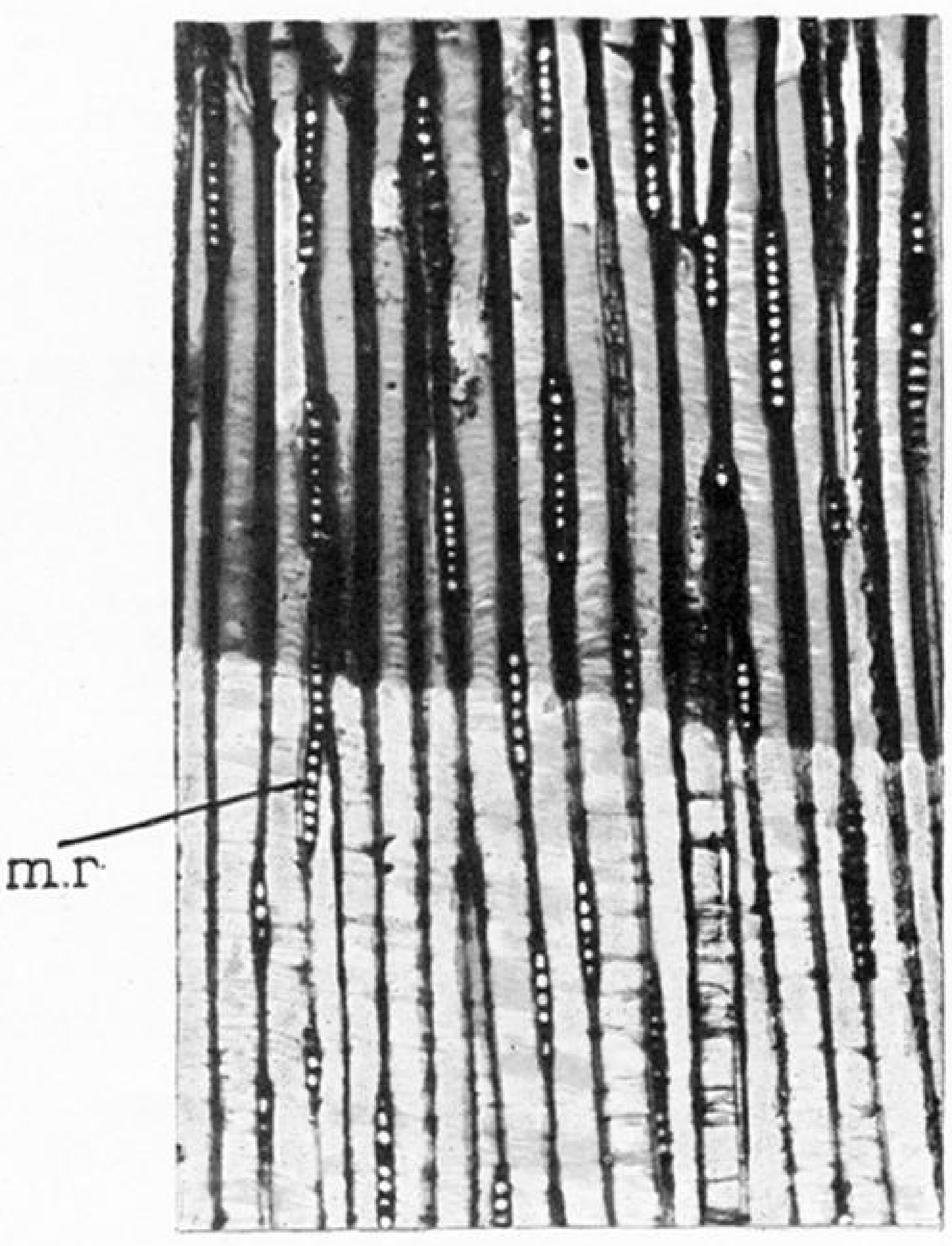

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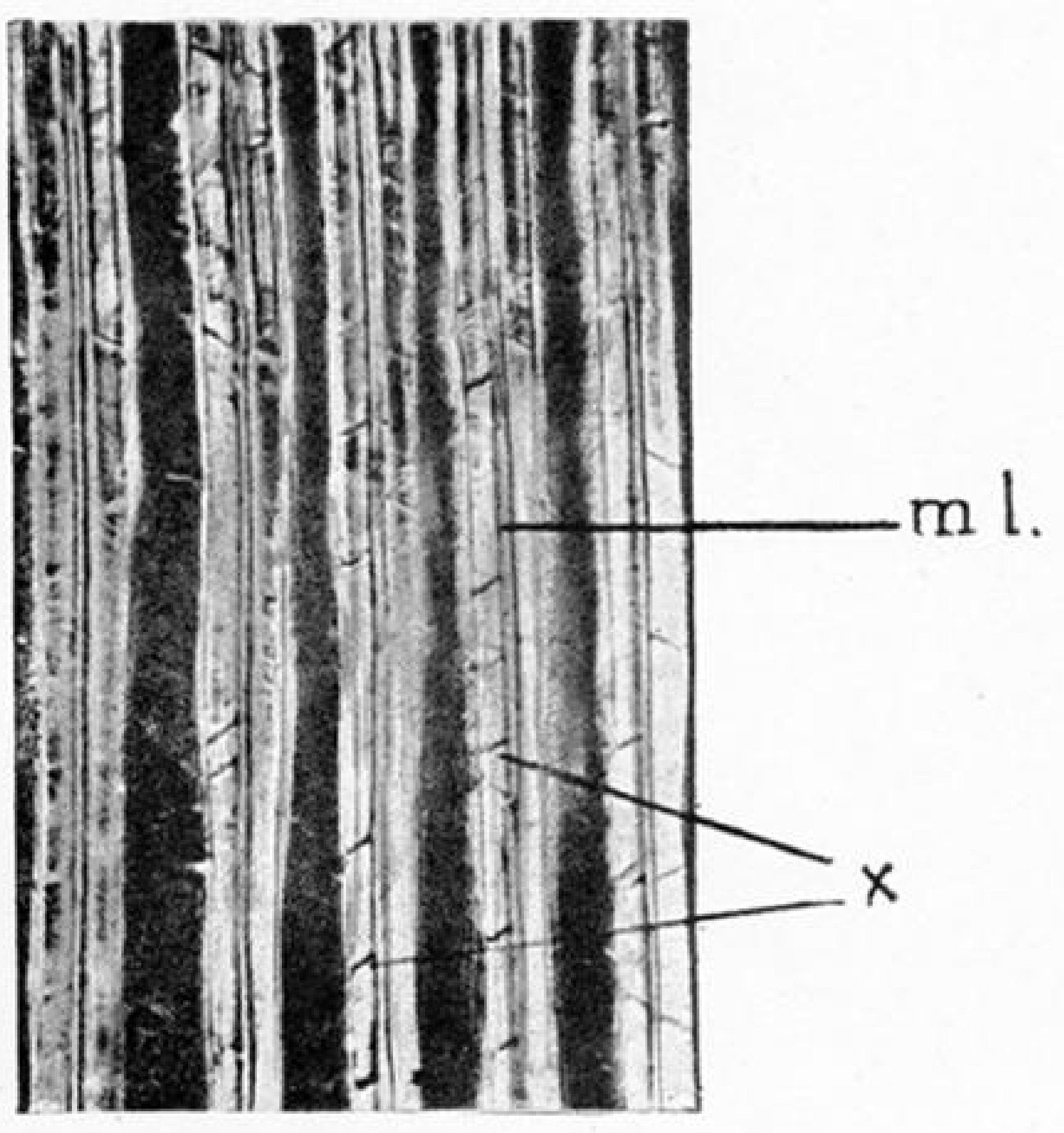

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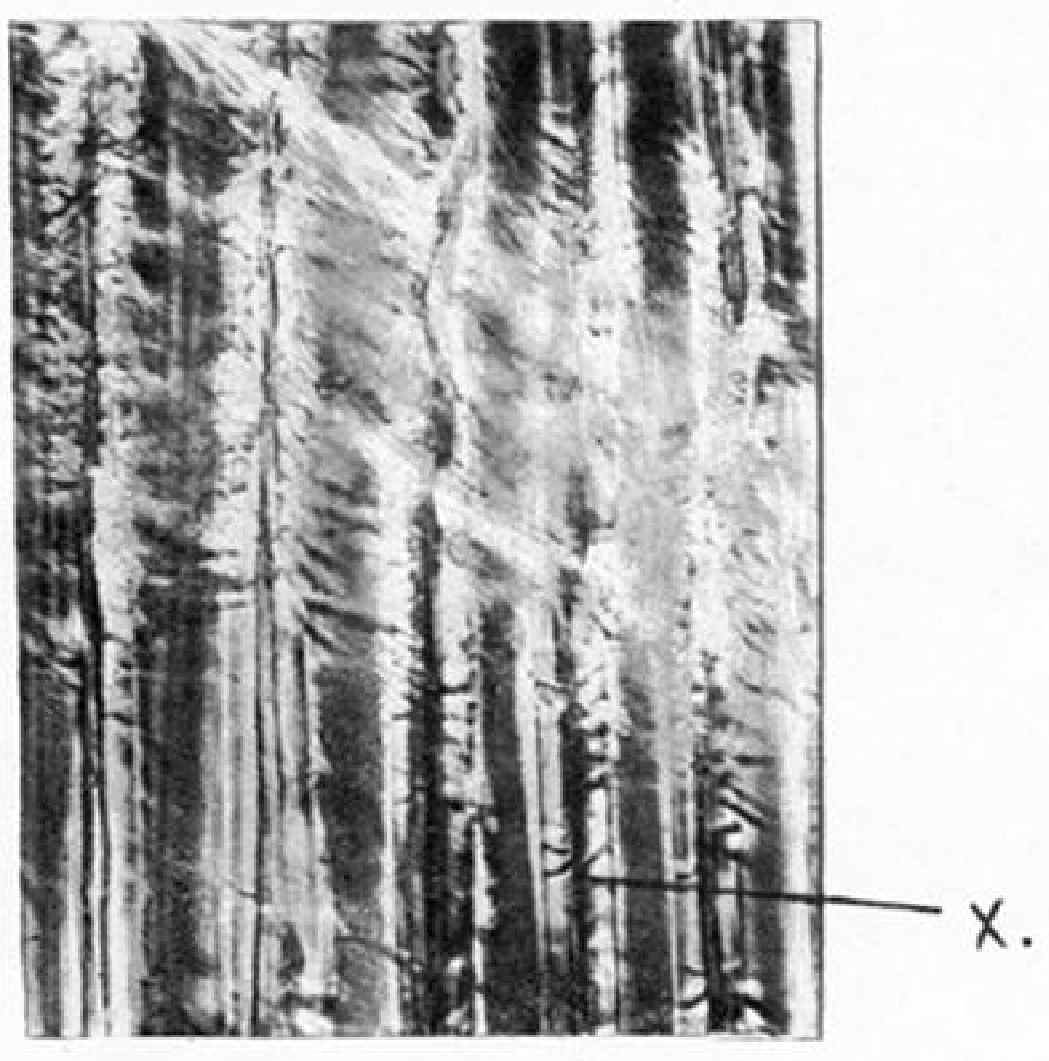

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Plate 2 (Photographs).

Fig. 10.—Tangential longitudinal section of a compressed piece of Spruce, showing early stage in failure by crinkling of the walls of the tracheides. × 67.

Fig. 11.—Radial longitudinal section of a compressed piece of Spruce, showing slightly later stage in failure by crinkling of the walls of the tracheides. × 67.

Fig. 12.—Radial longitudinal section of a specimen of Spruce, fractured by longitudinal shear in a tangential plane. × 67.

The shearing has occurred in the walls of tracheides of the spring wood, and the wall substance has been stretched out into obliquely running shreds. (See also Plate 4, fig. 19.)

Fig. 13.—Tangential longitudinal section of a specimen of Spruce, fractured by longitudinal shear in a radial plane. The shearing has taken place in the walls of the tracheides, and the incipient production of shreds is seen. × 67.

Fig. 14.—Transverse section of similar piece, fractured by longitudinal shear in a tangential plane, to that shown in fig. 12. × 67.

The drawing out into shreds is seen to be confined to the substance of the radial walls of the tracheides.

Fig. 15.—Portion of radial longitudinal section passing through marginal portion of zone of failure in Spruce treated with chlor.-zinc-iodide. × 67.

The deep stain within the zone of failure is seen to be due to the multiplicity of bars of wall-substance which have stained selectively. These bars extend beyond the actual zone of failure, but are much less frequent, being separated by considerable zones of unaltered cell-walls.

Fig. 16.—Portion of tangential longitudinal section similar to the tangential section shown in fig. 15. × 67.

Again the presence of the deeply staining bars is seen, even outside the actual zone of failure.

Fig. 17.—Walls of tracheides of autumn wood of Spruce, in radial longitudinal section, showing commencement of permanent deformation by the development of oblique planes of slipping in the secondary layers of the wall-substance. No slip lines are evident in the middle lamella.

Photographed by polarised light with crossed nicols. × 350.

Fig. 18.—Similar photograph to fig. 17, showing the multiplication of slipping planes leading to crinkling of the cell-walls. × 350.

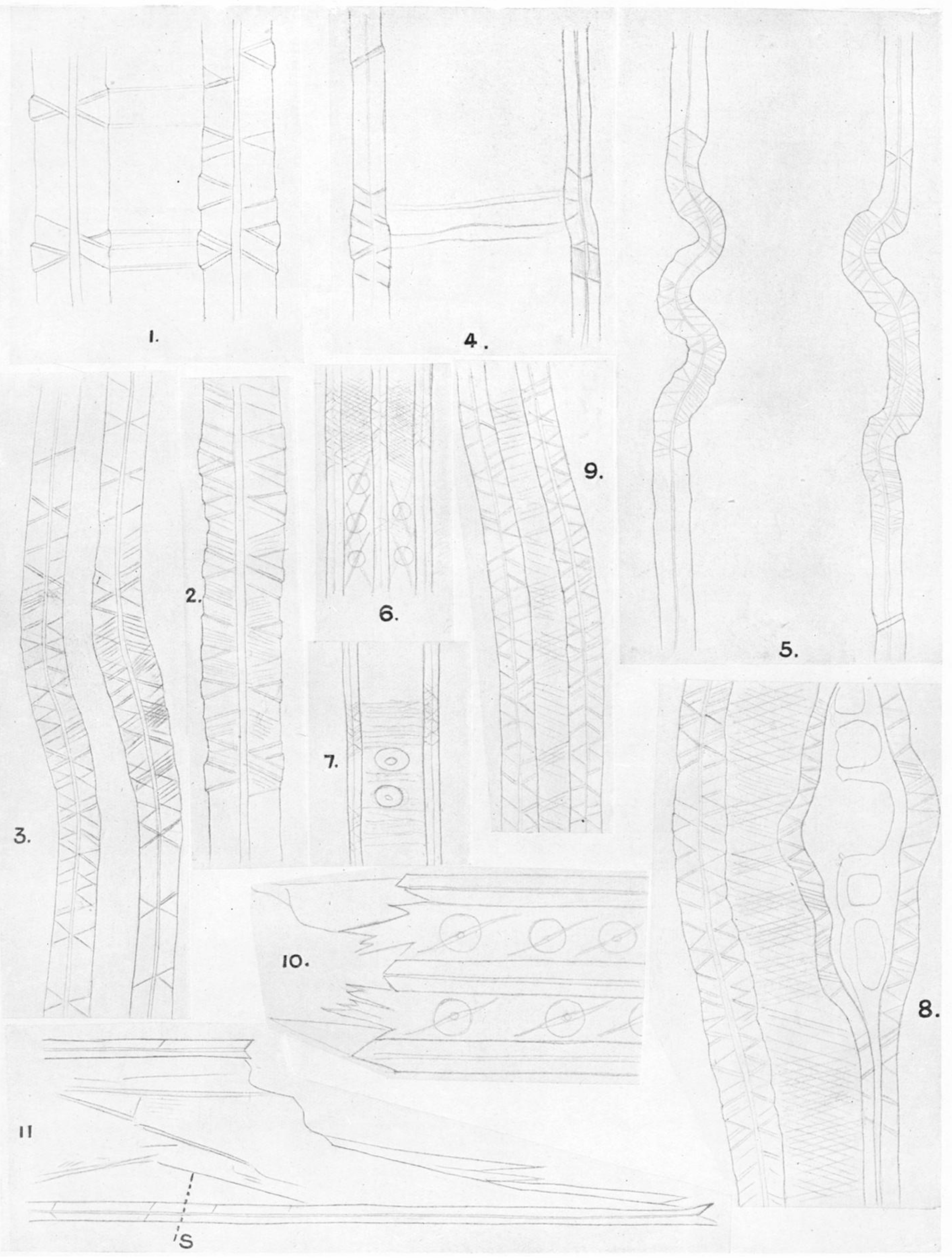

Plate 3 (Drawings).

(Figs. 1 to 7 of Spruce.)

Fig. 1.—The walls of the autumn tracheides of Spruce seen in tangential longitudinal section, showing very early stages in the development of slip planes. No bending has yet occurred. × 900.

Fig. 2.—Walls of two adjoining tracheides of autumn wood similar to those in fig. 1, showing later stages in the slipping. The number of planes of slipping has greatly multiplied, and buckling is about to occur. The step-like projections of the substance of the wall are shown. × 900.

Fig. 3.—Walls of tracheides of autumn wood of Spruce, showing still later stage than in figs. 1 and 2. Buckling has now taken place as a result of the great multiplication of lines of slipping. × 600.

Fig. 4.—Walls of tracheides of spring wood of Spruce in radial section, showing early stage in the development of slip-planes, and in this case rapidly leading to crinkling. × 900.

Fig. 5.—Walls of tracheides of spring wood of Spruce at slightly later stage than in fig. 4, showing crinkling due to the multiplication of slipping planes. × 900. (*Cf.* Plate 2, fig. 11.)

Fig. 6.—Walls of tracheides of Spruce in radial section, showing oblique slipping lines both in the thickness of the tracheides and on the surface of the walls. The lines on the latter are not inclined at the same angle as the slits of the pits. × 275.

Fig. 7.—Walls of tracheides of spring wood of Spruce from same radial section as fig. 6, showing obliquity of slip-planes in the thickness of the walls and the horizontal character on the surface of the walls. × 275.

Fig. 8.—Walls of the tracheides of autumn wood of Pitch Pine in tangential longitudinal section, showing multiplicity of shearing planes leading to buckling. × 600.

Fig. 9.—Walls of fibres of Ash, showing multiplicity of shearing planes leading to buckling. × 900.

Fig. 10.—Walls of autumn tracheides of Spruce, fractured in tension, showing fibrous character of the break owing to shearing having occurred both in the radial and tangential walls. The inclination of the planes of fracture is approximately that of the slits of the pits. × 600.

Fig. 11.—Walls of tracheides of spring wood of Spruce in same specimen as fig. 10, showing similar oblique planes of fracture. An incipient fracture is also seen developing along similarly inclined planes at S. × 600.

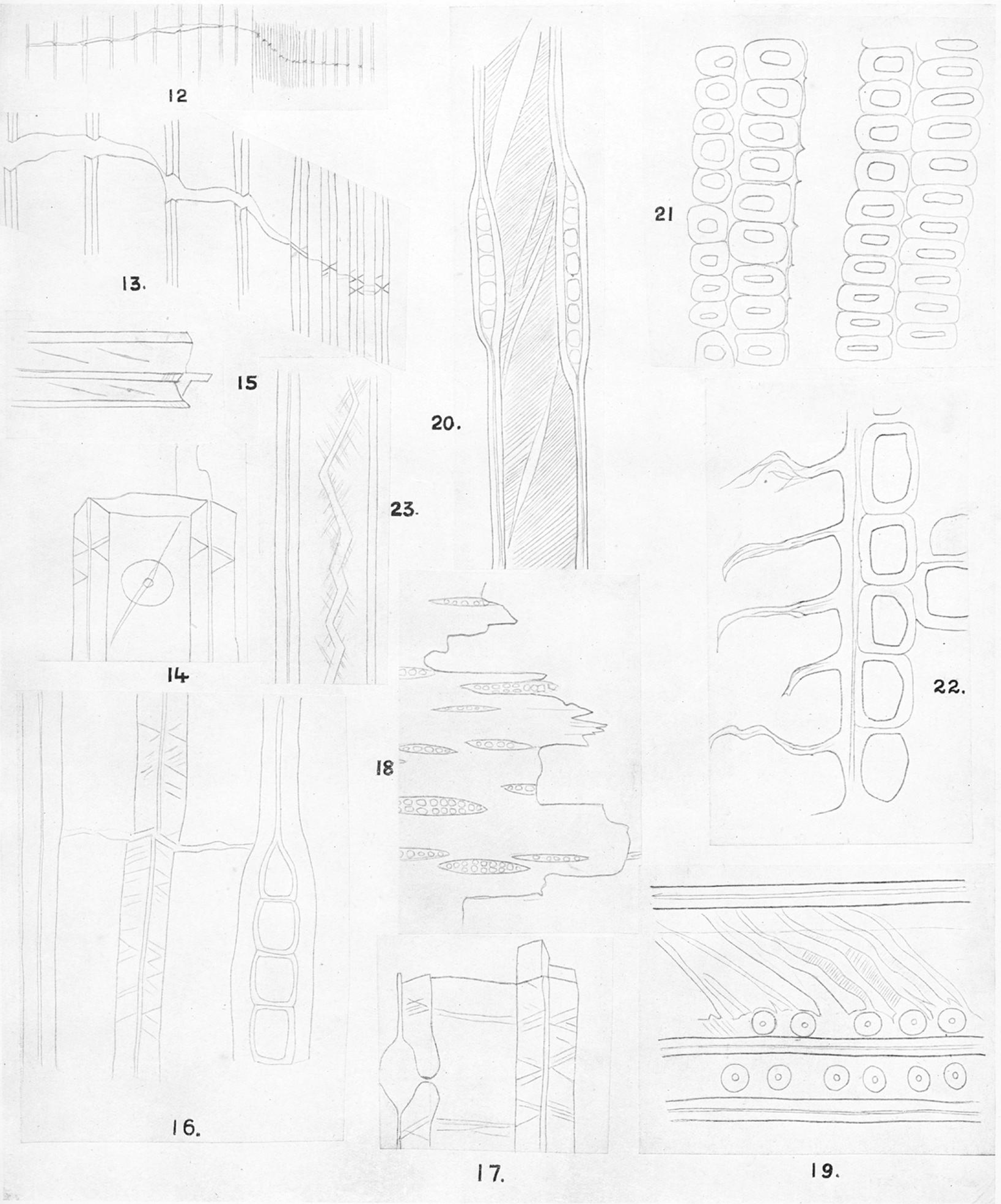

Plate 4 (Drawings).

Fig. 12.—Walls of tracheides of autumn and spring wood of a brittle piece of Spruce, showing tension fracture spreading across them. × 80.

Fig. 13.—A few of the walls shown in fig. 12. Rupture has occurred in the spring tracheides, and the development of a very few slip-lines is seen in the autumn tracheides. × 275.

Fig. 14.—Walls of tracheides of autumn wood of Spruce, showing the horizontal break on surface of wall and oblique break in the thickness of the wall along slip-planes. The inclination of the slits of the pits is indicated. × 600.

Fig. 15.—Fractured ends of fibres of Ash. The break is along the oblique slip-planes, which are not inclined at the same angle as the pits. × 275.

Fig. 16.—Tracheides of Pitch Pine, fractured in tension. The break has occurred along slip-lines which are developed also in the vicinity of the rupture. × 600.

Fig. 17.—Walls of tracheides in fractured tension specimen of Pitch Pine, showing slip-lines. A bordered pit is shown, and this clearly has not proved a source of weakness. × 600.

Fig. 18.—Tension fracture of Ash (somewhat diagrammatic). The break has had no obvious relation to the medullary rays. × 80.

Fig. 19.—Radial longitudinal section of a specimen of Spruce, fractured by shearing along a tangential plane. The shredding of the walls is seen and also the fine slip-lines on some of the shreds. The bordered pits are intact, and only a narrow zone of the wall is stretched out—*cf.* width with that of the adjoining tracheide. × 275. (*Cf.* with Plate 3, fig. 11.)

Fig. 20.—Walls of tracheide from fractured region of a specimen sheared in the radial plane. Stretching of the wall has occurred with incipient shredding and the development of fine lines of slipping. × 275.

Fig. 21.—Transverse section through autumn wood of fractured specimen sheared in radial plane. The separation has occurred at the middle lamella. × 275.

Fig. 22.—Transverse section through the spring wood of the same specimen as in fig. 21, showing the drawing out of the tangential walls into shreds. × 275.

Fig. 23.—Walls of tracheide from fractured region of specimen sheared in the tangential plane. Separation is taking place along two series of obliquely inclined planes. × 275.