REPORT

of

Committee on Thesis

The undersigned, acting as a Committee of the Graduate School, have read the accompanying thesis submitted by Walter B. Lang for the degree of Master of Science. They approve it as a thesis meeting the requirements of the Graduate School of the University of Minnesota, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science.

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DEFORMATION BY FRACTURE.

A thesis submitted to the
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by

Walter Barnes Lang

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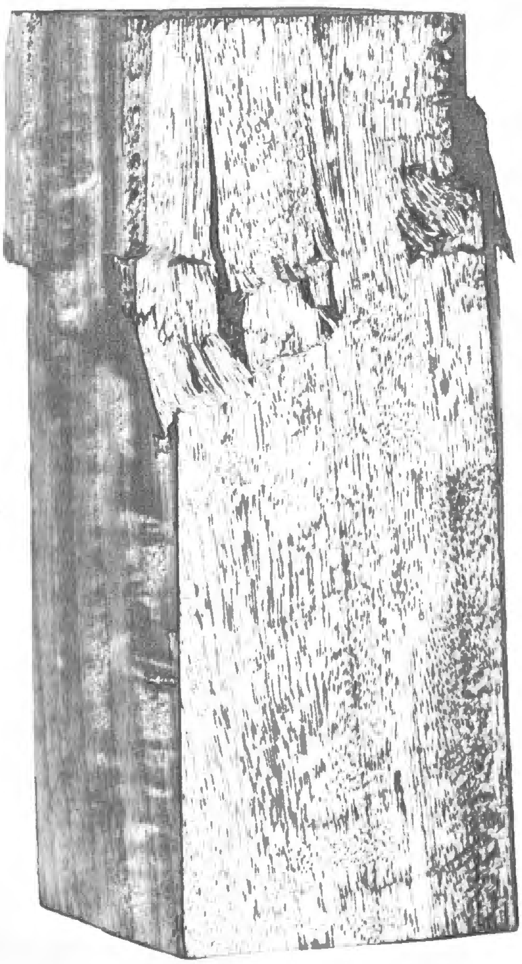

Fig, 1. Satin-wood block deformed under a pressure of 40,000 lbs. Note the brecciated zone of shearing. Scale full size.

DEFORMATION BY FRACTURE.

In attempting to produce fractures intended to illustrate those present in the earth, Daubrée in his now historic experiments employed a modeling wax (cire à mouler) which proved very satisfactory in producing rectangular systems of fractures when under compressive stresses from two directions. It was decided to continue these experiments along the same lines in an attempt to determine whether or not structures could be obtained by artificial means duplicating in one way or another some of the more complex fracture systems that have been observed in certain mining regions. Following Daubree[1], Willis[2], and others[3] waxes were first employed. Several

[1] Daubrée, A. Etudes Synthétiques de Géologie Expérimentale pp. 516-520.
[2] Willis, Bailey. "Mechanics of Appalachian Structure". 13 An. Rept. of U.S.G.S. pt 2, 1893. pp 241-253.
[3] Adams, F.D. An experimental investigation into the action of differential pressure on certain minerals and rocks, employing the process suggested by Prof. Kick. Journal of Geology Vol. 18, No. 6, 1910 pp. 489-512.
Kick, Freidrich. Die Prinzipien der mechanischen Technologie und die Festigkeitslehre: Zeit. de Ver. Deut. Ingen. Vol. 36, 1892, p. 919.

varieties of waxes were tested but in nearly all cases proved deficient in one way or another. Preserving wax, a low grade material similar to sealing wax was found too brittle and shattered when subjected to pressure. Such varieties as Japan and carnuba wax would not cast properly, the coefficient of expansion being so high that on solidification the mold was only partially filled, giving a cellular or imperfect block unsuitable for testing. The continued addition of a fresh supply to the setting mold was insufficient to over come the final contraction on solidifying at the center. Although paraffin shrinks on solidifying it was found possible to obtain a solid cast by adding a sufficient amount while cooling to overflow the mold and later after setting the extraneous material was removed with a sharp spatula. Good results were obtained by this method.

Compression of the blocks was accomplished with an oil hydraulic press. A series of tests were

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

made with varying results depending upon the rate of application of pressure. With a gradual addition of load the paraffin deformed by flowage bulging out on the four free sides. Up to a certain point increase in the rate of application of load produced no varying results, but on further increase shearing accompanied flowage. With pressure applied rapidly compression was relieved almost solely by shearing and always in the direction of the shortest axis. The paraffin blocks measured 1 1/4 x 2 1/8 x 1 1/10 inches and the pressure was applied parallel to the longest axis, leaving any lateral movement to take place in the direction of either of the shorter axes. In this position as stated above displacement was in the direction of the shortest axis, it being incidentally the shortest axis of the block. It is the shortest axis normal to the direction of pressure in which displacement takes place. In practically all cases the angle measured 45°, variations diverging less than two degrees either way. The results then are in accord with those of Daubree[1], the shearing

[1] Op.cit. pp. 516-520

angle being 45° to the direction of pressure. No systems of conjugate fracturing were evident, release of pressure by shearing centralized entirely in a single fracture.

Attention was next directed to other materials and plaster of Paris sawed into approximately 2" cubes were tested. These failed without systematic fracturing, no definite direction being recognizable with the exception of a tendency toward lateral relief and expressed by irregular vertical fractures.

Wooden blocks subsequently tested showed a considerable variety of fracture systems. The woods employed were oak, India mahogany, mahogany, maple, popular, fir and satin-wood in varying lengths and cross-sections. The tests were accomplished by the use of a 100,000 lb. Tinius Olsen Testing Machine affording ample means of obtaining any degree of pressure required.

As few persons except engineers are familiar with the mode of action of the machine employed a

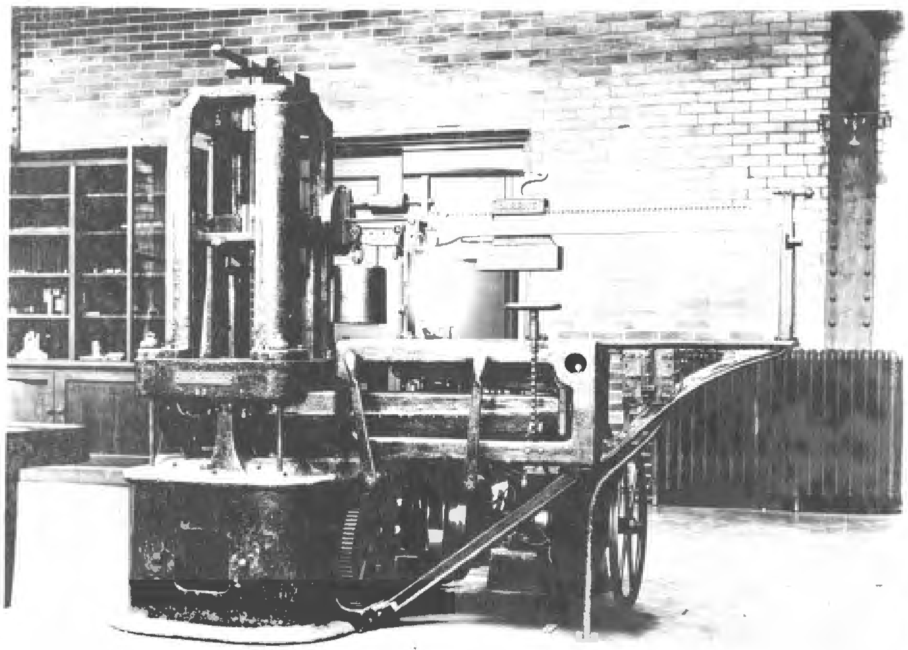

Fig. 6. Tinius Olsen Testing Machine, 100,000 lbs. capacity. Experimental Engineering Department, University of Minnesota.

few words of description and principle of operation will facilitate the discussion of the results. With reference to the illustration (fig.6) it will be noticed that the machine bears a likeness to a weighing scales, the underlying principle being identical in both. The bed plate, balanced upon steel knife edges supported by the base or foundation is interconnected by a series of lever arms, also supported on knife edges to the scale beam. This beam bears upon its face a scale calibrated in pounds pressure. Riding within a groove upon the top of the beam is a square-thread worm screw revolved by a hand-wheel, belt connected at the fulcrum of the lever. Manipulation of the hand wheel actuates the worm screw which in turn controls the scale weight either propelling it outward along the beam or returning it to zero position depending upon the direction of rotation of the hand wheel. A release lever on top of the balance weight affords a means of quick resetting. A movable head supported and actuated by four heavy steel worm screws is caused to move upward and downward at different speeds by a one half horse power electric motor interconnected by a speed changing transmission and brake. The pressure head suspended from the four worm screws by a loosely fitting ball and socket joint permitted a limited lateral movement of the materials under test.

The general procedure for running a test is as follows:- The material to be tested is placed upon a polished steel plate of sufficient size, capped by a similar one and centered upon the bed-plate. Riding weight is reset to zero and beam tested for balance. When this adjustment is accomplished the motor is started and the pressure head is brought down on high speed gear until within a half inch of the top plate when shift is made to slow speed and contact with block accomplished. After inspection for alignment and centering the test is commenced on what is called "brake" speed, a gradual though positive application of pressure. As the head descends it compresses the material under test upon the bed plate which in turn communicates this pressure through the lever arms to the weightbeam which rises. The riding weight is then run out upon the beam by means of the handwheel until the beam "floats" and such a condition is maintained until the material under test fails and the beam falls. The reading given by the weight on the scale at the moment it ceased to float is the pressure required to produce failure of the material.

Blocks of short column were first tested and consisted of best quality, seasoned, oak, mahogany and poplar and measuring 1 1/2" x 1 1/2" x 3". Oak proved to be an excellent medium for the production of fractures, exhibiting not only strong major failures but also good systems of incepient fractures. Illustrations of these are shown in figures 7,8,9,10,11. Figure 7 depicts clearly the two systems of failure lines, both as to direction and magnitude. Oak proved extremely resistant to loads and deformed only under high pressure.

Fig. 7. An oak block showing a well developed system of coördinate fractures. An overturn fold and thrust fault may be seen on the right side of block. Photographs are full sized illustrations in all cases except where otherwise stated.

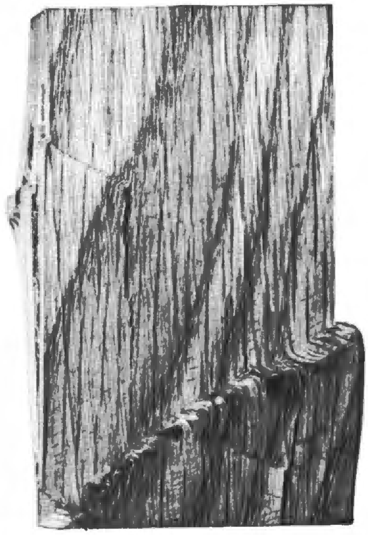

Fig. 8. Photograph of the opposite side of block shown in figure 7.

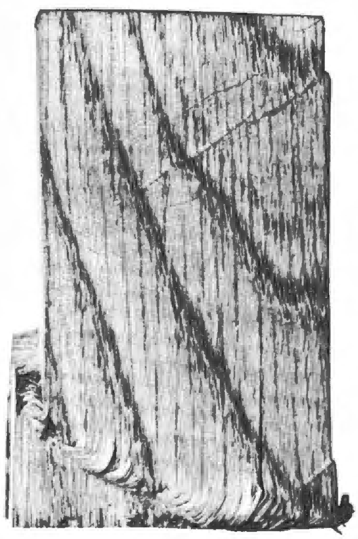

Fig. 9. Particular attention is called to the behavior of the fibres of the main shear in the lower left hand corner. Upper segment has shifted to the right and toward the reader causing the upper segment to over hang the lower. As a result the upper boundary of shear zone is not well defined.

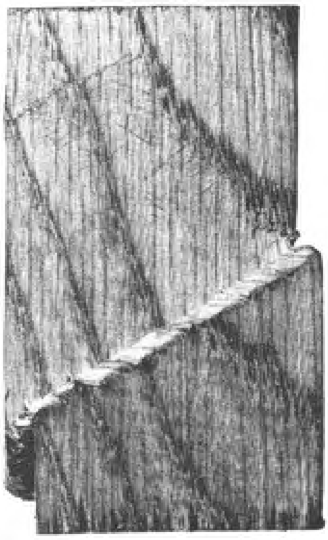

Fig. 10. Oak block showing a well developed major shear and a conjugate fractured zone.

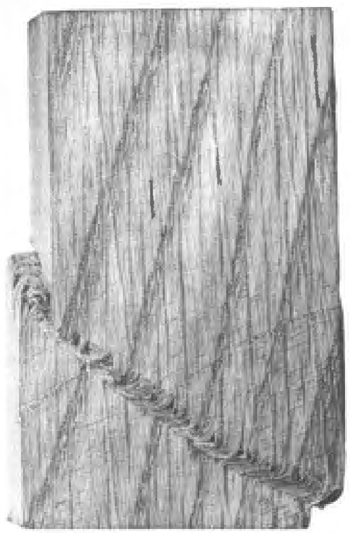

Fig. 11. Opposite view of figure 10.

When the pressure was applied no evidence of failure was visible until initial failure appeared in the form of a shear which is generally located near one end of the column. A continued application of pressure further accentuated the already developed plane of weakness and later produced new ones of less intensity than the first and as a general rule in the opposite direction. Difficulty was encountered in determining at exactly what period the incipient fractures appeared but it is believed that they developed contemporaneously with or just subsequent to the occurrence of the major shear, many of them later with continued subjection to pressure becoming the seat of location of minor shears.

It is interesting to note that these shears in many instances are not symmetrical, one of the sides having a particularly well defined edge and from which the fibres depart at a sharp angle; while the opposite boundary is ill defined, the fibres having been flexed to conform to a smooth curve. This difference is due to a variation in the degree of freedom offered to movement. The reason for this difference in freedom will be evident after a study of the blocks illustrated in figures 12 to 19 which disclose this point clearly. If the reader will refer back to figure 9, he will observe that the major shear in the lower position of the block is fairly wide and may be bounded by two parallel lines. No difficulty will be encountered in locating the lower boundary but a course for a straight line marking the upper boundary is difficult to trace out as there is no sharp division between the flexed fibres of the shear and the surrounding material. Following the fibre of the wood downward it will be noticed that they enter the shear by an easy curve ahd depart at the lower boundary at a sharp and well defined angle. When shearing occurred movement of the portion above the shear was to the right and toward the reader. As the upper portion moved outward and away from the small triangular section compression of the fibres attached directly to the upper section was changed to a

Fig. 12. Oak cylinder showing a double fail-
ing. Small cross lines in center of bottom
segment are fractures.

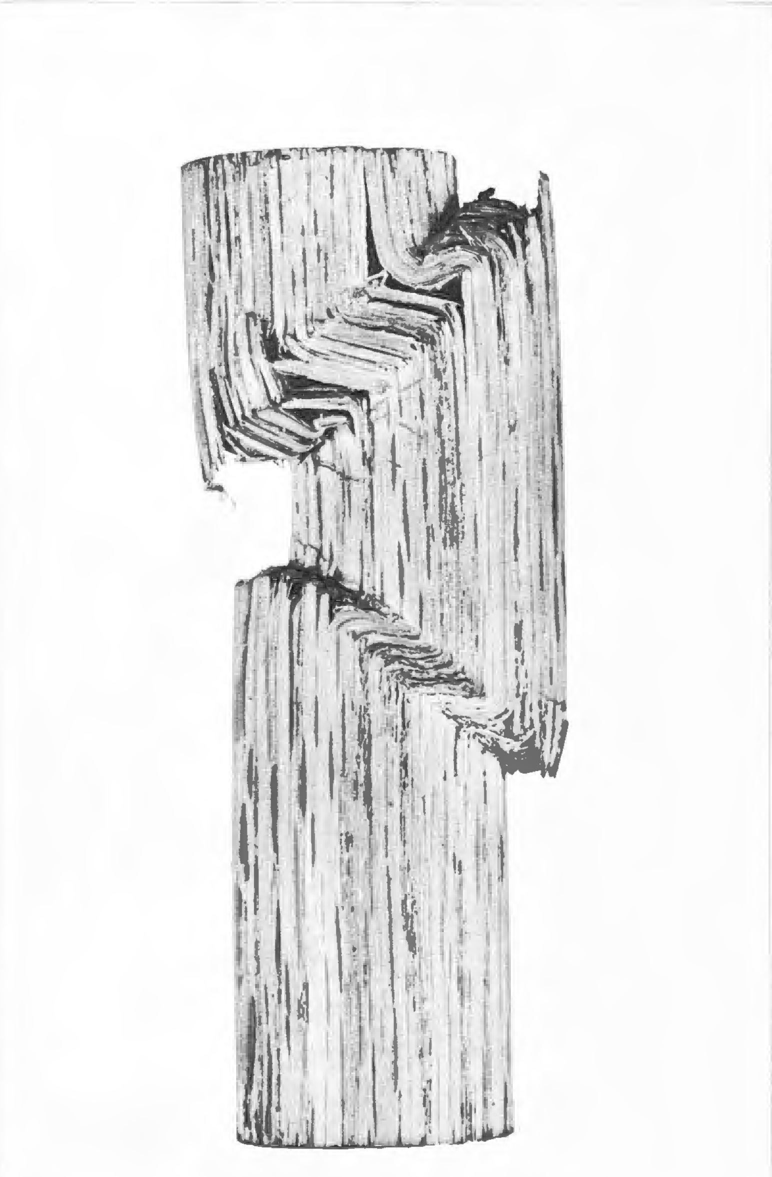

Fig. 13. Opposite side of cylinder shown in figure 12. Note the brecciated appearance of upper shear.

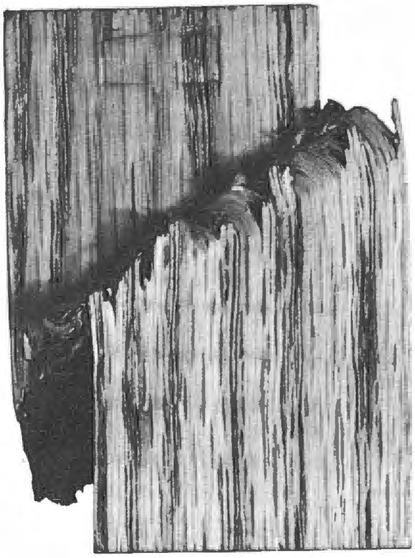

Fig. 14. Oak block bearing a strong shear; the deforming pressure was continued for a considerable period after failure.

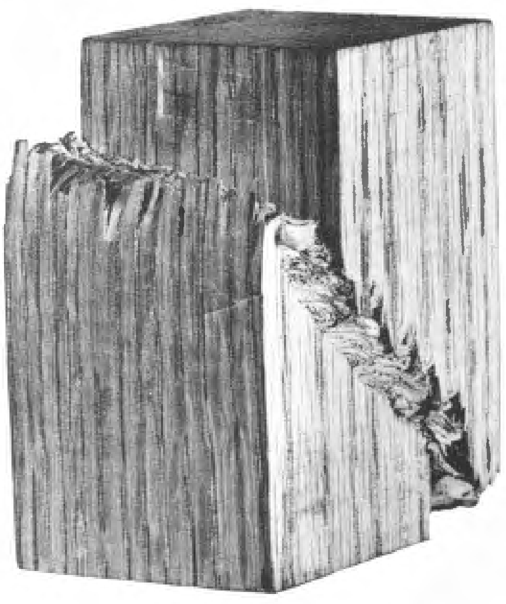

Fig. 15 Same block as shown in figure 14. Right-hand face is the opposite of that shown in figure 14.

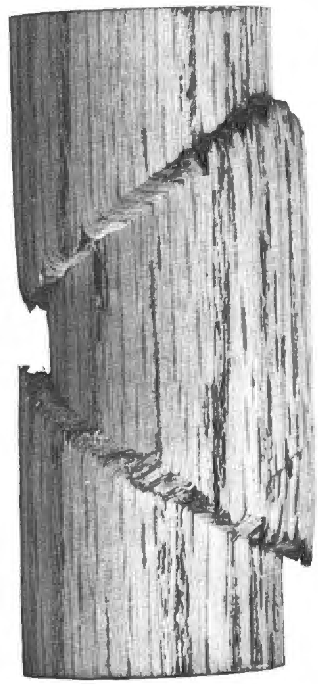

Fig. 16. Oak cylinder showing a double failure, both shears being of equal magnitude.

Fig. 17. Oak cylinder.

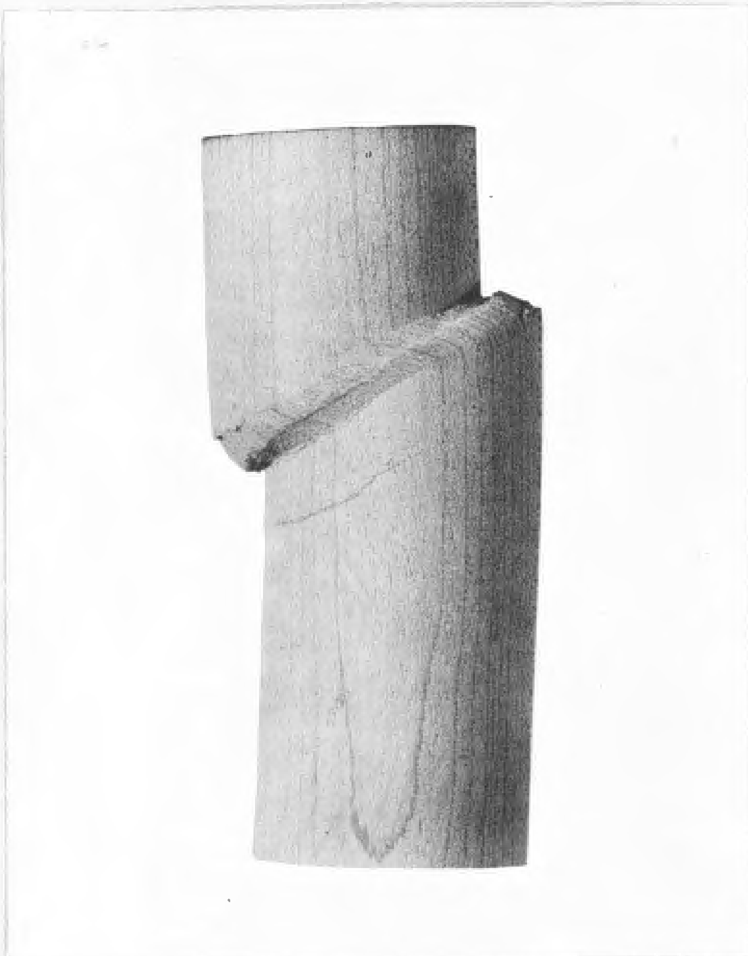

Fig. 18. Maple cylinder.

tensional force and produced the easy flexures. On the other hand, the fibres where they were directly connected to the lower section were under full compressional load and as a result sharply bent. With these facts in mind, let us return to figures 12 and 13 which are those of an oak cylinder deformed by a double failure, a segment having moved out of position on application of excess pressure. In the central portion of the lower shear of figure 12, it will be observed that the boundaries are well defined straight lines. Following the upper boundary to the left or the lower one to the right, sharpness gradually alters to an easy flexure and the active force from compression to tension. In figure 14-15 it is plainly evident that the type of fracture is not a function of the direction of application of load. These views are both of the same object but of opposite faces. Pressure was applied from above and lateral release resulted when the limit of resistance was reached. In one face (figure 15) the line of sharp division is on the under side while the reverse is true in the opposite face (figure 14). Wherever movement along a shear has been such that one side glides free of the other and a tensional stress is the prevailing force acting upon the fibres, that side which is free bears the uneven or smooth curved flexures, the opposite margin being sharply defined.

In order to observe the structure of a shear within a block one of the columns was split and a half section is shown in figure 19. Within the block the structure on both sides is of the straight line type and only assumes a rounded form where the release of pressure on the over hanging side has permitted its formation. This specimen shows also two secondary shears at the base. These shearing planes outline a segment of wood and converging inward at angles of 54 and 62 degrees intersect within the interior. Although the movement has been only about .5 mm, we have here a typical example of a horst fault which may be best viewed by turning the block upon its side. In the corner diagonally opposite a

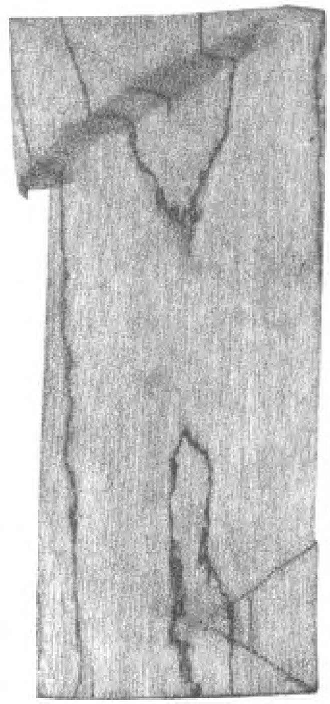

Fig. 19. Photograph of a split maple cylinder. Particular attention is called to the horst fault developed in the lower right hand corner.

second horst fault may be seen in the process of efformation, the major shear acting as one of the thrust faults, the other not having become sufficiently developed to be plainly visible. When this column was placed under compression and failed, relief came by lateral shearing along the major fracture plane. In so doing it shifted the lower portion out of center and concentrated a greater portion of the load upon what appears in the split section as one of the corners. This resulted in an increasing pressure per unit area from the center to the corner and brought about the squeezing out of a segment as the accumulation of pressure exceeded the resistance of the wood fibre. It is therefore evident that the pressure which was active in producing the horst fault was greater at the surface than at the apex and if a comparison is to be made to geological conditions it implies that the surface or crustal portion of a horst-faulted area is under greater lateral pressure than the material of greater depth. Whether this analogy is possible or not is a question and it is for the field geologist, who has the examples of nature to draw upon to credit or discredit this hypothesis.

One of the short column oak blocks developed a number of interesting features as shown in figures 7 and 8, which are photographs of opposite sides of the same block. The first thing to be noticed is the well defined system of coördinate fractures present upon the face of the block, practically parallel to the major shears and inclined to the direction of pressure at angles varying from 48 to 63 degrees, the average being approximately 56 degrees. It is the prevailing conception that materials shearing under pressure, do so at an angle of 45 degrees to the direction of force applied. Wherein the material acted upon is of a homogenious nature, that is, offers equal resistance to deformation in all directions, this rule appears to be adhered to with remarkable exactness as exemplified in the paraffin blocks where a variance from the angle is less than two degrees. When pressure is applied to a heterogeneous medium such as wood and especially in the direction parallel to the grain, in which position the greatest resistance to pressure is offered without previous adjustment, the angle of fracture is in practically all cases greater by from 6 to 15 degrees, the general average for all blocks being 54 degrees. With especially brittle and resistant woods such as India mahogany, the angle may run as high as 80 degrees. Angles below 45 degrees were rare and with the exception of those cubic block tests made normal to the grain, none were registered whose value was less than 40 degrees.

Figures 9,10,11 are those of two similar oak blocks, illustrations 10 and 11 being opposite views of the same block and depicts clearly the well defined major shears, secondary shears and coördinate systems of fractures. The marked similarity of the three oak blocks with respect to agreement of angle of major shearing and coördinate fracture pattern becomes very evident on comparison of the prints. The major shears lie within a range of 5 degrees from 60 to 65 degrees to the direction of pressure and shows that for a given material of uniform quality there is a definite angle at which shearing will take place and may be depended upon to occur within a limited variation of this angle once it is known. As a general rule, the fracture systems are not to be found close to the main shear but in a plane of secondary weakness nearly always located at the other extremity and approximately at an angle of 60 degrees to the direction of pressure and the predominant shear. The pattern produced by the fractures is diamond shaped and very similar to the clevage of hornblende cut normal to the vertical axis. These fractures are not merely a surface phenomenon but extend through the block at angles of approximately 60 degrees to the surface and in many instances it is possible to trace prominent fractures and their counterparts entirely about the block. It is these small fractures, which are the forerunners of all well developed secondary shears and it only requires a continuance of stress to transform them into the large and more conspicuous deformational breaks.

In the study of figure 19 it was observed that the horst faulting was a consequence of variation in the application of pressure at the ends of the column. A similar occurance of conditions appears to have been the cause for the deformation shown in figure 7. Failure commenced along one edge of the block and extended upward and across the face at an angle of 65 degrees to the direction of pressure. As the edge of the lower end of the shear rested squarely upon the base block any further addition of pressure became more or less centered upon this limited area as the remaining portion had within it a well defined weakened plane wherein adjustment could be more readily accomplished. As the test was continued after failure began a bulging of the block was observed at the middle portion and subsequently, arching, vertical spliting, over-

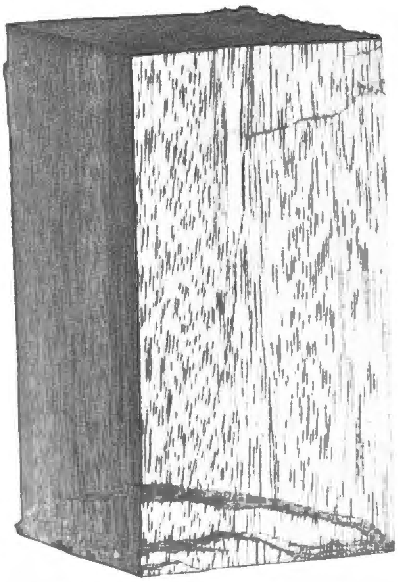

Fig. 20. A mahogany block illustrating the manner in which this wood fails. Splitting along the grain is a common occurance.

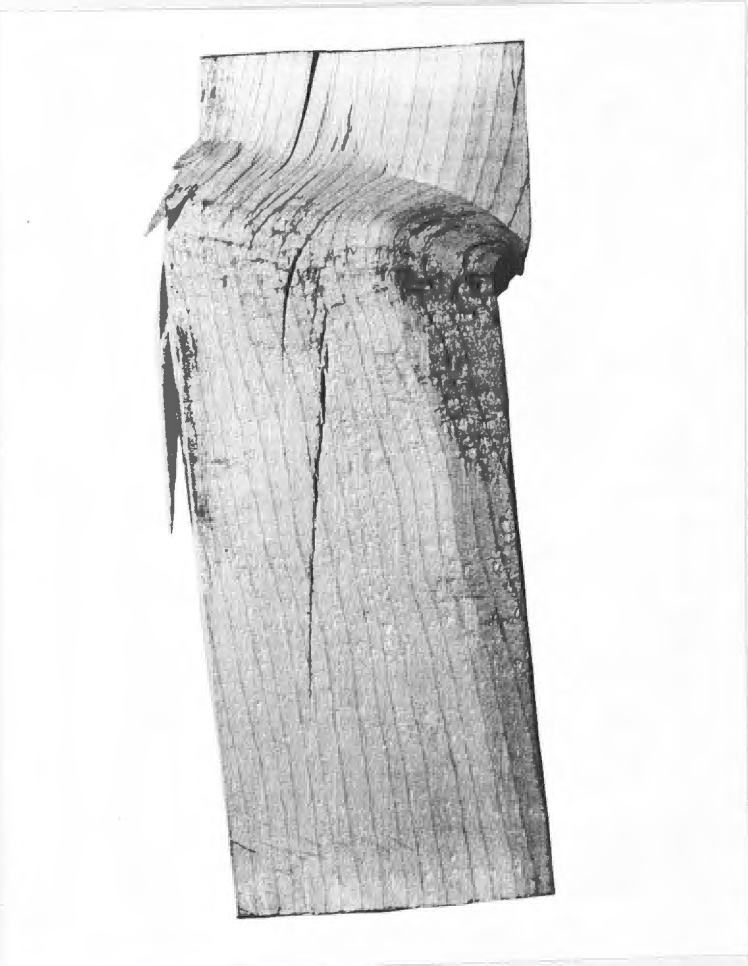

Fig. 21. A maple block.

Fig. 22. View of opposite side of maple block illustrated in figure 21.

Fig. 23. Maple block showing an extremely wide shear zone due to a continued application of pressure. Note also the fracture pattern in the center of block.

turn folding and thrust faulting. A clearer conception of the thrust fault may be gained by viewing the block turned upon its side. It will be noticed that faulting has extended to the interior and is accomplished by three independent off-set faults and also that the width of faulting decreases as the center is approached lending further evidence to the conclusion that the total compression on one side was wholly absorbed by the major shear. The shears themselves are in fact drag folds.

Mahogany and poplar proved to be very poor media for the production of fractures as compared to oak and maple. Poplar, though possessing a comparatively high compressive strength, evinced a marked tendency toward mashing out at the ends without the development of any fractures, while mahogany fractured slightly at a high angle and split vertically.

Believing that a softening of the wood fibres by steaming for many hours would render the material more pliable and therefore more comparable to rock masses under certain conditions[1], a number of different varieties were subjected to a steam bath for 24 hours and tested. The results did not prove as interesting as was expected. Again the most illuminating fractures were obtained from oak and maple. Figure 24 illustrates a poplar block which in failing gave fractures similar to those of oak or maple but dissimilar to dry poplar.

The most interesting feature brought forth by the experiments with steamed blocks was the remarkable degree of elasticity exhibited on release of pressure. The poplar column 3 inches long was compressed one third of its length and returned to within three twentieths of an inch of its original dimension on release of pressure. The oak and maple blocks (figures 25,26,27, and 28) subsequently tested, in order to retain the shape developed under maximum stress, were allowed to dry over night under pressure and as a result reflexed only slightly

[1] Gilbert,G.K. Geology of the Henry Mountains, Washington, 1880 pp. 81-83.

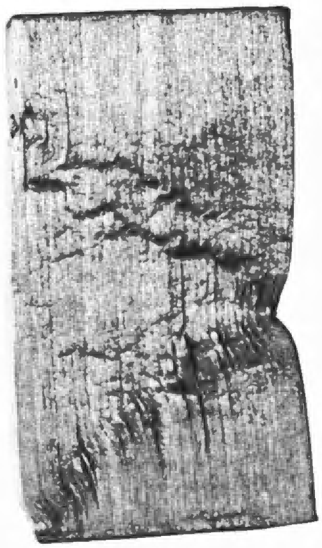

Fig. 24. A steamed poplar block.

Fig. 25. Steamed oak block. Note the width of shears and the absence of any sharply flexed fibres.

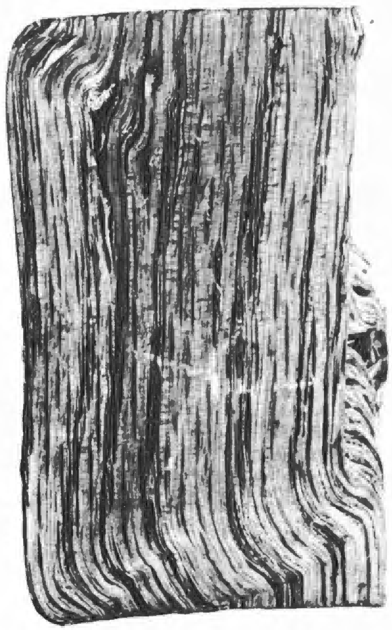

Fig. 26. Opposite side of oak block shown in figure 25.

Fig. 27. Steamed oak cylinder. Note the overturn folds within the shear.

Fig. 28. Steamed maple cylinder.

when removed from the machine. Little of interest can be said of these blocks except that the flexures retain a very easy contour, are very open and are from 3 to 4 times the width of a shear in dry wood.

All of the tests with wood described above have been made with the direction of application of pressure parallel to the grain. To test the performance of wood with pressure applied normal to the grain a number of cubic blocks of maple and oak were cut and subjected to trial. The first one experimented upon (figure 29) was a maple block 1 3/4 x 1 3/4 x 1 8/10 inches high. As the load was applied, instead of floating the beam as is the case when the grain is one end, it yielded and compressed until a pressure of 9,074 lbs. per sq. inch was reached, when failure resulted by fracture. In so doing the block was compressed 44 per cent of its original height without any very noticeable bulging of the free sides parallel to the grain, while the cross-cut faces gave no measurable elongation what-so-ever. This result is particularly interesting when it is remembered that hard maple is a very close grained wood with comparatively little open pore space. By drawing circles and diagonals upon the faces of the blocks, the character and amount of distortion could be observed. Figure 30 is that of a maple block subjected to a pressure of 5,172 lbs. per sq. inch without failing and shows the one inch circle transformed into an ellipse whose horizontal and vertical axes measure 1 3/64 and 45/64 inches respectively. The shortening of the vertical axis has therefore been 6 1/3 times the elongation of the horizontal, signifying that the vertical compression of a block is not necessarily accompanied by an equal lateral bulging even when the sides are free to move. The experiment expresses strongly the possibility of a reasonable amount of compression of formations without fracture or disruptive distortions giving evidence to movement. If instead of a circle covering the face of the block one with a diameter of 1/20 of an inch were drawn, the dis-

Fig. 29.

Fig. 30.

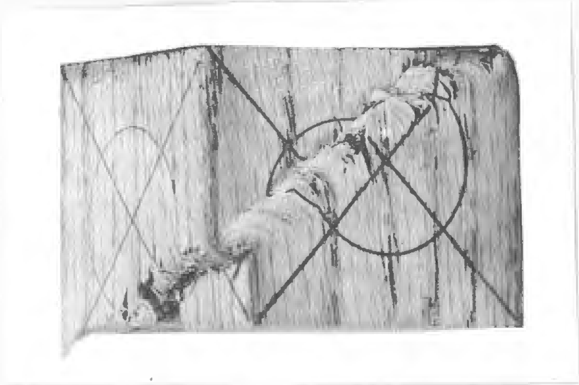

Fig. 32.

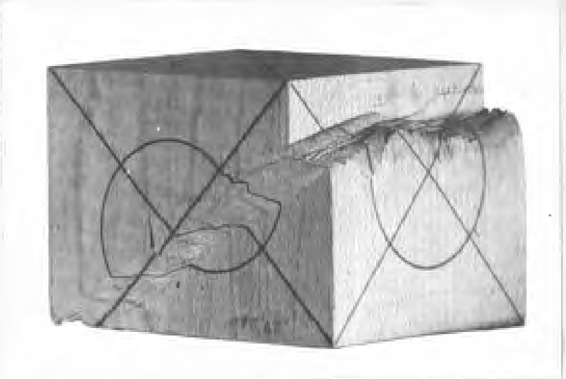

Fig. 31.

Fig. 34.

Fig. 35.

Fig. 35.

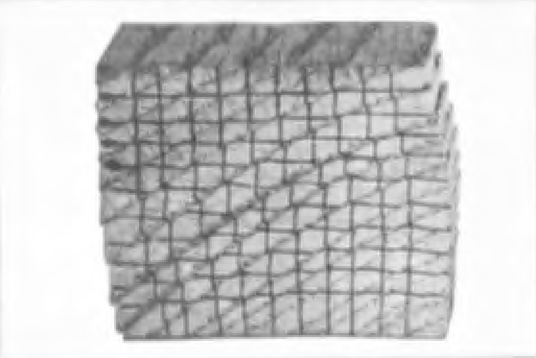

Fig. 36.

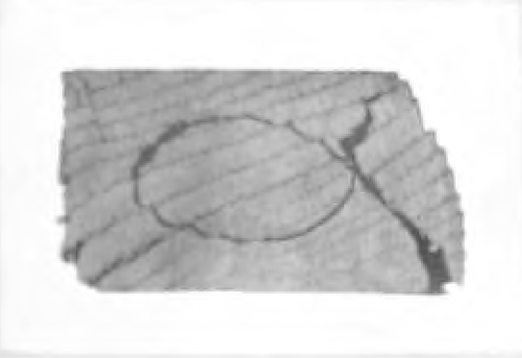

Fig. 37.

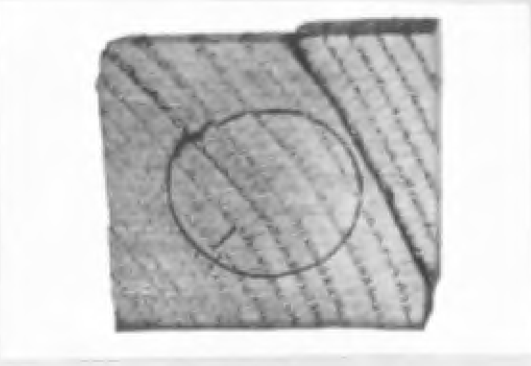

Fig. 38.

tortion of it would have been imperceptable and unnoticed. The accumulated adjustment of sub-microscopic dimensions between the granules of a medium grained sedimentary rock would afford ample opportunity for considerable compression of the rock as a mass. It may therefore be erroneous to assume that crustal shortening of a given amount will produce mountains of a certain height or that the product of linear uplift and length of shortened area gives the depth affected[1] without considering the compressive factor of the strata deformed.

Illustrations 31 and 32 are those of an oak and maple block of the same dimensions as the preceding tests and contrasts clearly the type of failure developed depending upon the direction of pressure to grain. The position of the grain also influences the failure pressure. Maximum resistance is offered to deformation when the grain of the wood is parallel to the direction of pressure and when shearing

[1] Chamberlin, T.C. and Salisbury, R.D. Geology, Vol. II, 1906 pp. 125-126.
Leith, C.K. Structural Geology. 1913, pp 125-126.

takes place relative movement of the two sides of the shear is unfailingly in the direction parallel to the growth rings. If the block be placed so that the pressure is normal to the grain and parallel to the annular rings a second position is found though weaker than the first, that shows a much greater sustaining power than when the grain and annular rings are both normal to the pressure. Figures 31, 39, and 33 make a typical set of maple blocks illustrating the above fact with failure pressures of 10,089, 9,074, and 3,448 lbs. per sq. inch respectively. In figure 35 one can observe the entire independence of fracture to the grain and also the manner in which compression of the wood has taken place; the otherwise straight saw-tooth marks being distorted into a serpentine curve.

Illustration 36 shows an interesting result obtained by previously cross-sectioning the face of an oak block and subjecting same to pressure in a direction normal to that of the grain. In this case as will be seen by referring to the illustration, the growth rings are inclined across the face at an angle of 30 degrees. Application of pressure to the block brought about successive failure of the open portions of the wood fibre separating the more solid rings, the process continuing with movement in the direction of pressure, that is, vertically downward until all the cells had failed and compressed. With continued application of pressure deformation was effected by a lateral gliding of each solid section over the other. With the face of the block cross-hatched relative movement of the segments are readily perceived by the staggered displacement of the vertical and horizontal lines. Without these lines relative displacement within the face could not be discerned without close scrutiny.

Although the conditions are not exactly similar to earth structures there is yet sufficient likeness to permit of comparison. It illustrates a certain phase in structural geology that might be termed "interformational" shearing, a displacement of the layers along the bedding planes or the employment of a soft layer as a medium for effecting movement. The solid wood rings might represent a hard quartzite, the open portions affording movement a softer quartzite, sandstone or shale. The sheared portion of the wood bears the "f" shaped fracture described by Edward Steidtman[1] and may be best seen in the center of figure 37, and, provided the direction of relative movement of the laminae are reversed closely resembles the conditions to be found in a structural anticline or syncline. Interformational shearing is probably a greater factor in causing the displacement of formations in highly deformed and metamorphosed regions where obvious indicators are most likely to be obliterated than is commonly considered, and a careful study of its possibilities may lead to the

[1] Steidtman, Edward. The Secondary Structures of the Eastern Part of the Baraboo Quartzite Range, Wisconsin. Journal of Geology, Vol.18, 1910, p.261.
Leith, C.K. Structural Geology, 1913, pp 25-26

solution of many otherwise unsolved problems.

Several tests were made of oak and maple columns of varying lengths from 8 to 40 inches, in both the dry and steamed state, a few of which are shown in figures 39, 40, 41, 42. With long columns especially those whose length is in excess of ten times the cross section, the tendency toward buckling at the center is the most common mode of failing. Figure 39 is that of a maple column in the process of buckling while figure 40 is one of the exceptions, an oak column failed by shearing and very little disalignment. It will be noted that a very good fracture system has been developed with rather high angles as is the rule with long columns, ranging from 50 to 75 degrees and averaging about 68 degrees to the direction of pressure.

By previously steaming the wood buckling of columns considerably under a foot in length was easily produced of which figures 41 and 42 are examples. The distorted portion may be divided into

Fig. 39. Maple column. With long columns buckling takes place very near the middle and the angle of the fracture lines are high.
Scale 1/3

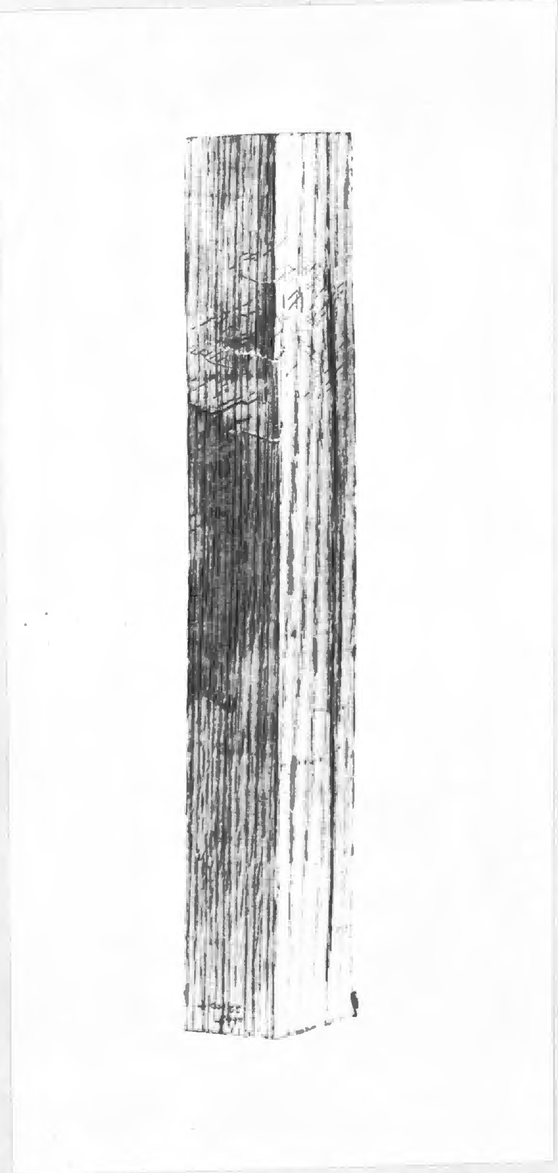

Fig. 40. Oak column with a well developed system of fractures. Scale 1/3

Fig. 41. Steamed oak column showing three zones, tension compression and a central neutral zone.
Scale 1/3

Fig. 42. Short steamed oak column wherein the neutral zone has been eleminated by the transgression of the other two. Scale 1/3

three parts (1) a zone of tension, (2) a neutral zone, and (3) a zone of compression. By more intense deformation the neutral zone may be entirely eliminated by the intrusion of the other two as shown in figure 42 and affords us a simple model of the three zones of (1) fracture, (2) combined fracture and flowage and (3) flowage of Van Hise[1]. Alternating hard and soft layers in the anticlines of drag folds often present exactly the same results and were undoubtedly produced under similar conditions.

Bailey Willis after a series of experiments on the artificial reproduction of folds came to the conclusion that folding was localized at or near the point of application of the deforming force. Such was not the case in the deformation of the wood blocks herewith described but rather the opposite as in the majority of cases failure resulted at or near the base or opposite end at which it should appear. This lack of agreement is

[1] Van Hise C.R. Principles of North American Pre-Cambrian Geology. 16 An. Rept. of U.S.G.S. p 589.

probably due to the much greater competency of the wood as the paraffin blocks sheared without. except at the pressure-head end.

It has been the intention of the writer in presenting this paper to give as clearly as possible a simple account of the experiments with only an occasional hint as to the geological comparison to be drawn. It is his belief that with the limited field experience at his command it is more desirable to leave the comparison of results to those whose practical and protracted association with geological phenomena better fits them for the position, or to battologize upon a literature which is only too familiar to those most likely to read this article. It is sincerely hoped that these results may prove of some aid to those whose interests in geology may lead them toward further research.

In conclusion the writer wishes to acknowledge his indebtedness to Dr. W. H. Emmons for the suggestion of the experiments and the indespensible supervision and guidance which has made possible this paper.

Walter B. Lang.