A STUDY OF SHAKE IN EASTERN HEMLOCK

by

Brayton Fuller Wilson, Jr.

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INTRODUCTION

Eastern hemlock (_Tsuga canadensis_ (L.) Carr) is often useless from a lumberman's point of view due to the presence of "shake." Shake is a crack, or separation, in the wood of a standing tree. In the case of hemlock each shake is circular and confined to one annual ring. In cross section a shake may form a complete circle in one annual ring. In such a case the inner core of wood is separated from the outer wood by the shake. If a disk is cut, the core is free and may fall out. There may be many shakes in one tree, each in a different annual ring. A tree is "shaky" if one or more shakes are present.

Shakes appear just above the general zone of the root collar. The first shakes are usually close to the pith, and later shakes occur in rings toward the bark (Fig. 1). Over time the shakes are extended upwards into the tree, sometimes even into the high branches. The shakes are not extended far downwards, presumably due to changes in structure and fiber orientation at the root collar. It is common logging practice to cut off the lower portion of the butt log with visible shake. In many cases these butted logs develop shakes when they dry. The tensions set up during drying apparently act on these weaker rings to cause further shake rather than the radial drying cracks which form in sound logs.

Lumber cut from shaky logs, or from most butted logs, cannot be used. In boards the different pieces which have separated from each other, in the standing tree or in the drying process, tend to fall apart. The strength of the board is lost. Apparently the only use for this shaky wood is for pulp.
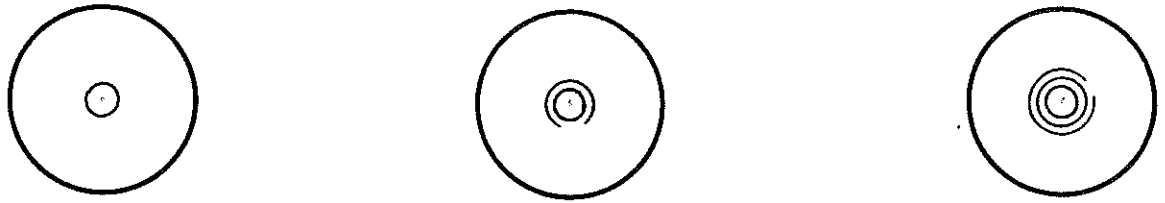
Cross sections at stump height - Annual rings not shown

Stump   Height
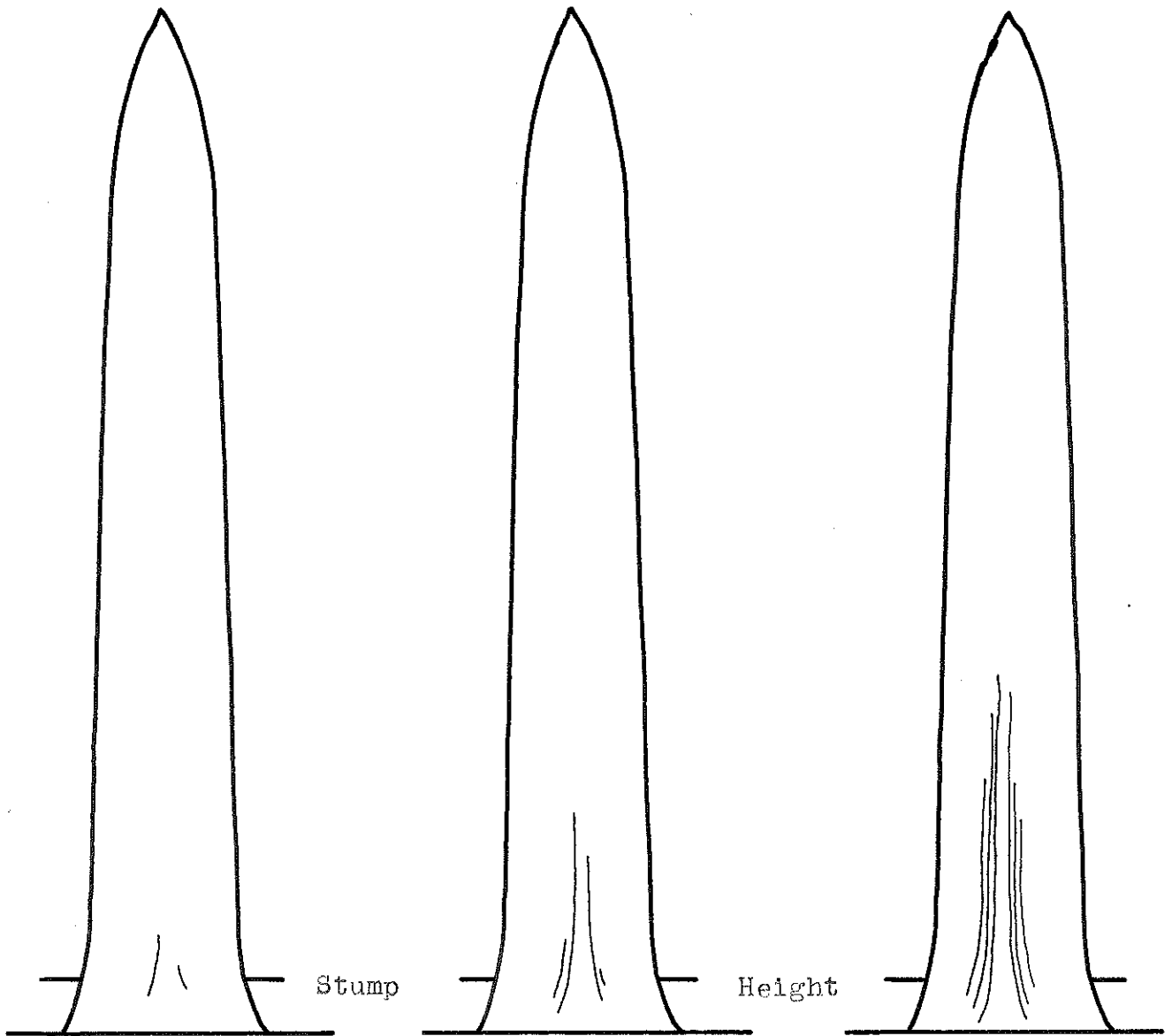
Longitudinal sections - Annual rings not shown

Fig. 1 Idealized diagram showing development of shakes

ACKNOWLEDGMENTS

The writer wishes to thank the staff of the Harvard Forest who were always ready with good advice and criticism. James H. Patric helped saw up the plank to demonstrate tensions and Fulvio Baldassini took the picture of it. Martin H. Zimmermann took the microphotographs of separation and maceration. Dr. I. W. Bailey and many people familiar with the woods, particularly N. W. Lake, contributed helpful observations from their experience.

REVIEW OF STUDIES OF STRESSES IN TREES

Loggers and wood technology textbooks generally attribute shake to the twisting and shearing effect of the wind. Frothingham (1915) attributed the cause of shake to wind, and before and since this has been generally accepted. Another factor is frost. Tryon and True (1952) and Day and Peace (1934) have shown that early frost can injure the cambium and cause it to separate from the wood, forming pockets and "shakes" in yellow poplar.

Since 1928 data and information have been gathered on the internal tensions of trees. Boyd (1950b) calls these tensions "the most important factor in causing shakes in standing trees." Martley (1928) first noticed the effects of tensions. He saw that sawn boards bent away from the pith, and he postulated a longitudinal strain gradient increasing towards the center. In the board the inner portion would always expand more than the outer, causing the board to curve. Koehler (1933) observed a circumferential compression of the annual rings which caused pinching when he sawed into a disk. He inferred a radial tension from this compression which might cause ring separation. Koehler was one of the first to suggest that shakes were not caused by the wind. Jacobs (1938) demonstrated a longitudinal strain gradient from tension on the outside to compression on the inside in Eucalyptus. His hypothesis was that the tension originated at the outside of the tree because the tension at the periphery was always the same for different diameters. The tension was resisted by the previously laid down central core, and the core was subjected to a cumulative compression. As the tension was evidently put on in each new annual ring he termed it "fiber tension." Jacobs (1939) refined his technique for measuring the longitudinal tensions.

He also demonstrated the circumferential compression and radial tension noticed by Koehler (1933) and was able to measure its magnitude. Jacobs postulated that the circumferential compression also originated at the periphery and that the resulting radial tension was cumulative on the center. Clarke (1939) reviewed the work done on tensions up till that time. Jacobs (1945) demonstrated the presence of fiber tensions in many species, both hardwood and softwood, including eastern hemlock. Boyd (1950a, b, c) confirmed the fiber tensions that Jacobs demonstrated. He used highly accurate measuring techniques and was able to make precise calculations of the forces involved. His calculation of the magnitude of the forces agreed closely with those that Jacobs had presented. The radial tension of up to 150 pounds per square inch is large, but not sufficient to cause separation in a normal tree. The longitudinal compression of 2000 to 3000 pounds per square inch on the central portion is tremendous and of a magnitude to cause splitting or "popping" when released by felling.

METHOD OF STUDY

Jacobs (1945) had found tensions present in eastern hemlock. Due to the possible importance of fiber tensions in causing shake the writer felt it necessary to reaffirm their presence in eastern hemlock. Jacobs' (1939) techniques for demonstrating longitudinal and circumferential stresses were used on a sample log (see Appendix). Both a peripheral longitudinal tension tending to compress the central portion and a circumferential compression setting up a radial tension were definitely present. Due to frequent knots and compression wood in hemlock the results varied quantitatively and it seemed futile to attempt measurements of the magnitude of stresses.

When the presence of internal tensions was established the writer felt that a microscopic study of shake might produce more information on its nature. Thin sections of wood containing shakes were made in order to see where the shake occurred in the annual ring. A white substance which frequently occurs in shakes drew the writer's attention to the fibers (tracheids) which face into the shake. The orientation of these fibers was studied under a dissecting microscope to gain insight into the manner of separation during the formation of a shake.

As this study was not intended to be wholly microscopic a reconnaissance survey of the incidence of shake also seemed to be indicated. Such a survey would assess some of the theories about shake, notably: 1) the writer's own observation that the total age of the tree might play some part in the incidence of shake; 2) that site (moisture, wind, and frost) was the most important factor; 3) that the incidence of shake was much higher in the larger diameters, because fiber tensions in most trees are cumulative with

diameter; 4) the observation of many loggers that suppression and release are somehow related to shake.   The survey was conducted in north central Massachusetts.   The author took data from 1250 stumps in 61 different samples on a range of sites.   Age, diameter, and site data were taken and general observations were made in the field.

ANATOMY OF SHAKY WOOD

Koehler (1933) noted that ring shakes occurred only in the large-celled spring wood and not in the dense summer wood. He also saw that the separation was rarely along the juncture of two successive growth rings. The writer's study confirmed Koehler's work. The shake continues in the spring wood and does not cross the summer wood except in the occasional "cup shake" when the circular shake ends in a radial crack. The weakest plane apparently is not at the sharp boundary between the summer wood of one year and the spring wood of the next, but a few layers of cells away in the spring wood.

Using a regular light microscope the shake appears to be winding among the cells through the middle lamella. Garland (1939) has shown that in none of the fractured specimens which he examined with a polarized microscope had lateral separation taken place through the middle lamella. In wood fractured under tension and compression the lateral separation was between the very thin outer and thick central layers of the secondary wall, and never crossed the central portion. It seems probable that lateral separation in a shake is similar to that caused during failure in a testing machine. The primary wall acts as a unit with the middle lamella and the shake would pass between layers of the secondary wall. From cell to cell the shake would cross the two primary walls with the middle lamella in between and continue in the secondary wall of the next cell.

Unfortunately it is difficult to get microscopic sections showing the shake as it actually occurs in the standing tree. Preparing the wood for sectioning usually extends the shake into the sample to be sectioned.

Separation and Maceration

The process of the opening and extension of a shake in a standing tree can be seen as a progressive series by looking at the surface of the walls of different shakes. The first step in this series is a separation in the spring wood area of the annual ring. The fibers facing into the newly formed shake are still aligned parallel to the other fibers although some are sticking out into the shake where they were pulled during the separation (Figs. 2, 3, 4). This first step is evidently a passive, and probably slow, pulling apart which does not affect the fiber orientation.

Once the shake is formed it is extended and the sides are rubbed together by wind and frost action. The fibers become unaligned and many more are rubbed from the sides to stick into the open shake (Figs. 5, 6). At this point bacteria may enter the shake. They probably loosen many of the cells and may be responsible for the amorphous white substance which is often seen on the fibers (Fig. 7).

The constant rubbing of the walls of the shake eventually causes a maceration of the cells which are sticking out from the walls. Under branches and at other points of great pressure the macerated fibers form a shiny, white surface on the wall of the shake. Occasionally the macerated fibers form a paper-like sheet inside the shake. Under the microscope this paper-like sheet is seen to be composed of completely unoriented fibers in a matrix of ground fibers and the white substance (Fig. 8). In some cases all fiber structure is lost (Fig. 9). The fibers making up the sheet are almost entirely spring wood.

The presence of a series from passive separation to maceration strongly suggests the operation of internal tensions and is a good basis for proceeding
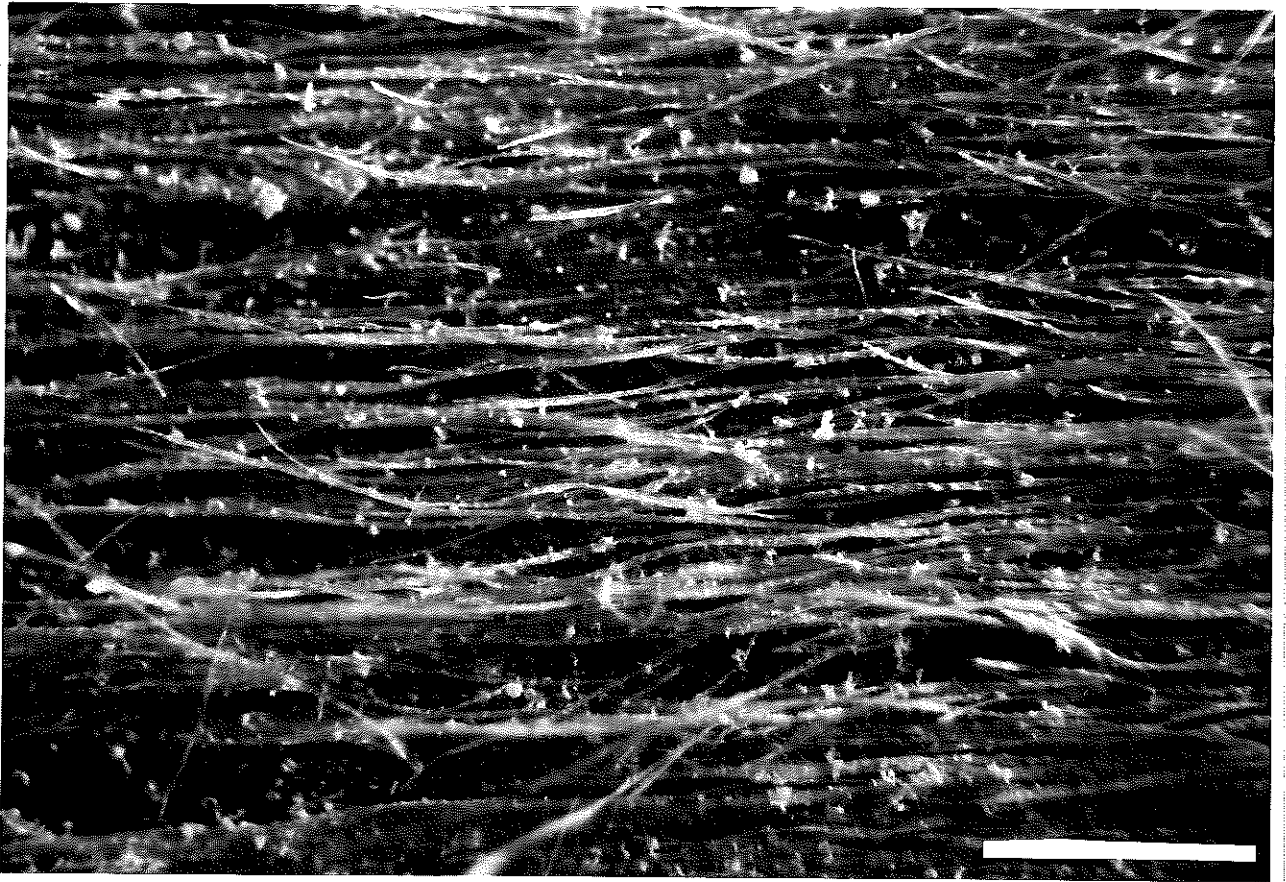
Figure 3. A later stage of separation with more fibers
sticking out and becoming unaligned. (X36)

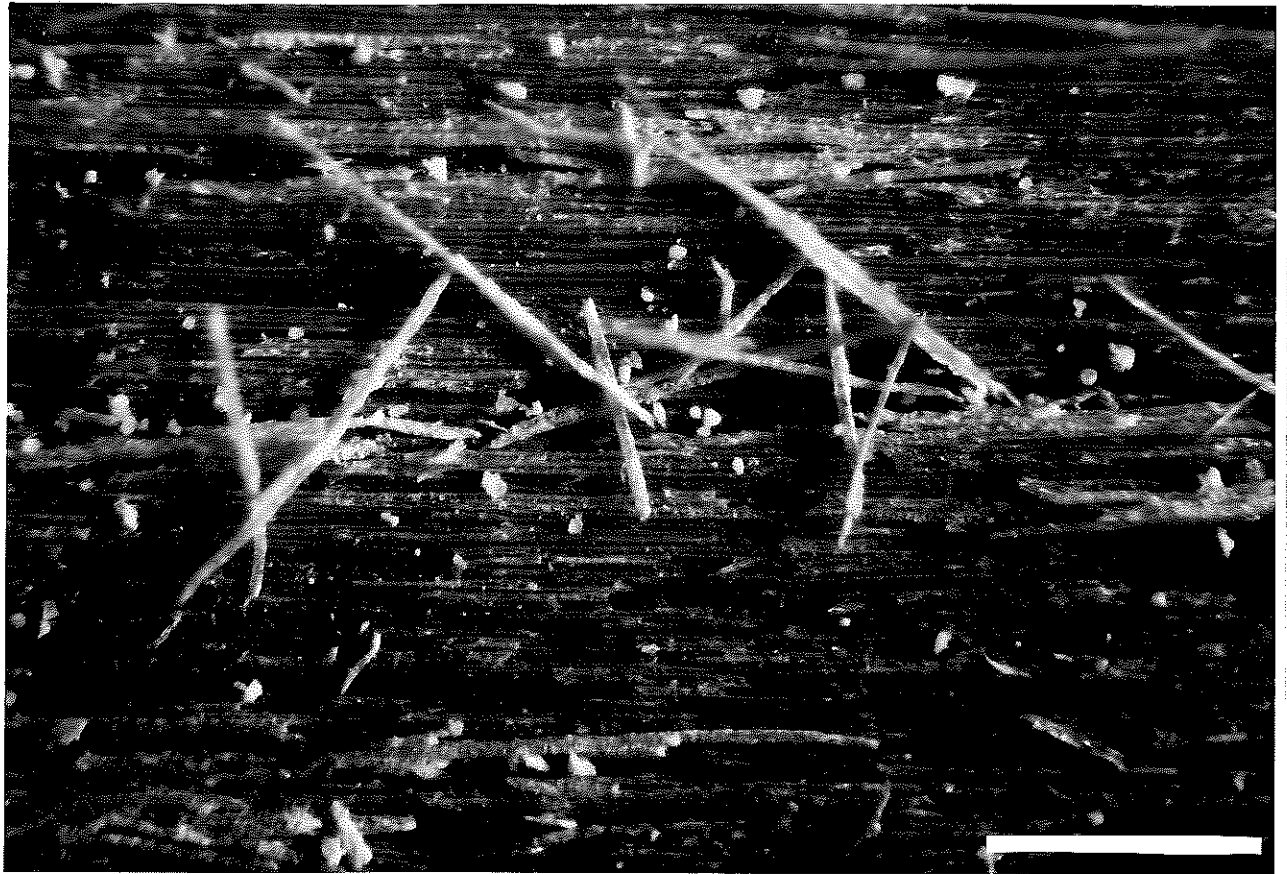Figure 4. Much the same as figure 3 with more fibers crossed.
(X36)

Figure 5. An example of the criss-cross effect which can
develop from rubbing. Most of the crossed fibers are
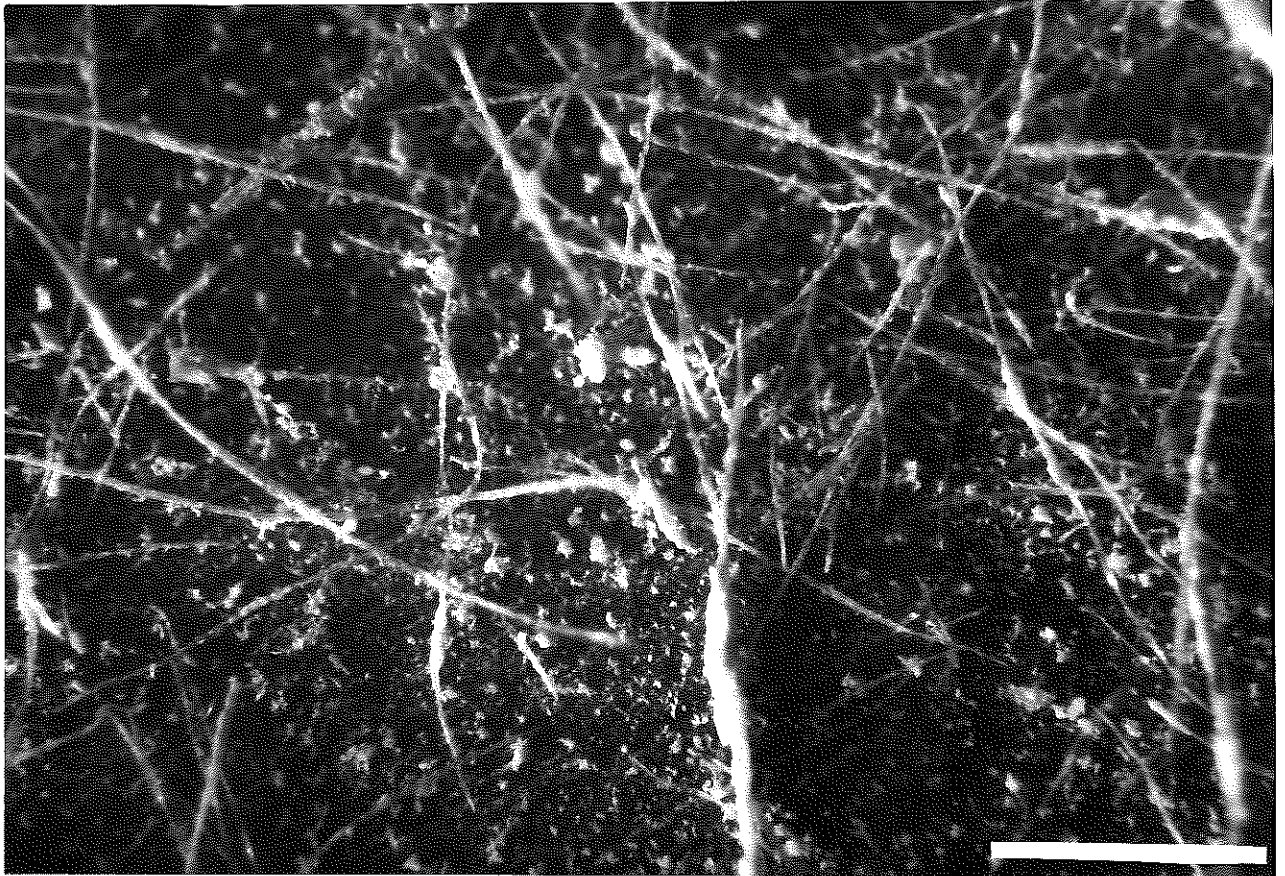still attached to the main wall. (X36)

Figure 6. Most fibers unaligned and maceration well started. Some of the white substance, possibly from bacteria, can be seen on the fibers. (X36)
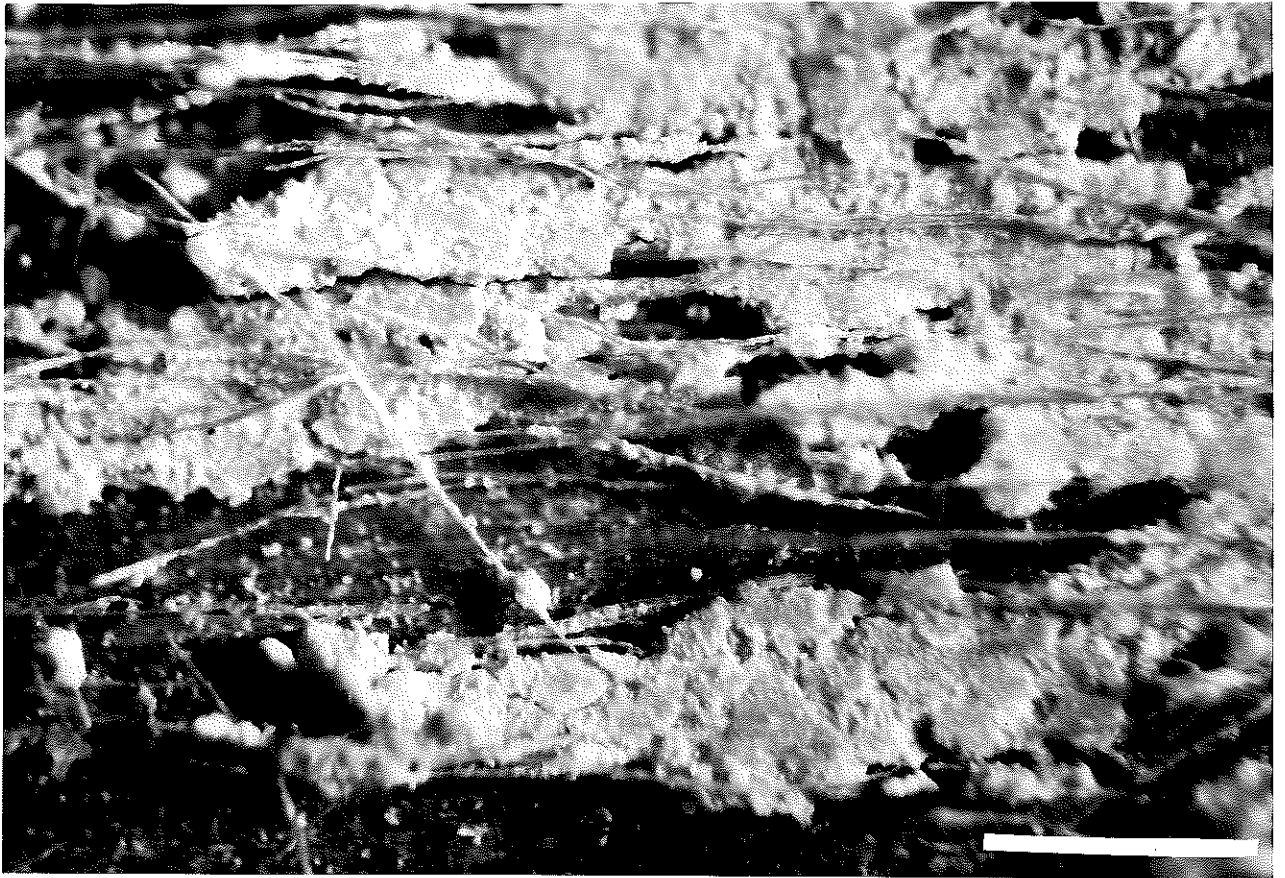
Figure 7. Fibers almost completely covered by the white substance. (X38)
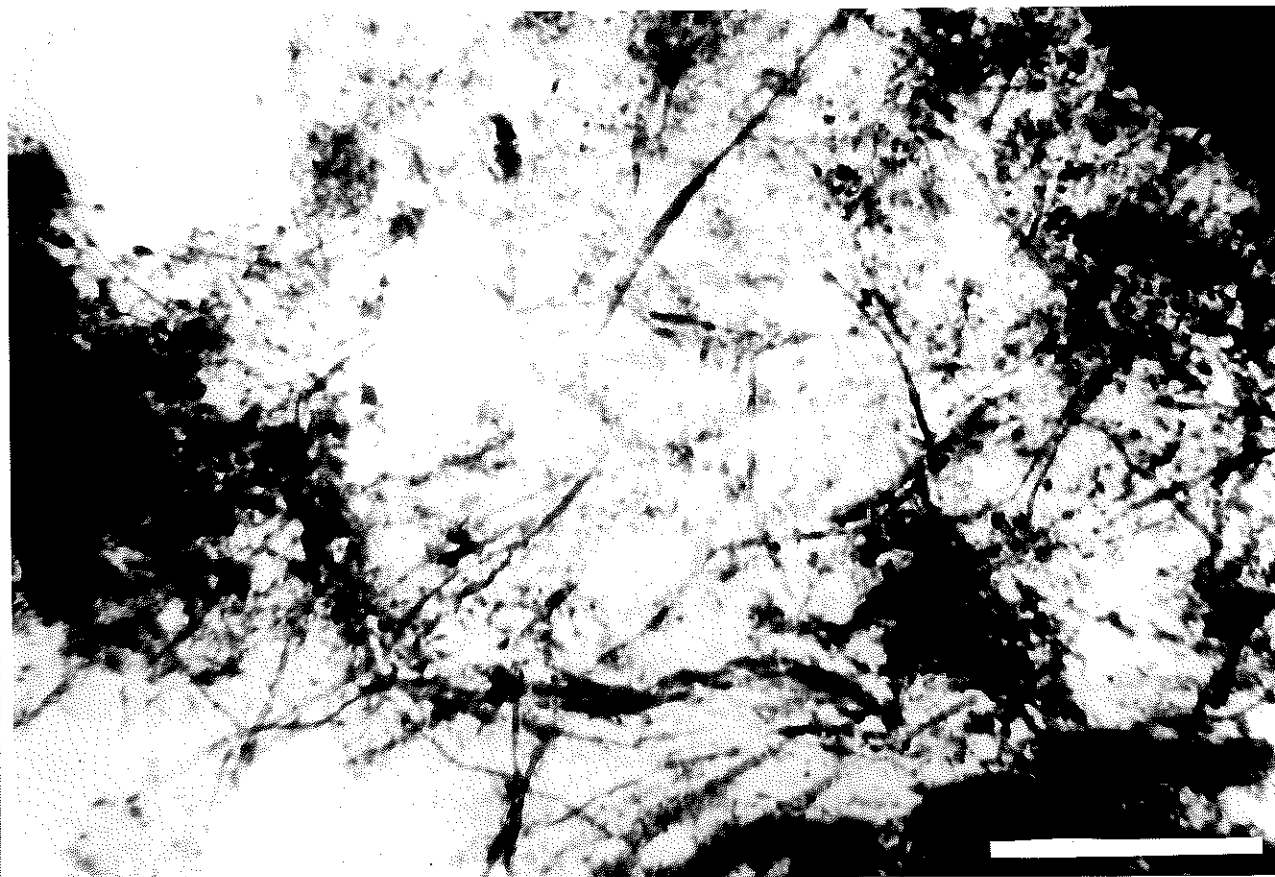
Figure 8. A slide from the paper-like maceration product.
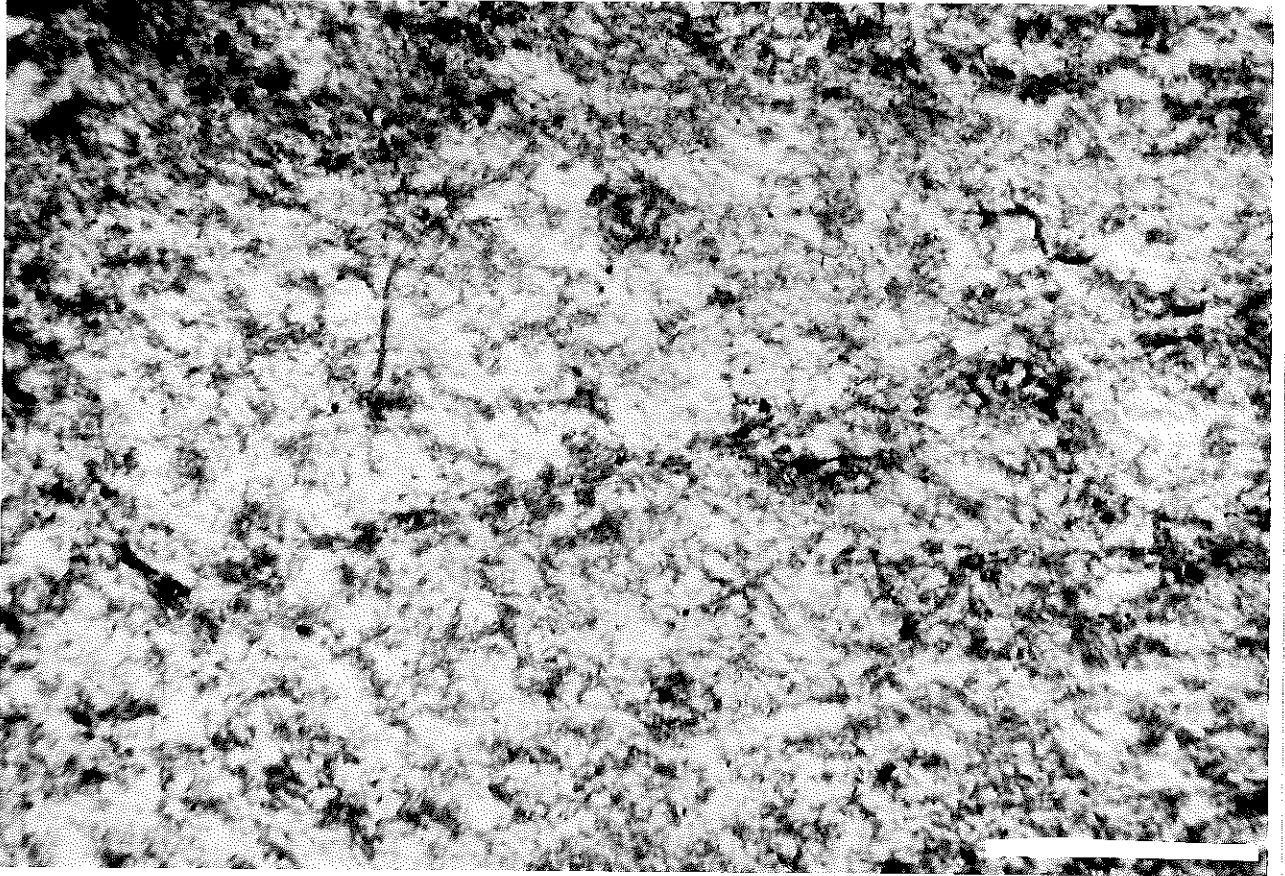There are a few unoriented fibers in an amorphous matrix.
(x38)

Figure 9. A very advanced paper-like maceration product.
Only a few bits of fiber are recognizable. (X36)

on the hypothesis that these tensions are of primary importance. Mayer-Weglin (1955) says "Hartig (1896) found in these checks of freshly felled oaks a flour-like substance consisting of macerated wood cells. This is proof that the shear forces move the sides of the check together." Mayer-Weglin attributed these shear forces to wind and frost. At least in hemlock it seems that the separation was not caused by a shear force but by a radial tension which could only be internal. A shear force would cause immediate criss-crossing of the fibers on the sides of the shake. The series shows that the first stages of separation are not the result of a sudden shear failure but of a gradual pulling apart under radial tension. The forces of wind and frost are probably important factors not in the original formation of the shake, but in its extension and by rubbing the sides of the shake together.

SURVEY OF INCIDENCE OF SHAKE

Previous to this survey no data had been gathered on the incidence of shake in hemlock. Most theories were based only on general observations. Loggers avoided hemlock stands on steep rocky slopes because the trees were so often shaky. The Australian studies of fiber tension seemed to indicate that there should be a high correlation between increasing diameter and the incidence of shake, as they postulated that tensions accumulate with diameter. The writer had observed in Vermont and New Hampshire that most of the older hemlocks were shaky and the younger ones sound. There was not enough information available to see if any of these general observations actually held true in the field. The presence of tensions in hemlock had been established. Wind seemed unlikely as a primary factor. Some hemlocks are shaky and others are not, but which ones? What effects, if any, did age, site, diameter, and growth conditions have on the occurrence of shake? Was shake predictable by place, size or time? As shake is not visible without cutting down the tree, a convenient way to study the incidence of shake is to look at the stumps of trees cut in logging operations.

The writer decided to make a survey of hemlock stumps in north-central Massachusetts. Under the Cutting Practices Law in Massachusetts every lot cut, except those for home use, is visited by the district forester. The forester records the location and approximate size of the lots on topographic maps and estimates the volume cut by species. This system permits easy location of the lots in the field.

Locations of the lots sampled in the survey were obtained from the information gathered under the Cutting Practices Law, with the help of the Boston office of the Massachusetts Natural Resource Commission and the district

foresters of Worcester, Hampden, and Hampshire counties (Fig. 10). As some
of the lots were sixty miles from the Harvard Forest only areas with concen-
trations of lots were studied in order to cut down on travel time. In addi-
tion to the above criterion the lots selected had had more than five thousand
board feet of hemlock cut from them less than five years previously.

Method of Survey

When a lot was visited the writer looked for a concentration of more than
twenty stumps on a site uniform as to slope, exposure, and topographic posi-
tion. Twenty or more stumps were recorded. (The average sample was twenty-
one.) The number recorded depended largely on accessibility, as some of
the lots were almost impenetrable.

The stump data taken were the presence or absence of shake, age, diameter
(at stump height), and the number of releases evident from the annual rings.
Site information taken was the presence or absence of ledge to indicate the
relative thickness of the mantle of soil, and whether or not the site was
swampy. The location of the sample was marked directly on a topographic
map for later determination from the map of slope, exposure, topographic
position, and relief features. General observations were made on the coin-
cidence of shakes with releases if both were present.

If there was any circular separation in all four quadrants of the stump
it was considered shaky. If the quadrants could be so arranged that one of
them contained no circular separation the stump was considered sound. This
criterion is much harsher than that applied by most loggers but it is con-
sistent and not dependent on any judgments of the degree of shakiness.
Stumps from sound trees develop cracks too but they are invariably radial
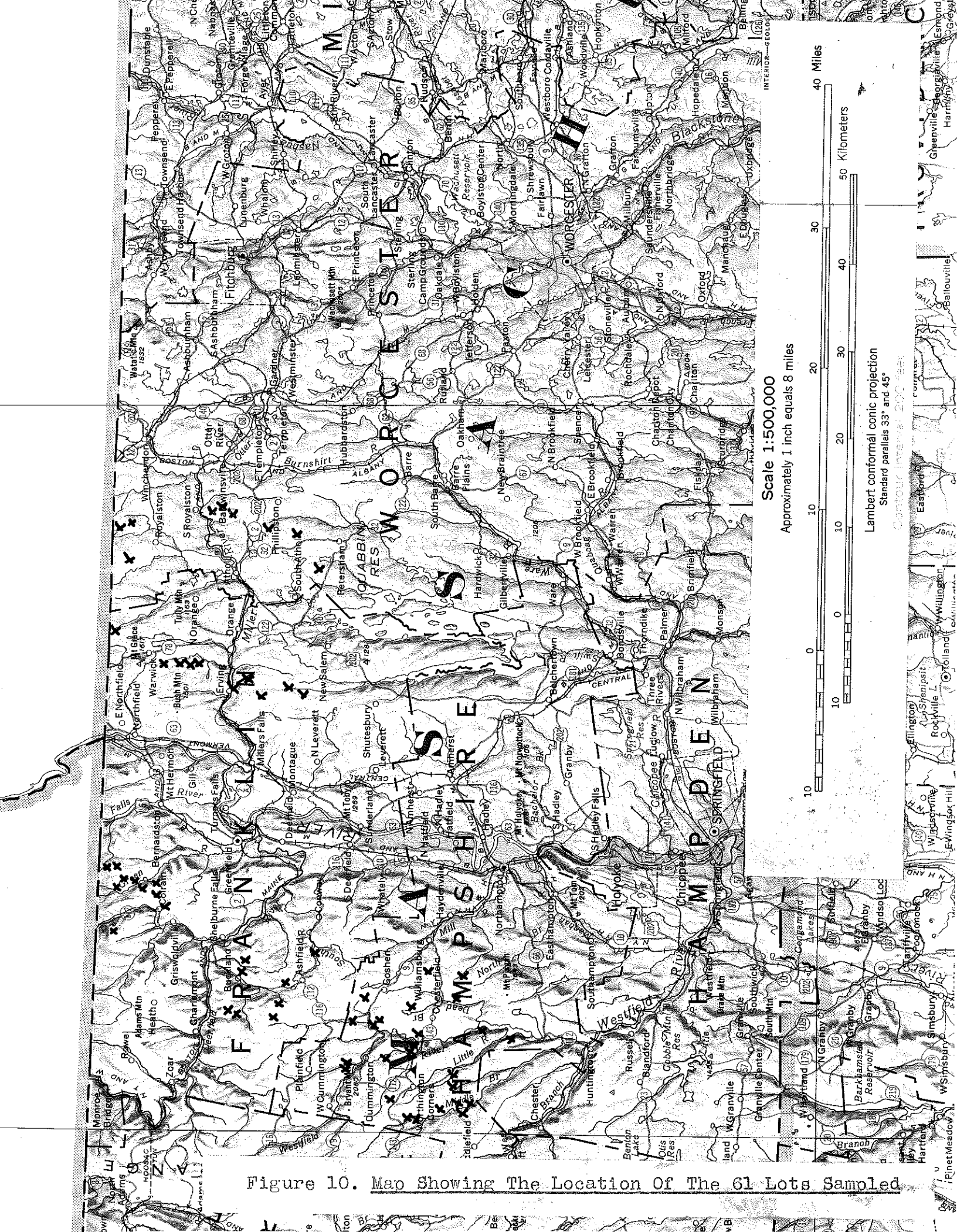and not circular. All but a few of the trees had been cut for at least six

Figure 10. Map Showing The Location Of The 61 Lots Sampled

months.   As the survey progressed the above criterion applied equally well
to stumps cut six months ago as to those cut five years ago.   Some of the
cracks noticeable at six months are not evident immediately after felling
and fresh stumps were avoided.   Beyond five years the stumps are too rotten
and moss-covered to count the rings with any accuracy.
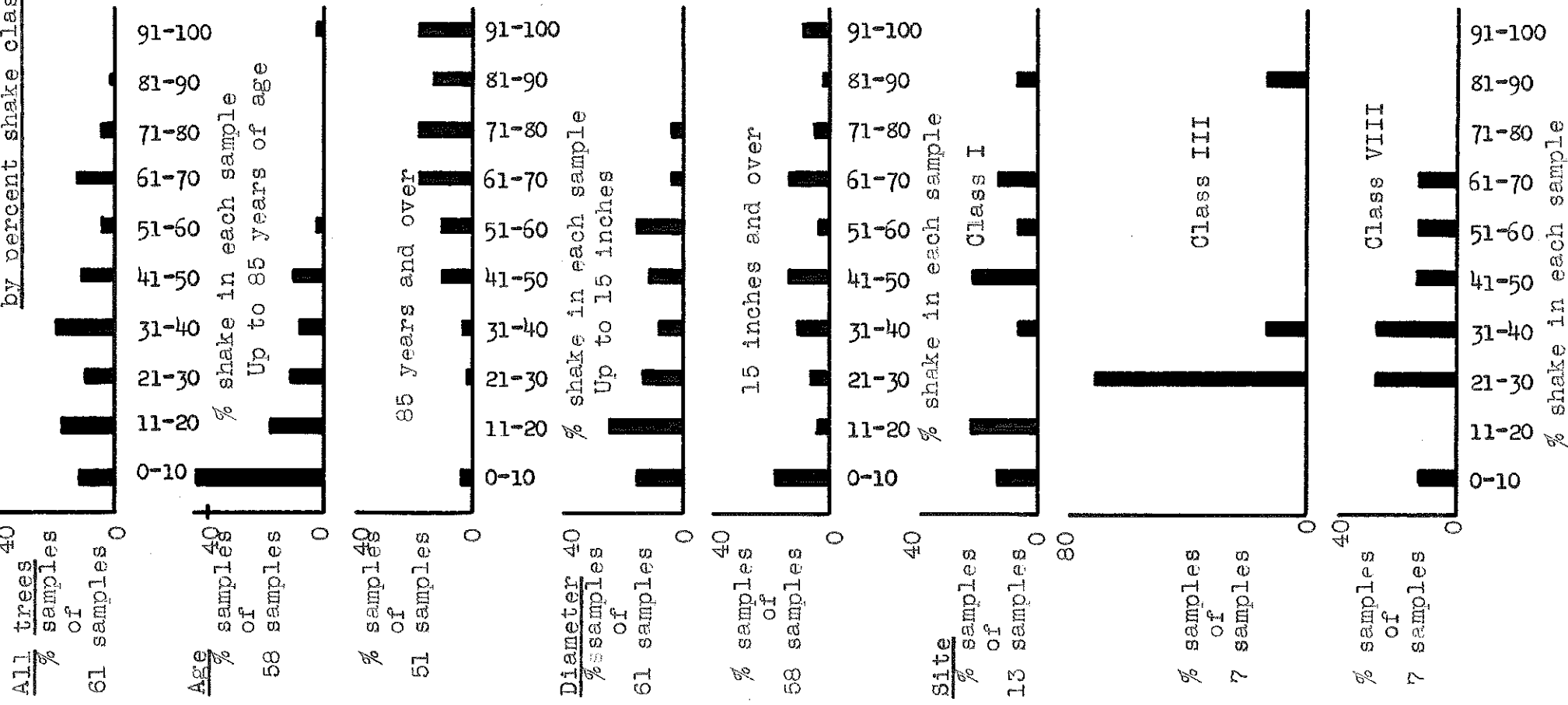
DATA ON THE INCIDENCE OF SHAKE

General

Data were taken from twelve hundred and fifty stumps in sixty-one different samples. One basic breakdown of the data is into sound and shaky trees. Four hundred and sixty-eight of the trees, or just over one third of the total, were shaky. The percentage of shaky trees in the samples ranged from zero to ninety (Fig. 11). Only one of the sixty samples had no shake. Figure 11 shows that the percent of shake present in the samples is highly variable. The incidence of shake is selective, not random. If it were random one would expect a grouping of samples in a percent class to form a bell-shaped curve. If a factor is related to the incidence of shake the samples should show a grouping when stratified by that factor. Figure 11 shows the result of stratifying the samples by some of the factors considered in the survey. Stratifying by the younger age class produces a considerable grouping of the samples in the low percent of shake. The older age class has a definite, though less clear, grouping in the high percent classes. Stratifying by diameter classes does not produce a clear grouping although the small diameters tend to be less shaky and the larger ones more shaky. The site classes have many fewer samples so that the sample may not be truly representative. Class III in particular shows a very marked grouping in the twenty to thirty percent shake class. This apparent effect of site is a special case which will be discussed in the section on the effect of site.

The Effect of Age

The youngest tree recorded in the survey was 29 years old and the oldest 210 years old. The writer first established in the field that the shakes were not associated with any particular annual rings such as the 1938 ring.

Fig. 11 Percent of samples, under different stratifications, by percent shake classes

the year of the last hurricane, or a year of early frost.   Rather than with

a particular annual ring, the incidence of shake seemed to be related to the

total age of the tree.

In the age group 0-60 only two of more than one hundred and fifty trees

were shaky.   Of sixty trees over 125 only two were sound and they both were

127 years old (Fig. 12).   Scatter diagrams of sound trees against shaky

trees were made with the trees stratified into five-year age classes.   The

diagrams showed a very marked grouping of sound trees in the 0-60 year class.

With each five-year increase in age class the scatter moved toward the shaky

axis until there was a marked grouping of shaky trees in the 125 and older

age class (see Appendix).   The scatter diagrams indicated that trees up to

85 years of age are fairly shake-free.   (There were six hundred and sixty

or just about one half of the trees in this class.)   From 85 to 100 years

is a transitional period with half or more of the trees shaky (four hundred

and twenty or about one third of the trees were in this class).   Over 100

years the incidence of shake is high (only two hundred or about one sixth of

the trees were in this class).   The break is quite sharp with only fifteen

years involved in the transitional period.   This fifteen-year period is

short when compared with the total age of some hemlocks.   Frothingham (1915)

noted a hemlock 420 years old.

In the field some attempt was made to divide shaky trees into two classes,

shaky and very shaky.   In a general way trees with only a few (1-5) shakes

were classed as shaky and those with more as very shaky.   Using this arbi-

trary division the percent of very shaky trees in the total shaky trees

showed a definite increase with age.   Eight percent of the shaky trees under

100 were very shaky, fifteen percent from 100-125, and sixty-six percent over
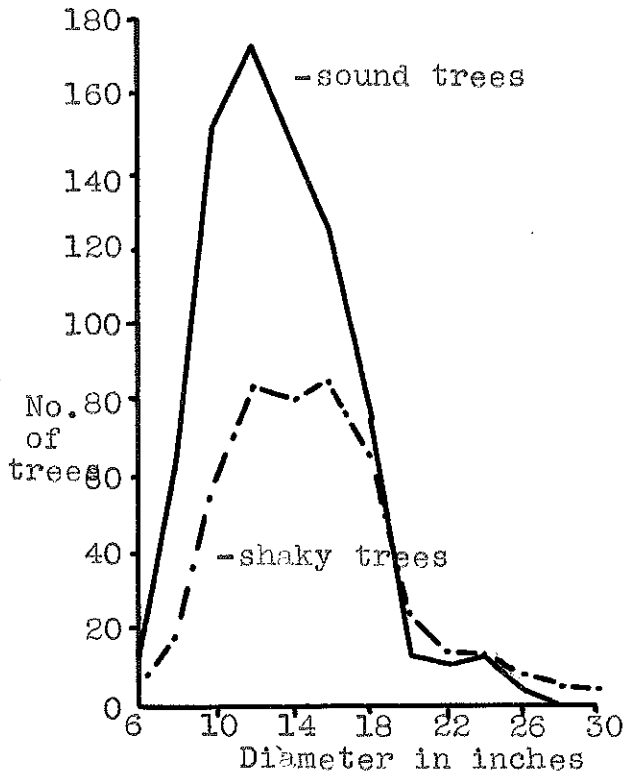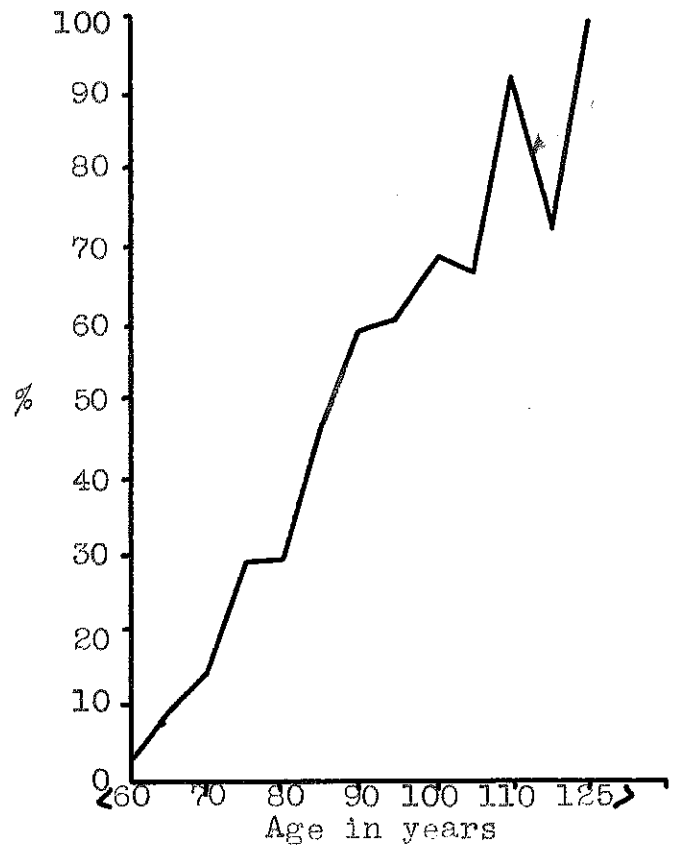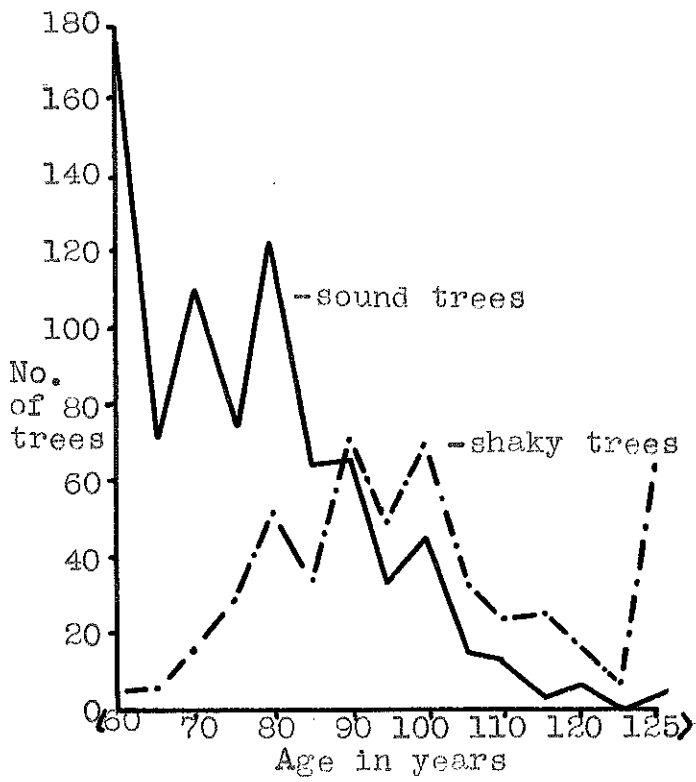
Figure 12 All trees stratified by
Age and diameter

125.   The relationship of age to the incidence of the first shakes apparently
holds, although to a lesser degree, in the formation of further shakes.

From a management and an ecological point of view it is interesting to
note that the samples taken from different stands were fairly even aged. The
standard deviation from the mean age of the sample ranged from 5.5 years to
41.0 years with the average being 14.1 years. The stands sampled ranged from
mixed hardwoods with scattered hemlocks, to pure hemlock stands. In the more
even aged pure stands all the trees could be in the fifteen-year transitional
stage at once. This period would be critical in the management of the stand.
In fifteen years most of the trees in the stand would be shaky. A different
stand fifteen years younger might be almost completely sound. The differ-
ence here is related to the age of the stands and not to differences in the
sites.

The Effect of Site

The sixty-one samples were broken into site classes using the data from
the field and from topographic maps. A fairly prevalent idea of the influ-
ence of site is that the incidence of shake is higher on particular sites,
steep rocky slopes and sites which are exposed to the wind. Recent studies
of the influence of site on growth and distribution have demonstrated the
importance of moisture as a site factor. Many site effects previously
attributed to available nutrients or the humus are now thought to be related
to available moisture. Because of the importance of moisture the basic site
divisions in this survey were made on a drainage basis. The two most dif-
ferent types of site sampled were 1) wet 0-8 percent slopes on footslopes
and sidehills with deep soil (Class I) and 2) dry, ledgy, 20-60 percent
slopes located on noses, hill crests, and convex side slopes (Class VIII).

These two sites represent the extremes in moisture regimes that were sampled in the survey. Various other site classes were formed using exposure, depth of soil, and slope, that were intermediate in moisture regime. Exposure to wind would probably vary most between the two extremes of site outlined above. The individual crowns are well protected from the wind on the flats and gentle slopes, but are quite exposed on the steeper slopes.

Grouping of samples on the basis of site characteristics was poor in most cases, but in some it was quite good (Fig. 11). With one exception the samples in site class III, consisting of all E, SE, S, SW, and W-facing 12-20 percent slopes, were essentially shake-free. Neither Class I nor Class VIII, the extremes of moisture regime, were well grouped (Fig. 11). On figuring the average age of the samples in site class III it was seen that the trees in all but one of the samples were quite young. Samples consisting predominantly of young trees were relatively sound but the sample containing older trees was almost entirely shaky. Apparently the age relationship overrides that of site.

The relationship between age class and incidence of shake holds on all the sites sampled, from one extreme of a shaky tree growing in a swamp to the other of a sound tree growing on a steep, exposed ledge. Only two trees under 60 years of age were shaky and they were on different sites. No tree over 127 years old was sound. The possible modifying effect of site on this relationship could at most be small with only the 65-year span to work with. Genetic variability might well account for most of the spread. The anticipated effect of site would be to move the fifteen-year transitional period in the 65-year span. Another effect might be to increase the length of the transitional period.

All trees

$$y = -66.4 + 1.25x$$

Site Class I

Wet 0-8% slopes

deep soil

on flats, footslopes,

$$y = -64.1 + 1.24x$$ and sidehills

Site Class III

Intermediate 12-20% slopes

both deep and shallow soil

facing E, SE, S, SW, and W

$$y = -101.1 + 1.62x$$

Site Class VIII

Dry 20-60% slopes

shallow soil

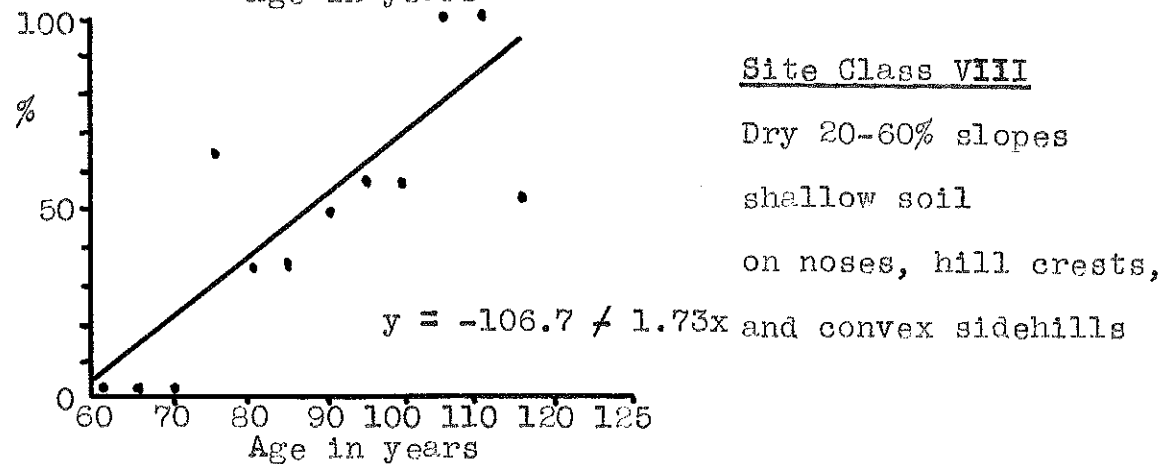on noses, hill crests,

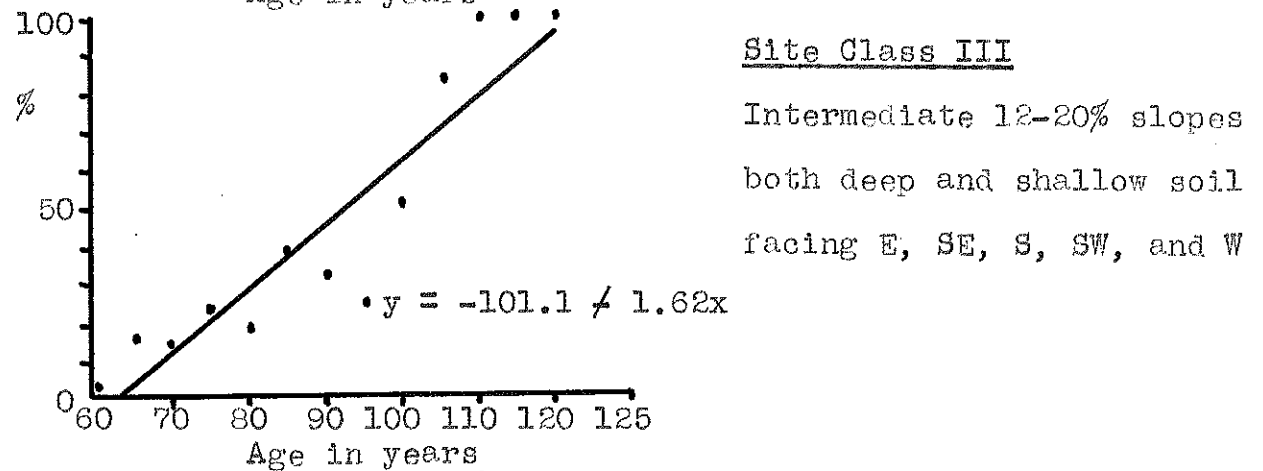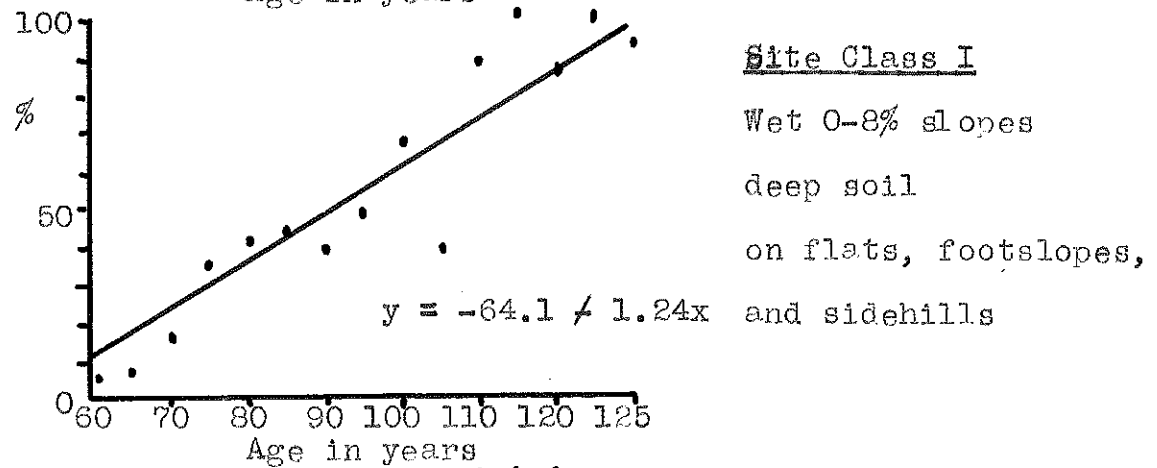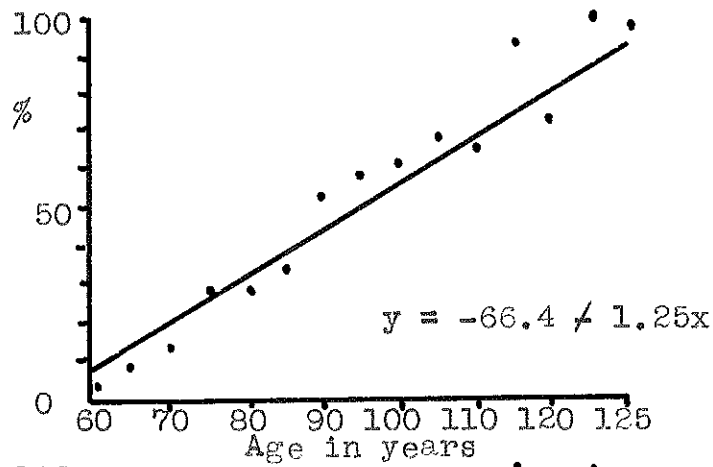$$y = -106.7 + 1.73x$$ and convex sidehills

Figure 13 Modifying effect of site on the

age-shake relationship

When the percent of shake by age classes is graphed for each site class (Fig. 13) the different sites appear to have very little effect on the incidence of shake. In those site classes with enough samples the percent shake against age curves closely approximate a straight line. For comparative reasons this straight line relationship was utilized and a least squares line was plotted to fit the scatter for each site. The difference in slope of these lines between sites is small (Fig. 13), the minimum being 1.2 and the maximum 2.08. These slopes are very similar to the slope of the least squares line for all trees (Fig. 13). There does seem to be a gradual steepening of slope of the least squares lines with decreasing available moisture. Such a steepening indicates a shorter transitional period between predominantly sound and predominantly shaky trees. Very few years are involved in the changes in slope and position of the lines. Between the two extreme moisture regimes the point at which fifty percent of the trees are shaky decreases only from 92 to 90 years. Apparently sites with a lower moisture regime have a slightly higher incidence of shake. The various intermediate sites have very similar least squares lines. One intermediate site (12-20 percent slopes with ledge showing) has a quite steep least squares line with a slope of 2.08. This exceptionally steep slope is probably due to sampling, but the modifying effect on the age-shake relationship is slight in any case.

The effect of site on the properties of wood is a matter of dispute. Harlow (1927) found only very slight effects. Keinholz (1931) found that the trees on better sites had larger cells. In both cases the extremes of site were greater than in this survey. Factors such as competition were not considered. As Avery (1940) clearly shows, great differences in moisture

regime have only slight effects on the growth of hemlock. The effect of site
on wood structure is far from clear. In any case moisture regimes of the
sites sampled probably had less to do with growth rates and wood properties
than early competition and suppression.

Suppression in early life is common to many hemlocks. This suppression
can be due to the ability of hemlock to grow under an overstory of hardwoods,
or to a high stand density in young, pure stands. The suppression does not
appear to harm the trees and may help them. Marshall (1927) states that an
increased period of suppression increases the "youthfulness" of the tree in
response to release. Suppression does allow the tree to survive for many
years without appreciably increasing its volume. An extremely poor site
would also cause the tree to grow very slowly. As a result these slow-grown
trees would be quite old by the time they reached a merchantable diameter.
Due to the age-shake relationship these trees will have a high proportion of
shake when cut. In a sense then, site is important in the incidence of shake,
but it might be possible to produce shake-free stands on almost any site by
keeping the trees free to grow; then the trees would be large enough to cut
before they had reached the transitional age class of 85-100 years. Marshall
(1927) felt that a short period of suppression will actually increase the
total increment of the tree by the time it is cut, but even using a differ-
ent approach he decided that the rotation of hemlock should be about 60 years.
Under this short a rotation the stand should be almost entirely shake-free.

The Effect of Diameter

Diameters were taken at stump height in two-inch classes. Jacobs'
(1938, 1939, 1945) and Boyd's (1950a, b, c) work indicates that internal

tensions are cumulative with increasing diameter.   Therefore the incidence

of shake might well be expected to increase with increasing diameter.   The

diameter at stump height of trees sampled ranged from six to thirty-six

inches.   Most of the stumps were in the eight to eighteen inch classes.   All

three of the trees over thirty inches were shaky but the other diameter

classes had both sound and shaky trees.

Scatter diagrams of sound trees against shaky trees stratified by diam-

eter classes showed poorer grouping than when stratified by age (see Appendix).

Most trees under twelve inches in diameter were shake-free and most trees

over twenty-six inches were shaky (Fig. 12).   A large proportion of the trees

(nine hundred and thirty or about three quarters of the total) were in the

fourteen to twenty-four inch classes which did not show clear grouping.   How-

ever, diameter seemed to have some effect on the incidence of shake because

trees having smaller diameters were relatively sound and the larger ones

relatively shaky.   Here, as in site, the age effect might well override that

of diameter.

Due to the age-diameter relationship it is often difficult to separate

the effects of age from those of diameter.   By graphing the percent shake

against age by diameter classes the relationship between diameter, shake, and

age can be clarified to a degree.   The least squares line for percent shake

against age can be plotted by diameter classes (Fig. 14).   These least

squares lines are almost identical to those for percent shake against age by

site (Fig. 13), at least up to and including the eighteen inch class.   Diam-

eter has very little modifying effect on the relationship between age and the

incidence of shake in those classes under eighteen inches.   The twenty and

twenty-two inch classes combined have a similar least squares line, but with

8 inch class

In b the age classes 95 and 100 are omitted as there is only one tree in each class

$a - y = -44.3 + .91x$

$b - y = -70.9 + 1.36x$

12 inch class

$y = -88.4 + 1.42x$

16 inch class

$y = -73.0 + 1.31x$

20 and 22 inch class

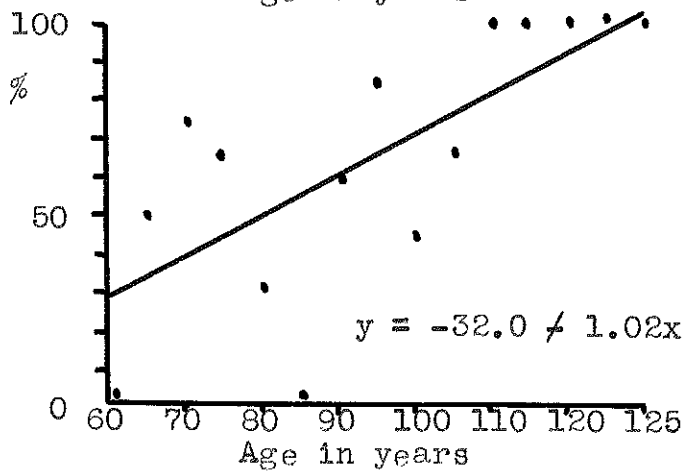There are not enough trees in these classes to separate them
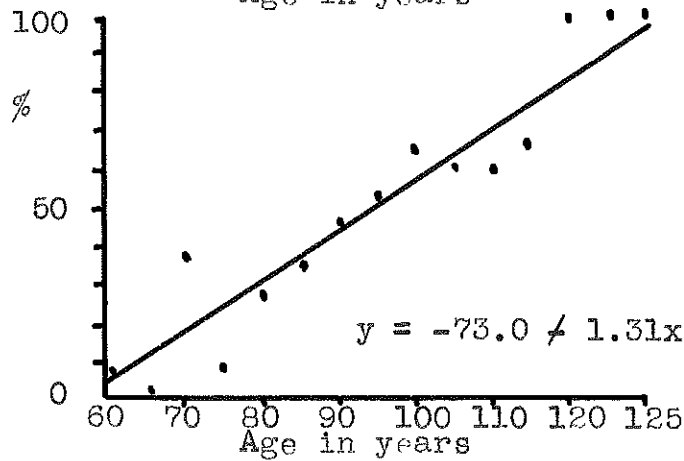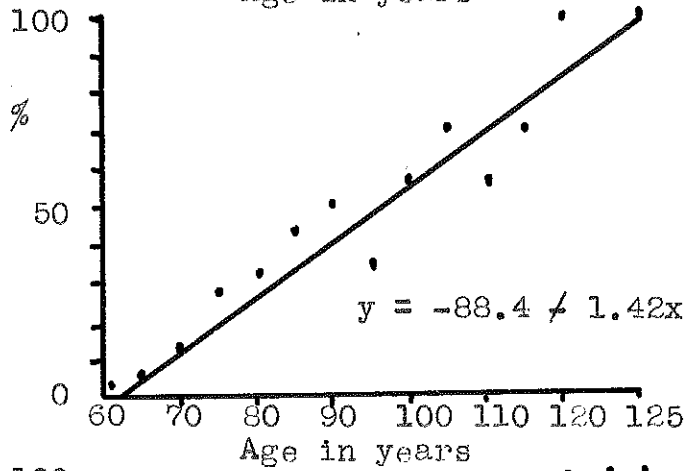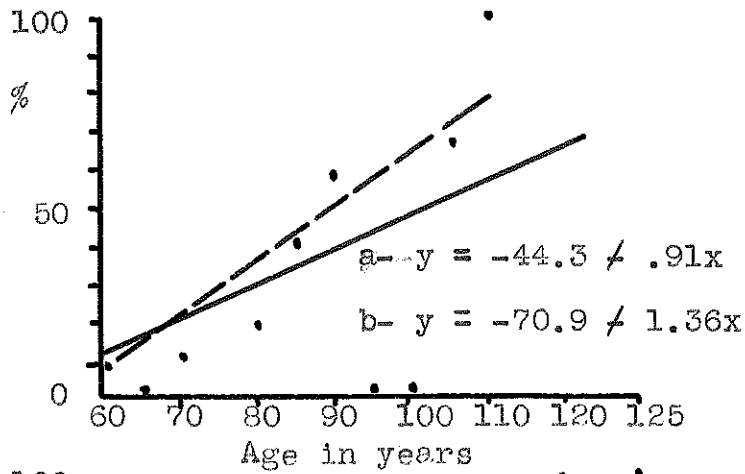
$y = -32.0 + 1.02x$

Figure 14 Effect of diameter on the age-shake relationship

a gradual slope of only 1.02.   Actually the scatter is so wide that a straight line relationship is not really justified in this class.   Unfortunately there are so few stumps in the survey above twenty inches that it is not possible to come to a conclusion about the effect of these diameters.   Apparently the incidence of shake is greater in trees more than twenty inches in diameter. With more samples the curves for these larger diameters might smooth out and become similar to the others.

If the age-shake relationships holds, the main difficulty in using diameter as a shake indicator is that the age-diameter relationship is very poorly defined in hemlock.   The habit of suppression makes it impossible to predict the age of a tree from its diameter.   Frothingham (1915) has shown this problem very clearly.   He recorded at twenty years of age trees from 0.1-4.0 inches D.B.H. and at 200 years of age trees from 4.9-39.5 inches D.B.H.   A five inch tree may be shaky (four six-inch shaky trees were recorded in the survey), but a twenty-six inch tree may be sound (six twenty-six inch sound trees were recorded in the survey).   The basic relationship seems to be between age and the incidence of shake.   At least, due to the fairly even-aged nature of hemlock stands, most of the trees in a hemlock stand of all diameters will have only about thirty years age difference.   In pure stands this difference may be somewhat less.

The Effect of Suppression

The writer was mainly concerned with seeing if a sudden release constituted a definite plane of weakness for the opening of a shake.   The change of properties at a release is quite sharp.   The amount of spring wood is suddenly increased and the density goes down.   Probably the fibers become

somewhat shorter.   After about a week of observation in the field it seemed
that although many shakes occur at a point of release a shaky, released tree
may not have a shake at that point.   The relationship between age and shake
holds regardless of the amount or severity of suppressions and releases.
Shaky trees with a small core of severly suppressed, dense wood most often
had a shake associated with the point of release.   Only observations on
releases were made, no data were taken.

DISCUSSION

In this survey the incidence of shake was found to be limited to the period from 60 to 125 years in the life of the tree. Other modifying factors, no matter how severe, do not increase this 65-year period. Winds of hurricane force, early frost or extreme cold have not caused trees under 60 years to be shaky; no tree has grown more than 127 years without becoming shaky. It is interesting to note in this respect that a theory postulated by Mayer-Weglin (1955) apparently does not hold in the case of shake in hemlock. He postulated that a ring separation may take place when a frozen tree is thawed quickly. The outer layers would expand around the frozen core and separation would take place. This type of shake would also occur at the outside first and then towards the center, not as in hemlock. The various non-selective factors of site such as wind, frost, and moisture have only secondary importance in the formation of shakes, although they may extend shakes that are already open. Diameter, the one selective factor considered beside age, may have an effect on the relationship of age to the incidence of shake. Trees with diameters over twenty inches may have a slightly higher incidence of shake at the same age than trees of less than twenty inches.

The internal stresses induced by fiber tension apparently cause shake in standing trees. Both Jacobs (1945) and the writer have demonstrated the presence of these tensions in hemlock. The progressive series of separation and maceration is a further indication that shakes are caused by tensions. There are two types of tension set up in the living tree. The longitudinal tensions compress the center of the tree. Boyd (1950c) points out that at the pressures involved (over 2000 pounds per square inch) the wood is compressed beyond its elastic limit. The cell must accomodate to the pressure

by "plastic flow" or actual irreversible physical changes in the cell structure. The plastic flow would change the properties of the cell wall and probably weaken the cells in the central portion. At the same time the radial tension tending to pull the rings apart is increasing with growth and time and is strongest in the weakened central portion. At some point the two factors combined will be sufficient to cause shake. It is interesting to note that shake occurs only in the central zone of compression where cell wall properties have been changed. As Boyd (1950b) points out, the largest radial tension that he measured, 150 pounds per square inch, was not sufficient to cause separation in normal wood. But as the center of the tree is compressed its properties may differ from those of normal wood and allow separation to take place.

Why eastern hemlock should so frequently be shaky and other trees not is not clear. Ring shake is occasionally, but infrequently, found in other conifers such as red spruce. The tensions that cause shake are apparently present in all trees. One would expect western hemlock (Tsuga heterophylla (Rafinesque) Sargent) to be subject to shake but it is not. The division between successive annual rings is particularly marked in eastern hemlock. The great contrast between spring and summer wood may set up a weak plane. Knots and compression wood are weaknesses common to all conifers. The habit of suppression does set up many areas where there are sharp changes in properties which would seem to be particularly susceptible to shake, but if there is no suppression the shake occurs anyway.

It is very unusual to have a marked change in a tree related to its total age. Most of the changes which do occur are related to the "physiological age" or age after release from suppression. Morriss (1948) finds

sexual maturity, butt rot, and budworm attack in fir related to the physio-
logical age.   In the case of shake in hemlock a year of suppression seems
to be just as significant as a year of free growth.   A few other changes in
hemlock appear to be connected with total age.   Bailey (1918) shows that
the increasing fiber length of coniferous wood tends to level out during the
period from 60-125 years.   Spurr and Hsiung (1954) indicate that at about
100 years the specific gravity of coniferous wood starts decreasing.   The
years from 60-125 may be crucial ones in the tree's development.   The changes
definitely take place, but are they related to total age, phisiological age,
or diameter?

Changes in fiber length may be closely connected with fiber tension.
Boyd (1950c) gives a good summary of previous hypotheses advanced to explain
fiber tension.   He shows that most of them are not valid.   He feels that
the most promising hypothesis is one advanced by Münch in 1938 in connection
with compression wood.   Münch postulated that there is a change of shape of
the fibers, a simultaneous decrease in length and increase in tangential diam-
eter after the cells have elongated completely.   Thus both longitudinal and
radial tensions could be the result of a single change of fiber shape.   If
all fibers undergo this change equally, then tension should be cumulative
with the number of cells and diameter.   Possibly most of the tension is con-
tributed by the summer wood.   If so, the suppressed portions of hemlocks,
which are mostly summer wood, would have high stresses and they would accumu-
late approximately with age regardless of the growth rate.

The changes of the central portion of the tree under compression may be
closely related to the amount of time the wood is under compression.   The
length of compression may be more important than the magnitude of the applied

compression.   If the changes in properties require a certain length of
time, then diameter increase alone, regardless of increased tensions, could
not effect the change.   When the changes begin to take place the radial
tensions which have been accumulating, possibly in the summer wood, would
be able to pull apart the weakened central portion.

SUMMARY AND STATEMENT OF PROBLEMS

Longitudinal compression and radial tension set up in the wood of standing trees seem to be the primary factors causing shake in hemlock. There is a relationship between the action of these factors and the total age of the tree. Shake occurs in all hemlocks sometime during the period from 60-125 years. The nature of the relation of age to the action of fiber tensions is not known. The 65-year span covering the incidence of shake may be closely connected with the observed leveling off of the increase in fiber length. A change in the shape of the fibers is at present the most logical explanation for the cause of fiber tension. As fiber length seems to be intimately connected with fiber tension one of the first problems seems to be to make sure that the leveling off of fiber length is related to age, as previous studies indicate, and not to diameter or the number of years after suppression. If the age-fiber length relationship holds, then the fact that the incidence of shake and the leveling out of fiber length occur in the same period would indicate that some connection exists between the two. The age relationship to the incidence of shake may be mechanical as suggested in the discussion, and merely depend on the passage of time for physical change and the accumulation of radial tension. It is difficult to see how such a relationship could influence the size of cambial initials or their elongation. If the relationship of the incidence of shake to age is due to the more basic relationship of fiber length to age, then two questions are raised: 1) what connection could there be between the leveling out of fiber length and the simultaneous occurrence of shake, and 2) what is the relationship between the age of the cambial initials and changes in their length or elongation? The whole question of the changes in the wood over time is raised. Most probably there are many physical and chemical factors interacting here.

APPENDIX

## Demonstration of Tensions in Hemlock

A tree was chosen that was straight and with as little taper as could be found. Following the technique of Jacobs, a plank was cut from the log using an axe and saw and leaving the ends intact (see photo). One-inch strips were laid out from each edge towards the center to parallel the annual rings. Two screws were set 100 inches apart in each strip and the distance between them measured to .005 inches. The strips were then cut off in pairs, one from each side of the plank, moving towards the center. (When the ends of the log were cut off there was no splitting as in Eucalyptus.) After each pair of strips was removed they were straightened and remeasured. The strips left uncut in the plank were also remeasured. The strips from the outside contracted and those from the inside expanded, indicating that the periphery was under tension and the center under compression. An interesting feature was that two strips on the outside had compression wood in them and did not contract but expanded. Apparently as compensation, the inner strip next to those with compression wood contracted a great deal so that the average of the three was a contraction. The data show a definite stress gradient from tension on the outside to compression on the inside. Longitudinal tensions are definitely present in hemlock.

To test radial stresses disks were cut and V's marked on them. Pairs of screws were set on opposite sides of the V's and the distances between them measured to .0005 inches with a dial gauge micrometer. The V's were then removed and the distances between the screws remeasured. In every case the distance between the screws decreased. The circular expansion was a fairly constant .004 inches per inch of circumference. The expansion

Determination of longitudinal stresses (All data in inches)

Strip No.	In stem	Strips 1 & 10 gone	Strips 2 & 9 gone	Strips 3 & 8 gone	Strips 4 & 7 gone	Out of stem	Change in length	
1	99.85	-	-	-	99.88	+.03	Compression wood
2	99.88	-	-	-	99.88	.00	
3	99.91	99.88	-	-	99.85	-.06	
4	99.92	99.91	99.93	-	99.91	-.01	
5	99.89	99.90	99.91	99.90	99.91	+.02	
6	99.80	99.83	99.84	99.83	99.82	+.02	
7	99.89	99.91	99.90	-	99.90	+.01	
8	99.91	99.94	-	-	99.92	+.01	
9	99.90	-	-	-	99.89	-.01	
10	99.94	-	-	-	99.92	-.02	

Diameter at butt of 14 foot log, 11.2 inches. Tapered to 10.0 inches
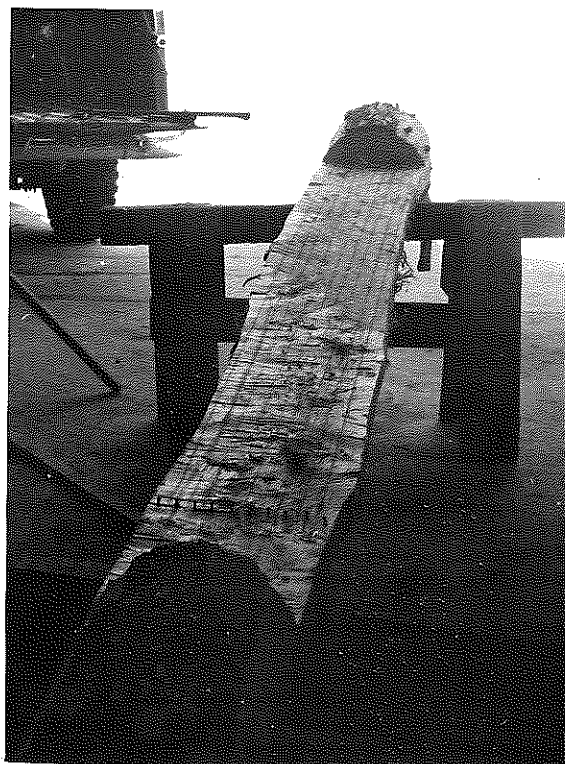
Demonstration log with strips marked before cutting

Disk no. 1

Pair	In	Out	Change	Radius inches	Expansion per inch of circumference
1	1.972	1.966	-.006	1	.002
2	1.492	1.468	-.024	2	.004
3	1.680	1.640	-.040	3	.004
4	0.767	0.715	-.052	4	.004
5	0.868	0.807	-.061	5	.004
6	0.902	0.827	-.075	6	.004

Disk no. 2

Pair	In	Out	Change	Radius inches	Expansion per inch of circumference
1	1.034	1.022	-.012	1	.004
2	1.641	1.624	-.017	2	.003
3	1.032	0.996	-.036	3	.004
4	0.656	0.610	-.046	4	.004
5	0.776	0.715	-.061	5	.004
6	0.793	0.728	-.065	6	.003
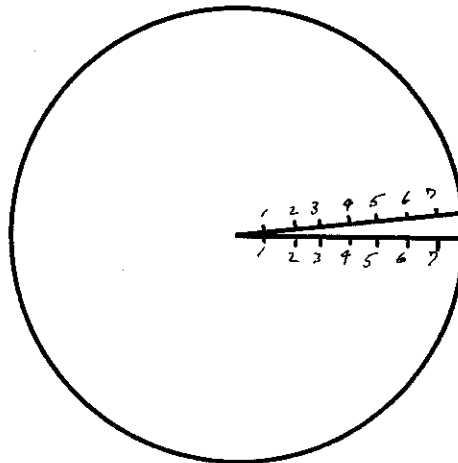
Diagram of setup for radial stresses

indicates that there is a circumferential compression present in the annual rings which would cause a radial tension. The compression is constant along the radius but the tension would be cumulative towards the center. Attempts to measure the radial tension directly by cutting out successive concentric circles and remeasuring fixed points were unsuccessful (see Boyd 1950b). Apparently the frequent knots cause very unequal expansions of the circles and the data are confusing. Jacobs also had difficulty working with conifers.

Effect of age on the incidence of shake

No. of sound trees (y-axis) vs No. of shaky trees (x-axis), for age groups: Up to 60, 66-70, 76-80, 86-90, 96-100, 106-110, 116-120, 125 and over.
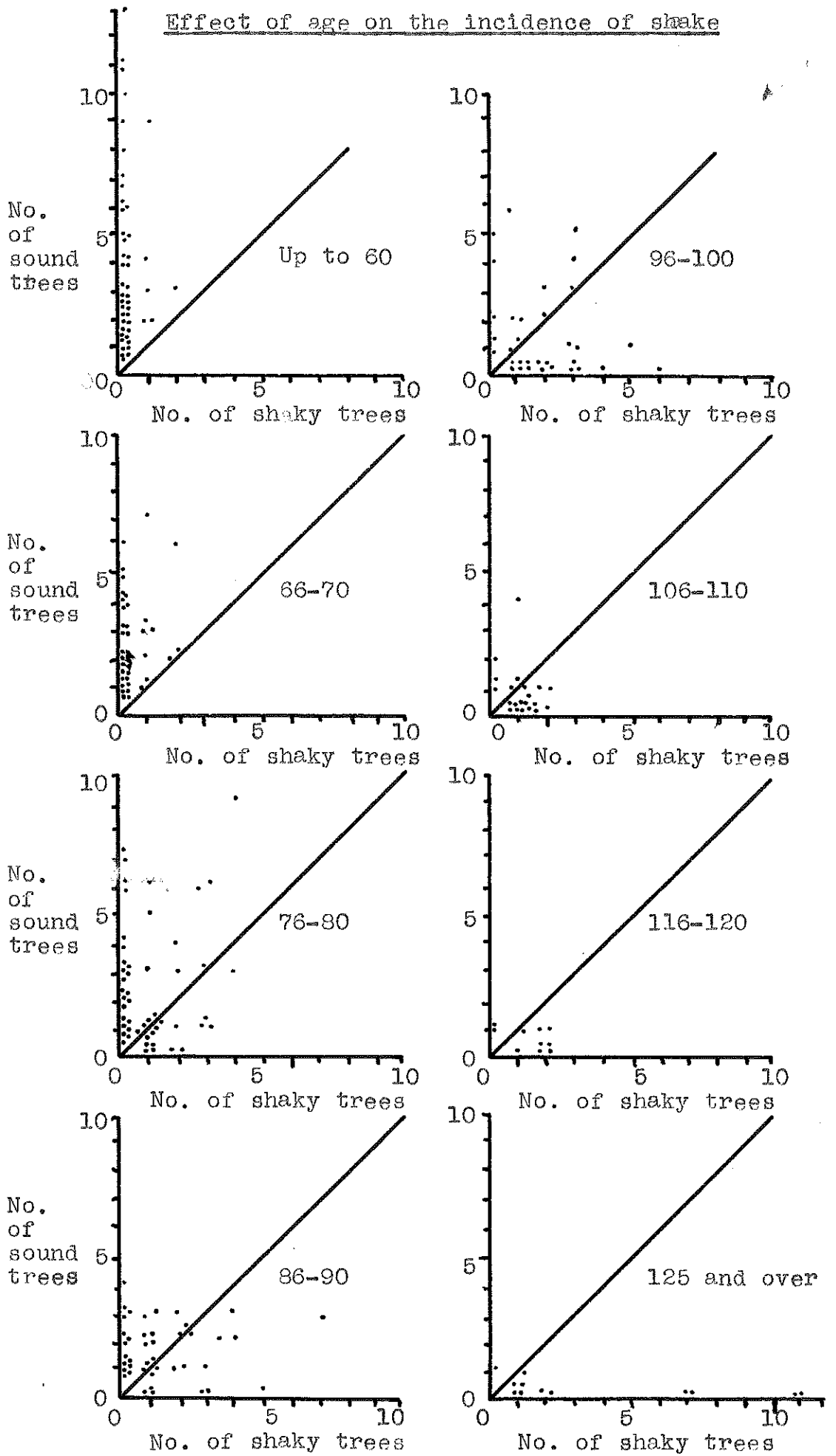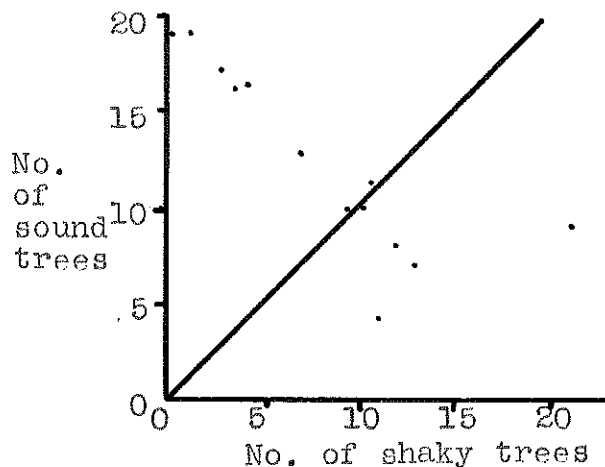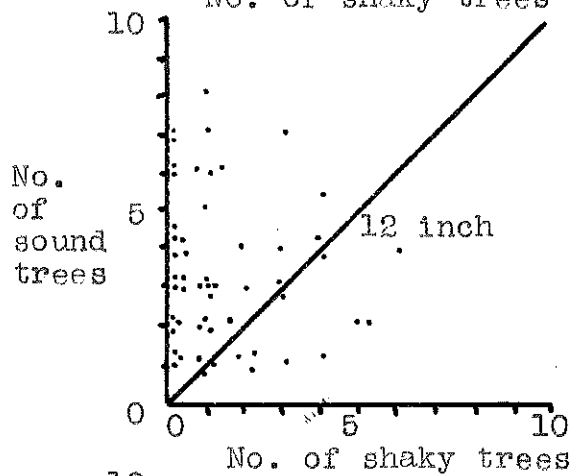
Class I

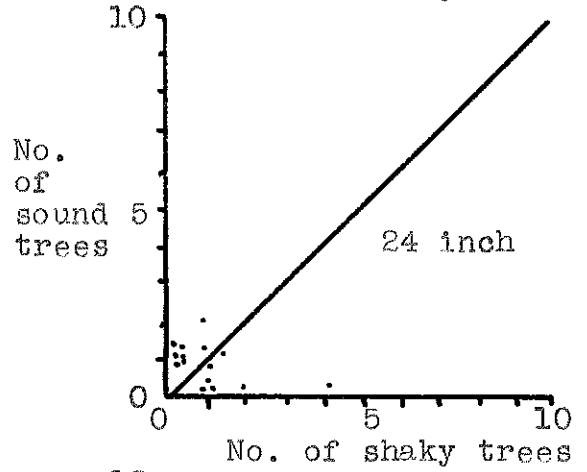Wet 0-8% slopes,
deep soil
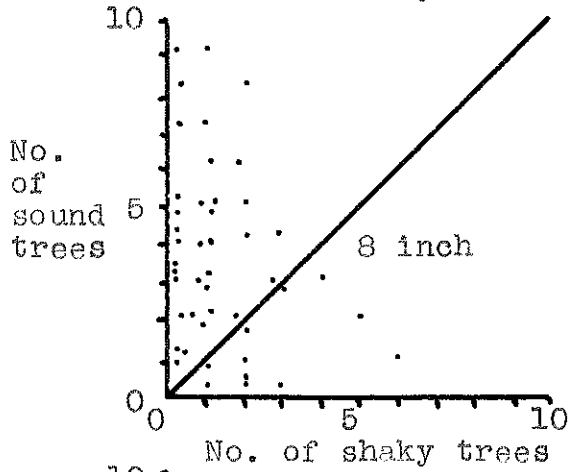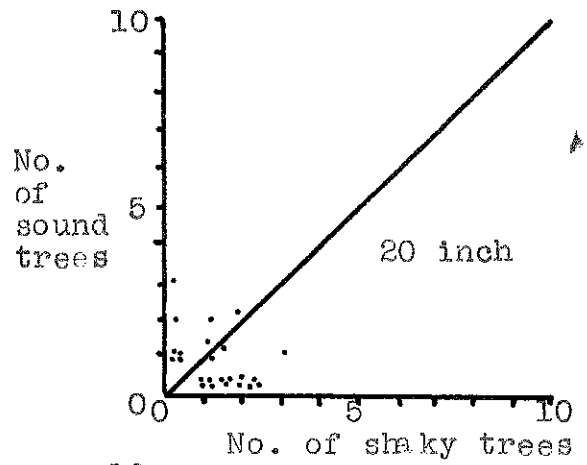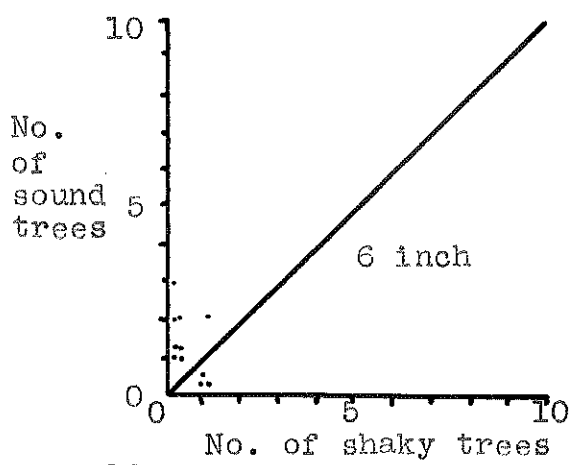on footslopes and
sidehills
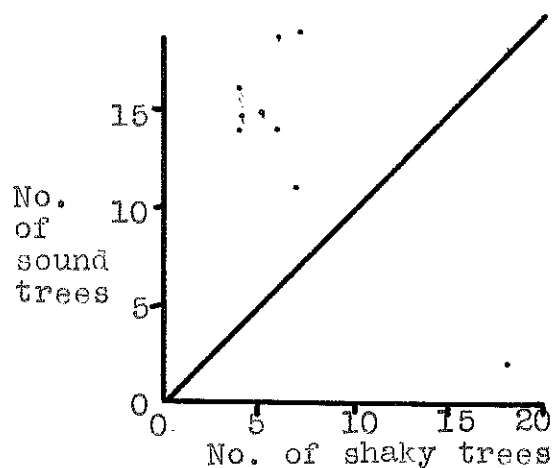
Class III

Intermediate 12-20%
slopes, deep and
shallow soil, facing
E, SE, S, SW, and W.
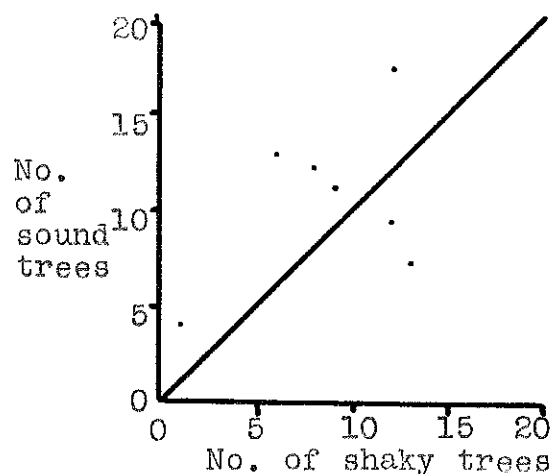
Class VIII

Dry 20-60% slopes
shallow soil
on noses, hill crests,
and convex sidehills

Effect of site on the incidence of shake

(Each dot represents one sample)

No. of sound trees (y-axis) vs No. of shaky trees (x-axis)

6 inch
20 inch
8 inch
24 inch
12 inch
28 inch
16 inch
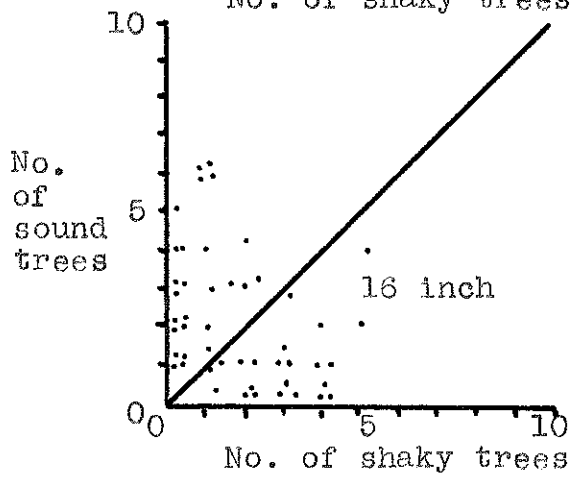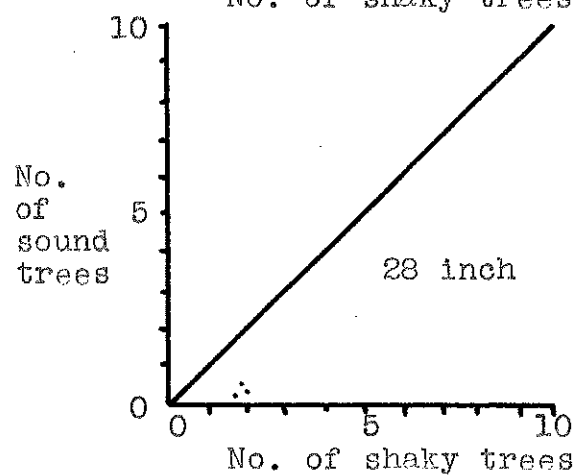
Effect of diameter on the incidence of shake

(Each dot represents one sample)

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