

THE MORPHOLOGICAL RESPONSES OF TREES TO
AVALANCHES: A COMPARISON OF ON-PATH
VS OFF-PATH RESPONSES

By

CARL LEON BRYANT

Bachelor of Science in Arts and Sciences

Oklahoma State University

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Thesis Approved:

John D. Vitek

Thesis Adviser

David R. Butler

Richard D. Hecock

Norman D. Muehman

Dean of Graduate College

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CHAPTER I

INTRODUCTION

Tree-ring data have been widely accepted as an accurate method to determine the dates of occurrence for a number of natural processes (Shroder, 1978, 1980). Dendrochronology, or tree-ring dating, utilizes the evidence from the annual rings of trees in a disturbed area are examined for scarring, bending, suppression and tension wood, along with other factors which are commonly present in the trees which border avalanche paths.

Whereas tree-ring dating has been the most widely used method for dating the occurrences of avalanches, other methods have been utilized. In many recent studies of snow avalanches, topographic maps and aerial photographs have been used to determine the location of avalanche activity (Butler, 1979a; Corner, 1980; Huber, 1982; Ives, 1976; and Luckman, 1978). While these aids provide a method of location, they are not precise enough to do any actual measurement of avalanche mechanics or to date occurrences. Additional methods include the annual inspection of the volume and rearrangement of debris slopes. Gardner (1979) used transects made of painted rocks to determine annual movements of the debris present in the avalanche zones.

Plant succession (Akifyeva, 1978; Khapayev, 1978) and lichen dating (Corner, 1980) have been used as dating techniques. These techniques examine the time it takes for an area to be recolonized

by vegetation or the removal and reestablishment of lichen or mosses from boulders in the disturbed area. Shroder (1978) pointed out that these types of dating are only approximate because rates of succession are highly variable and depend upon several controlling factors, including climate, altitude, exposure, and slope angle.

Whereas a vast amount of chronological work has been done, much more remains to be done in order to develop other methods and to refine those which have been used. Burrows and Burrows (1976) stated "...it is likely that, when better chronologies are available, they will add appreciably to our understanding of avalanche problems."

Statement of Problem

Tree-ring analysis has become an accepted technique to date and calculate the forces involved in a number of natural processes. Although tree-ring analysis is widely accepted in the studies of mass-wasting and avalanche processes, the accuracy of this methodology has yet to be tested. The question to be examined in this thesis is: Do differences exist in the morphological responses of trees that occur in and near an avalanche path and those that are located off the actual avalanche path but in close proximity to those affected by avalanches? The concept that the growth rings of trees, which are tilted and scarred on the borders of the avalanche paths, are actually different than those which are further removed has not been tested.

The focus of this thesis is to compare the morphological responses in trees which are located on or border an avalanche path with the responses in the trees that are located off the avalanche path. Creep, wind, and other forces acting on each sample may contribute to noticeable

impacts on the tree-rings. Comparisons will be made of the trees located on the avalanche path with those located off the path for both the low angle runout zones of the paths and the steep up-slope sections of the paths. The paths to be examined are all similar in that each path follows a west to east direction and each path is confined to a gulley, as described by Burrows and Burrows (1976).

Justification of the Problem as Important in Geomorphological Research

Numerous studies of avalanche paths have utilized the evidence of occurrence as found in the reaction wood in tree-rings of those trees located on the avalanche path. Reaction wood is the product of the plant process which attempts to orient the plant to the vertical. Two basic types of reaction wood occur in response to gravitational force. Compression wood is commonly, if not always, present in the wood of conifers. Tension wood is the name most commonly applied to the reaction wood found in angiosperms. Compression wood develops on the lower side of lateral branches (Sinnott, 1952), on the lower side of any part of a coniferous tree that is inclined from the vertical plane (Scott and Preston, 1955), below various crooks and deformations of the trunk and on the leeward side of trees exposed to strong prevailing winds (Spurr and Hyvarinen, 1954). Comparison of cross-cuts should reveal that in compression wood (conifers), the pith is nearest the upper side and in tension wood (angiosperms) the pith is nearest the lowest side. These morphological responses in trees affected by snow avalanches can be used to date the occurrence.

Burrows and Burrows (1976) describe a complete procedure for the use of the morphological responses in trees to date the occurrence of avalanches. Many studies have utilized these guidelines and similar practices to date the occurrences of avalanches (Potter, 1969; Ives et al, 1976; Butler, 1979a, 1979b; Carrara, 1979; Shroder, 1976, 1978, 1980). In none of these articles, or others which deal with the use of tree-rings for dating the occurrence of avalanches or other similar events, has it been proven that the morphological responses which commonly occur in the trees on the path are significantly different than in the trees off the path. Conclusions which are derived from the analysis of the annual rings of damaged trees depend on the presumption that a difference does exist in the dates of responses in trees affected by natural events and the dates of responses in trees affected by avalanches. The focus of this research, therefore, is to examine the morphological responses in the trees located on-path or bordering the path and those which are located in the same general slope but not directly affected by the occurrence of avalanches (Figure 1).

Description of the Study Area and Each Path to be Examined

The study area is located on the east slope of the west ridge of the Huerfano Valley, Colorado (Figure 2). The Huerfano Valley is located directly north of Blanca Peak in the Sangre de Cristo Range of south central Colorado. The elevation of the area lies between 3,000 meters (10,000 feet) and 4,000 meters (13,000 feet) above sea level. The last known large-magnitude avalanche occurred in 1973 on the southern-most path to be examined. This path is informally known as

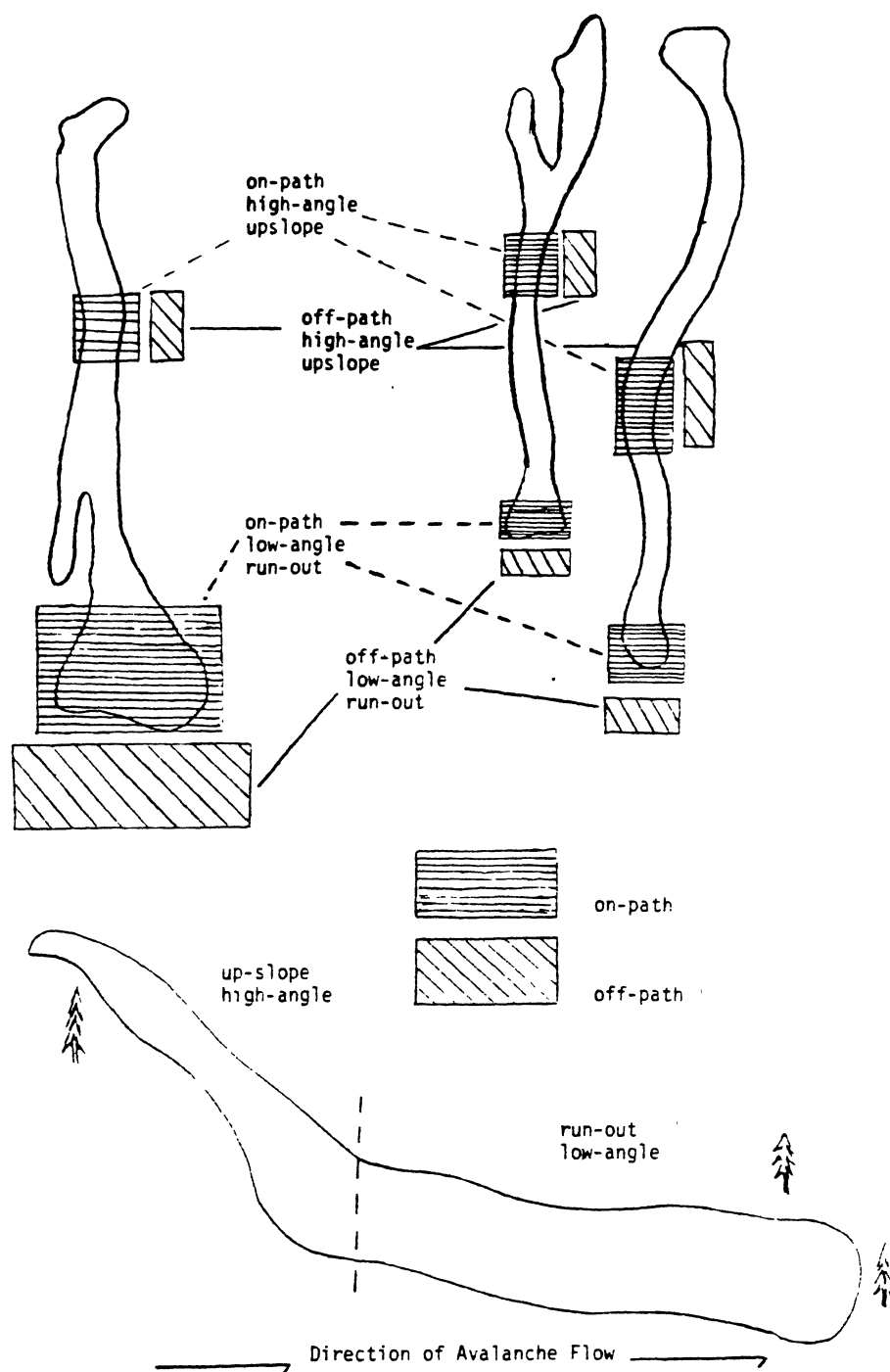


Figure 1. Showing Locations of Sampling Along Avalanche Paths

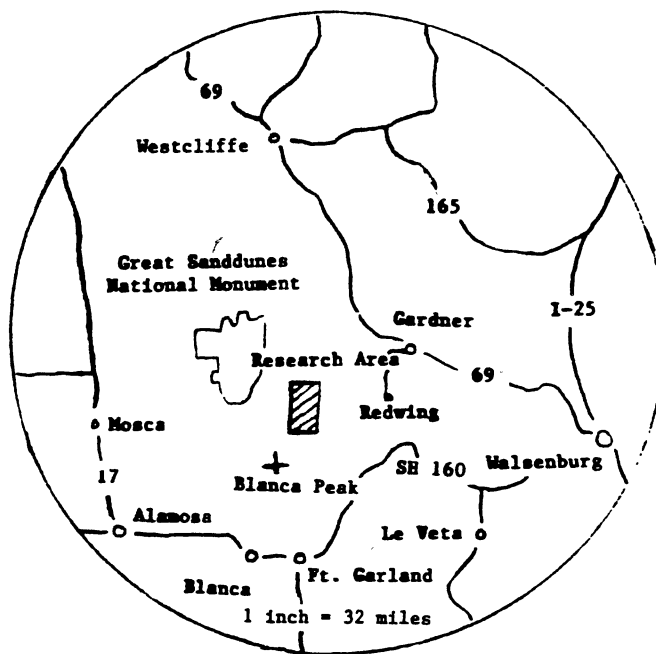
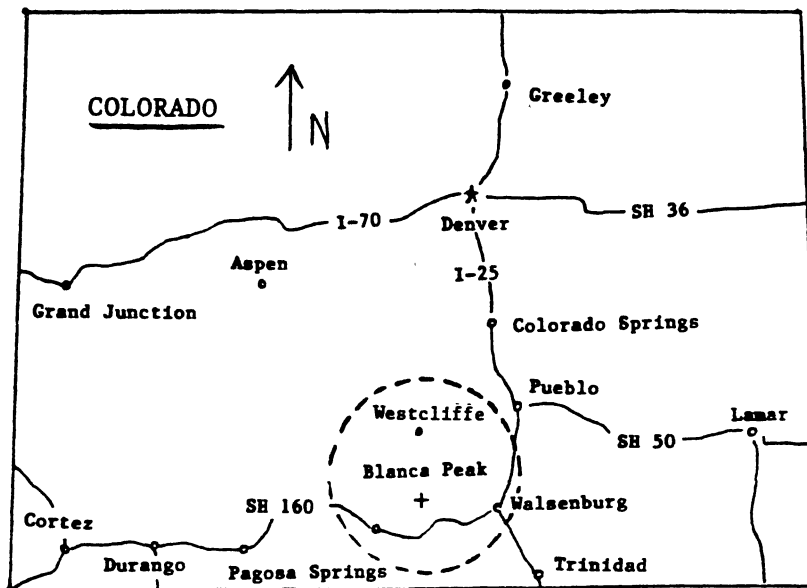


Figure 2. Research Area: Location in South-central Colorado

the Campsite Avalanche (Salisbury, 1983). The most common tree species in the study area, Aspen (*Populus tremuloids*), Englemann Spruce (*Picea Englemanni*), and Blue Spruce (*Picea pungens*), will be examined for morphological responses.

This study will utilize tree-ring samples taken at locations on the steeper angle, up-slope regions and the more gentle angle, run-out zones of three snow avalanche paths in the Huerfano Valley. These paths are located on the east slope of the west ridge near Montez Reservoir and Sheep Ridge (Figure 3). These paths were chosen because of the similarity in size and magnitude of avalanche that occurs on them. They are also similar in slope angle and aspect. The "Campsite" path is greater in length than the two paths located to the north, but the slope angle and aspect are similar. The slope aspect variable must be considered because of its significant impact on the growth characteristics of the trees. For ease of identification in this thesis, the northernmost path will be identified as the "alpha" path, the next path to the south will be "beta" path, and the path located furthest south will be referred to as the "campsite" path (Salisbury, 1983).

Alpha, the northernmost path lies parallel to the Beta path. These paths are located to the south and west of Montez Reservoir and northeast of the intersection of the Huerfano Pack Trail with the Alamosa/Huerfano County Line (Figure 3). Alpha path has a linear distance of approximately 900 meters (3,000 feet) and a vertical drop of approximately 330 meters (1,100 feet). Beta path, slightly shorter with a linear distance of approximately 790 meters (2,600 feet), has a vertical drop of approximately 300 meters (1,000 feet).

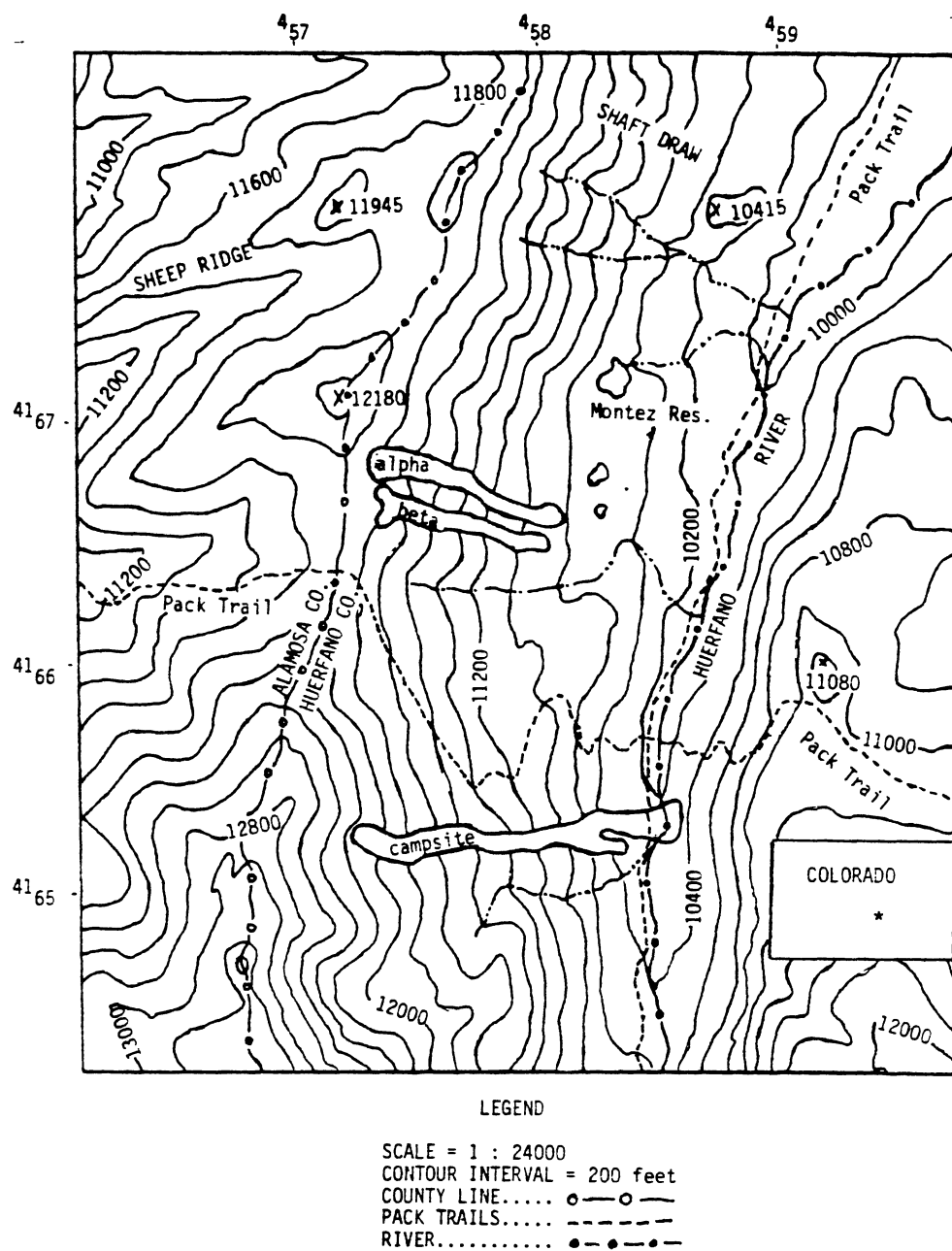


Figure 3. Research Area: Location of Avalanche Paths Examined in Research Area

The Campsite path is located south of the Huerfano Pack Trail and south of the Alpha and Beta paths. Its source area is 180 to 250 meters (600 to 800 feet) below the west ridge at an elevation of 3,660 to 3,780 meters (12,200 to 12,600 feet) and follows a path to the east, crossing the main axis of the valley at the Huerfano River. This path is considerably longer than Alpha and Beta path, covering a linear distance of approximately 1,575 meters (5,200 feet) and a vertical drop of approximately 600 meters (2,000 feet) (Figure 3).

CHAPTER II

DEFINITION OF REACTION WOOD

Reaction wood is the product of the morphological response which attempts to orient the plant to vertical. The two most commonly studied orientation responses are geotropism, the response to gravity, and phototropism, the response to the direction of available light (Figure 4). Ray (1972) points out that the study of these responses led to the knowledge that plant growth is influenced by hormones and helps to explain how plants regulate and control development.

Anatomy of Reaction Wood

The product of the morphological response in trees is reaction wood. Compression wood and tension wood are quite similar, in that they respond to correct any variations in the vertical position of tree growth. While they serve a common function, they also exhibit differences in their anatomy. As mentioned earlier, compression wood is found in angiosperms. Reaction wood is also found in other plant types which lack woody cells (Meylan, 1981; Minz, et al., 1981).

Reaction wood is characterized by the presence of fewer and smaller vessels than normal wood and a corresponding increase in the proportion of fibers which are thick walled. In conifers, it consists of a thickening and shortening of the lower side of a leaning stem. In angiosperms, it consists of an exaggerated thickening of the walls

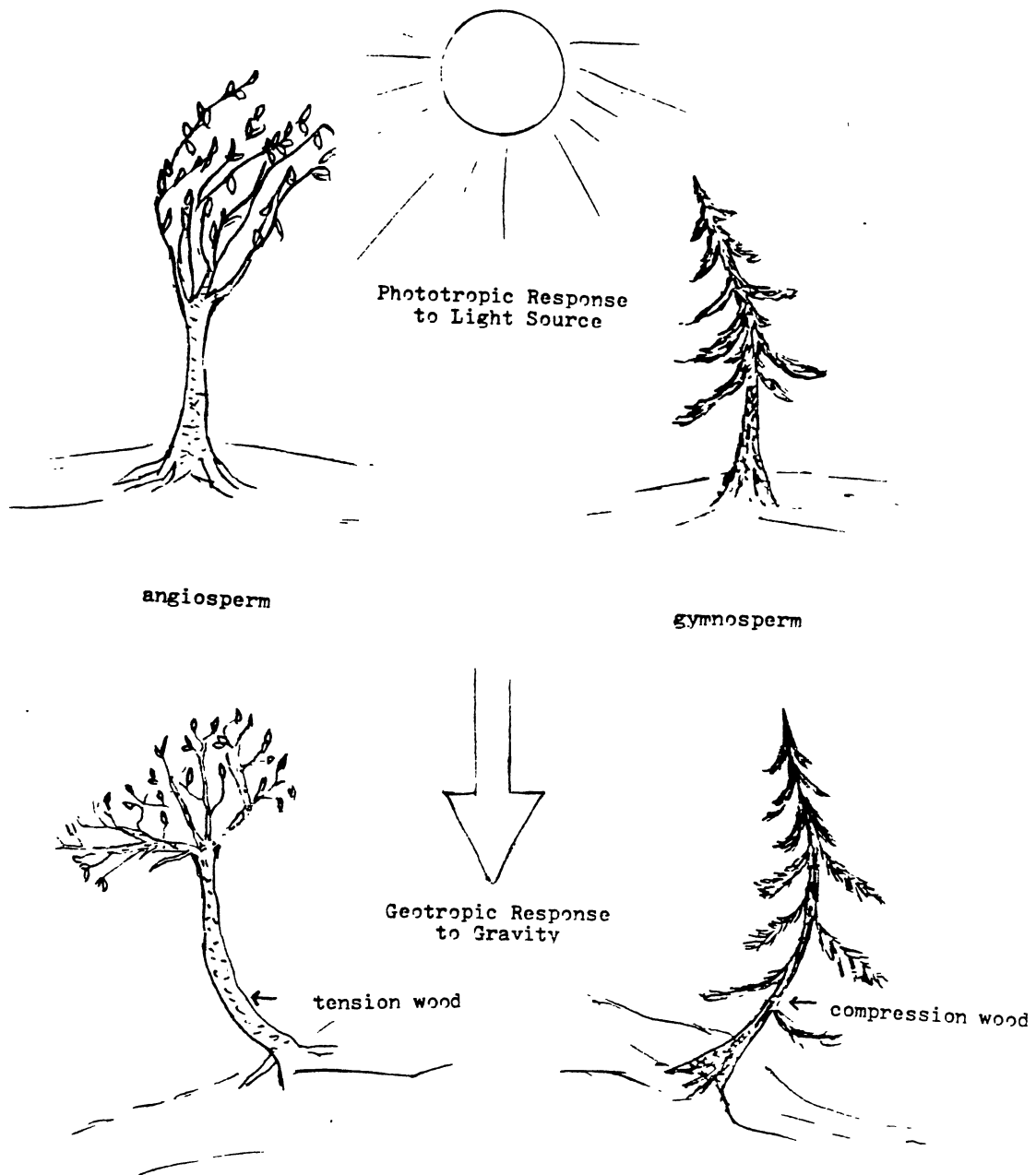


Figure 4. Comparison of Geotropic and Phototropic Responses

of the fibers on the upper side of a leaning tree (Figure 5) (Leopold and Kriedmann, 1975). In conifers, reaction xylem may occur in the early wood and late wood and may extend over more than one growth ring. In angiosperms, the reaction wood is mostly developed in the early wood and does not extend to the last-formed cells of the late wood (Wardrop, 1959). Reaction wood always has a much higher content of gelatinous fibers than normal wood. In tension wood of angiosperms, the innermost part of the wall is unlignified and is relatively thick and gelatinous in appearance. Compression wood is extremely rich in lignin and poor in cellulose. In both types of reaction wood the amount of mobile water is less than in normal wood which contributes to the varied changes in longitudinal lengths between the reaction wood and normal wood. In most cases the formation of reaction wood causes a circumferential variation in ring width, whole-ring traced length and whole-ring specific gravity (Jain and Seth, 1980).

Geotropism and Orientation of Reaction Wood

Tropisms are movements caused by differences in the intensity of environmental factors such as light or gravity, which are applied in greater intensity to one side of a plant structure than to the other side. Eccentric growth and formation of reaction wood tends to correct the displacement, and concentric growth gradually resumes (Degraff and Agard, 1984). Geotropism is the tendency of stems to grow upward and roots to grow downward. Phototropism is the tendency of the stems to bend toward the light. Both of these tropisms result in the eccentric

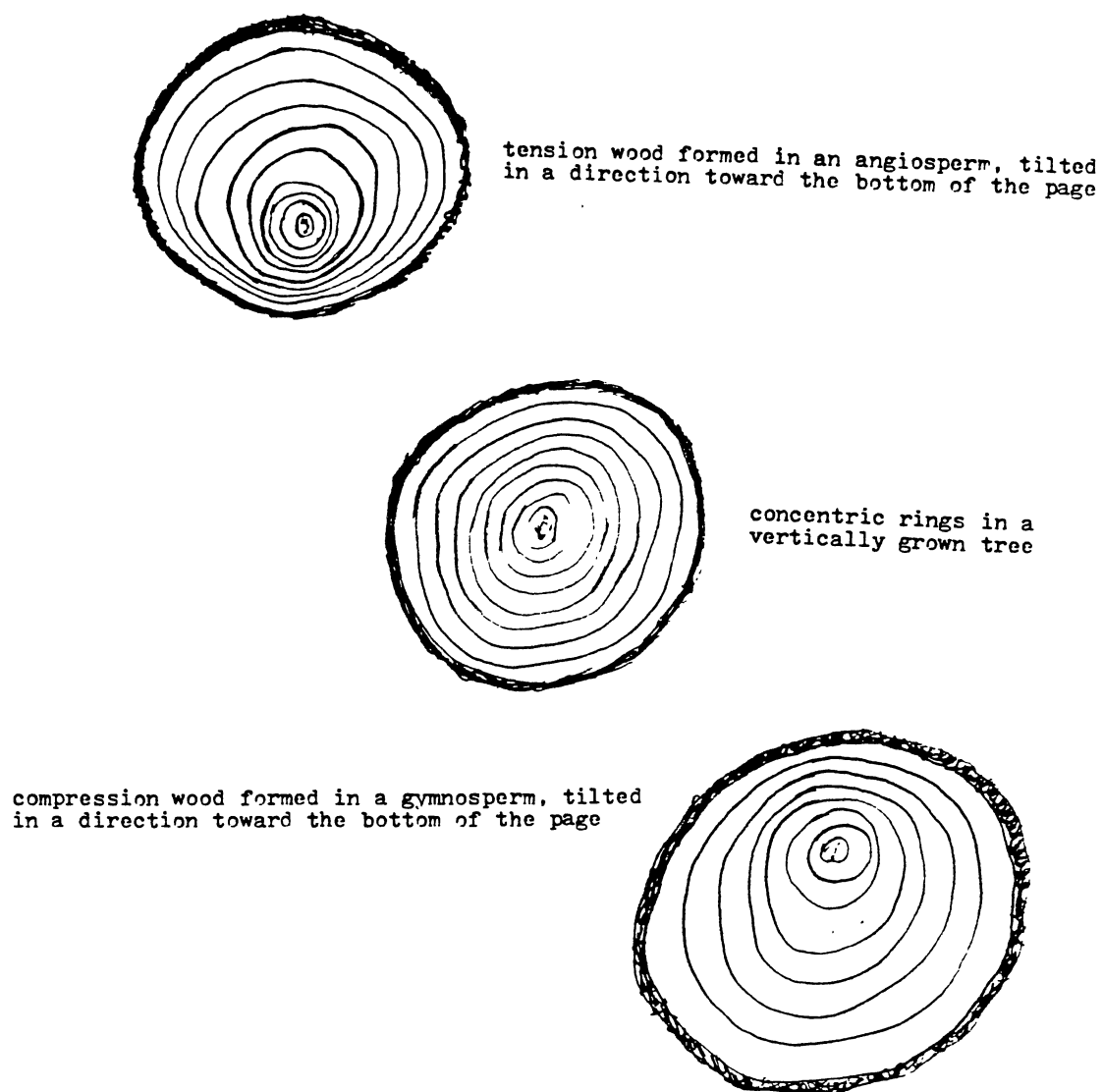


Figure 5. Comparison of Reaction Wood: Crosscuts for Angiosperm Compared to Conifer

growth and formation of reaction wood. Because phototropism is not very important in the orientation of a tree crown or mature stem (Wilson, 1970), it will not be considered in this study.

Geotropism appears to be caused by unequal distribution of auxin, in this case unequal distribution between the upper and lower halves of horizontally oriented stems and roots. The greater concentration of auxin tend to occur in the lower halves of horizontally placed stems and roots. This in turn stimulates the cell elongation on the undersides of stems, causing them to grow upward. High concentrations of auxin inhibit elongation of root cells, causing the lower sides to grow more slowly than the upper sides and causing the root to bend downward (Kramer and Kozlowski, 1960). Wilson (1970) notes that the root and shoot appear to have a receptor that can detect the stimulus of light or gravity.

Gravity is known to affect the distribution of auxin. Auxin was first isolated by Fritz Wentz in 1927 when he investigated why plant shoots were affected by light. It was later identified as indoleacetic acid (IAA). Because gravity affects the distribution of auxin (IAA) in various plant organs, it is not surprising that the formation of reaction wood on the upper or lower side of a branch or leaning stem should be related to the presence of more or less IAA in these regions. Test by Wershing and Bailey (1942) conducted on soft wood seedlings treated with IAA found that tracheids developed similar to those of compression wood. Wardrop and Davies (1964) extended this experiment by using gibberellic acid (GA), another growth regulator, separately and combined with IAA, to get similar results. Onaka (1949) induced the formation of compression wood with IAA and NAA, where NAA

(naphthalene acetic acid) is a synthetic auxin-like substance. He found that the auxin concentrations were higher on the lower side of leaning conifers than on the uppersides.

Necessany (1958) induced compression wood formation in upright stems of conifers with the use of IAA and found that the normal formation of tension wood in the stems of angiosperms could be suppressed by auxin treatment. The idea that auxin treatment may cause the formation of compression wood and suppresses that of tension wood suggests that compression wood is produced in regions of relatively high auxin concentrations and tension wood is formed in circumstances of auxin deficiency. Additional supporting evidence came from the work of Crenshaw and Morey (1965) and Kennedy and Farrar (1965), who showed that the application of 2-3-5-tri-iodobenzic acid (TIBA) a recognized anti-auxin, induced tension wood formation.

Cambial Growth and Scarring

The cambium is the area where tree growth takes place. Cells of the cambium divide and subdivide, with the inner cells producing the xylem and the outer cells forming the phloem or inner bark. With time, the inner bark changes to the outer bark which serves two functions: (1) it prevents water loss, and (2) it protects the tree from mechanical injury such as a hard blow or fire damage (Sharpe et al, 1976).

Auxin is known to play an important role in the growth of vascular cambium. The stimulation by auxin promotes cell division rather than simple cell elongation, as with reaction wood. Because of the downward movement of auxin in the trees vascular system, auxin tends to

accumulate just above any site of damage in the stem and root system (Ray, 1972). Following damage to the cambial layer, the tree attempts to reproduce the cambium. The presence of auxin causes rapid cell multiplication which produces a rather disorganized mass of cells called a callus. The development of this callus gives evidence as to the year in which the tree was damaged by impact.

When avalanches cause the bending of a tree stem away from vertical, the force exerted by the blast of the avalanche along with the debris which is present will cause a pronounced scarring of the cambial layer (Allix, 1924; Mears, 1975, 1980). This results in a scar which is evident in the cross cut sections of the tree. As the tree attempts to replace the damaged cambium, annual rings are gradually added over the scarred area. By counting these newly deposited annual rings, from the present years growth to the scar or reaction wood, one can accurately date the occurrence of the event (Burrows and Burrows, 1976). Because scarring is sometimes accompanied by bending of the tree from the vertical position, reaction wood is commonly present at the same locations as the scar (Figure 6). The presence of reaction wood can reconfirm the date of the scarring and therefore the date of the occurrence of the avalanche when examined. Potter (1969) notes this method is a reliable method of dating avalanche occurrence, therefore, it will be the method used in this thesis. Without these detectable physiological responses, the science of dendrogeomorphology as described by Shroder (1978, 1980) and Alestalo (1971), would not be possible.

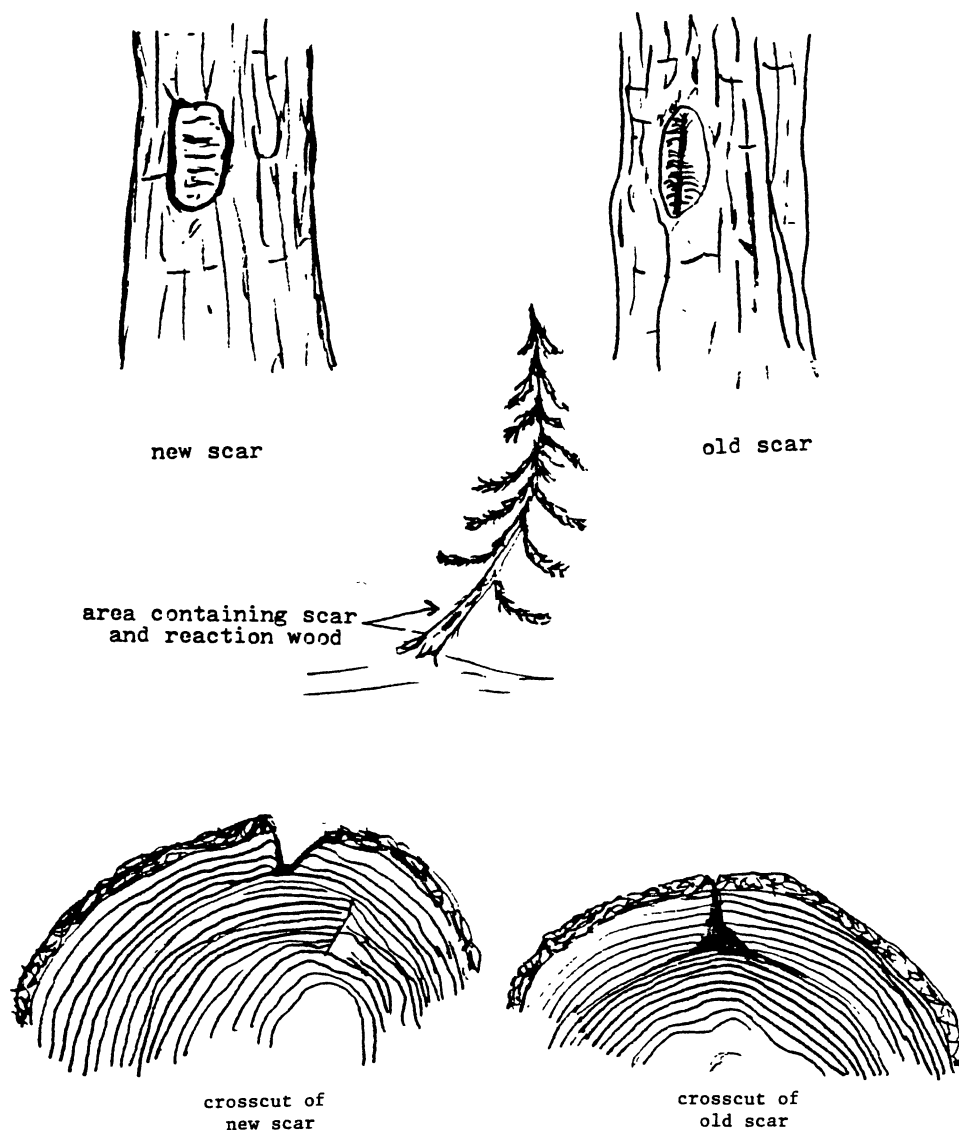


Figure 6. Illustration of Scars and Annual Rings

CHAPTER III

REVIEW OF RELATED LITERATURE

Dendrochronology and Tree-Ring Analysis Related to Avalanching and Mass Wasting

Reaction wood has proven to be a useful tool in dating the occurrence of a number of natural processes. In the studies which utilize tree-ring data, the trees in a disturbed area are examined for scarring, tilting, compression and tension wood, and other factors which are commonly recorded by the annual growth rings. The use of annual growth rings to date natural events has been accepted and utilized to collect event-response data for many events (Shroder, 1978, 1980).

Dendrochronology and tree-ring analysis has been used to reconstruct past events such as fluctuations in glacial activity (Cooper 1931, 1939; Lawrence, 1950, 1958; Luckmann and Osborn, 1979), mass movements (Butler, 1979b; Clague and Souther, 1982; Hupp, 1983; Giardino et al, 1984; Oelfke, 1984) and snow avalanches (Akifyeva et al, 1978; Butler, 1979a, 1985; Butler and Malanson, 1985a, 1985b; Carrara, 1979). Other processes studied, utilizing dendrochronology and tree-ring analysis are flooding (Butler, 1979b; Yanowsky, 1982), volcanic activity (Heath, 1959, 1960; Oswalt, 1957), and fires (Heinselman, 1973; Tande, 1979; Romme, 1982; Arno and Gruell, 1983). Because the growth processes of woody plants naturally record evidence

of the dates and intensity of disturbances in an area, they have been used to reconstruct events such as avalanches in remote locations where other types of observations are not feasible. Potter (1969) concluded that evidence from reaction wood and scars were the most reliable morphological responses for dating avalanche activity.

Tree Ring Analysis as a Methodology to
Reconstruct Years of High Magnitude
Avalanche Occurrences

The use of reaction wood and scar data from avalanche occurrences have proven to be the most accurate means of dating these occurrences. The dating of avalanche occurrences requires the taking of core-samples with the use of an increment borer or by taking cross-cut sections from damaged or tilted trees. Under normal conditions, the main stems of trees have more or less concentric growth rings (Figure 6). As noted by Degraff and Agard (1984), a certain amount of eccentric growth occurs in any tree. If tilting occurs, they tend to respond by a curvature of the actively growing part of the stem which brings the long axis of the tree back to a near vertical position (Figure 5). In the wood an often well-marked band of reaction wood is produced, resulting in growth rings which are wider than normal on one side. The leaning tree acquires an eccentric cross-section in contrast with the normal concentric rings (Pillow and Luxford, 1937). In conifers, the eccentricity results from the formation of wider rings, normally on the downslope side of the stem. In angiosperms such rings are usually present on the upper side of the stem. By counting the annual rings inward from the present years growth to the point where the

reaction wood first appears, precise dating of the tilting event can be achieved (Burrows and Burrows, 1976). Accurate dates can be derived by using the same method to date scars from impacts to the tree stem.

Wood types, such as spruce, sub-alpine fir, or oaks, generally produce well defined annual rings while some angiosperms such as aspen and maples have vessels of relatively small diameter, dispersed diffusely and uniformly through each annual ring. Species like oak, however, have vessels of very large diameter in the early-wood and vessels of small diameter in the late-wood which is characteristic of ring-porous species (Kramer and Kozlowski, 1960, 1979). The diffuse porous species, such as aspen and maples, generally have wood in which it is difficult to count annual rings. Tujill (1975) recommends staining the sample with a four percent solution of pentachlorophenol in a solution of kerosene after shaving freshly obtained cores and thoroughly drying them followed by a second drying. The ring-porous species (conifers) generally require only sanding to a smooth finish to easily observe the annual rings.

CHAPTER IV

PRESENTATION OF THE DATA

Description of the Study Area and the Characteristics of Each Data Collection Site

The avalanche paths to be examined are located in the Huerfano Valley directly north of Blanca Peak in the Sangre de Cristo Range of southcentral Colorado. These three paths are located on the east slope of the west ridge near Montez Reservoir and Sheep Ridge (Figure 3). They are similar in size, slope angle, and aspect. The upslope areas of the Alpha and Beta paths were heavily damaged by fire. The best estimate of the year in which this fire occurred was from two samples that showed evidence of fire in 1955. Revegetation of the mid-zones was primarily by aspen (*Populus tremuloids*). A greater number of Englemann spruce (*Picea englemanni*) and blue spruce (*Picea pungens*) were present further up-slope and increased toward the on-path zone. The run-out zones for both paths were densely vegetated by aspen with very few spruce present. A large proportion of the samples, therefore, were collected from aspen. In the on-path run-out zones of both paths, many blown-down aspen were present. These paths are crossed by an artificial water channel which directs snow melt

to a stock watering pond. Care was taken to avoid sampling trees which may have been damaged during the construction of this channel.

The Campsite path is located south of Alpha and Beta paths. The species in the on-path zone were a mixture of aspen (*Populus tremuloides*), Englemann spruce (*Picea englemanni*) and blue spruce (*Picea pungens*) with the spruce being more common here than on Alpha or Beta paths. The aspen became more dominant as the distance away from the on-path zone increased. A road bisects the path at the beginning of the run-out zone and the Huerfano River crosses the path near the end of the run-out zone. Samples were taken only on the west side of, and some distance from the river because of the difference in slope aspect on the east side and to alleviate the possibility of sampling trees scarred from flooding which occurs in the area.

Data Collection

Collection of data involved the gathering of cross-cuts and core samples from each of the distinct zones on all paths (Figure 1). These include on-path and off-path zones in the higher angle upslope zones and on-path and off-path zones in the lower angle run-out zones. All samples were taken during August, 1983 and June, 1984. To maintain uniformity of slope aspect with regard to incoming solar radiation, a total of 180 samples were taken from only the south-facing slope of the avalanche paths. The designation between the on-path and off-path zone was made by taking off-path samples from areas well removed (20 to 25 meters) from the area actually affected by the flow of debris in the avalanche chute. A random sample of the most notably scarred and bent trees was acquired by taking cross-cuts and core samples from

damaged trees which lay parallel to each path in the on-path zones. Sampling in the off-path zones was done by throwing a weighted marker from one sample area to another and sampling affected trees in a 20 foot radius. The data recorded for each sample included: slope angle, slope aspect, direction of impact, species, height of samples, diameter of scar, diameter at breast height, evidence of trimming, and evidence of clastic tools.

Because of the population of the vegetation in the area, the greatest percentage of the samples were from aspen. Samples from the Campsite path consisted of 36 aspen and 24 spruce, Alpha path had 48 aspen and 12 spruce samples, and Beta path had 50 aspen and 10 spruce samples (Table I). A total of 134 aspen and 46 spruce samples were collected for this comparison of the dates of morphological responses to the avalanches occurring in the study area. It is important to note that a number of the trees sampled were not scarred but were notably tilted from vertical and showed evidence of geotropic response. This was particularly true with many of the aspens sampled. The sample population consisted of trees that were at least 15 years old.

Preparation of the samples involved several steps. The samples were air dried and stored to prevent the growth of mold which tends to occur with the cross-cut samples. Second, they were oven dried at a temperature of 100° C for a period of approximately 72 hours. After drying, the samples were sanded to reveal the annual rings and corresponding impact scars or reaction wood, as described by Burrows and Burrows (1976). For aspen samples, a second sanding was often necessary because the annual rings were too narrow to differentiate between one another.

TABLE I
RATIO OF ASPEN TO SPRUCE SAMPLES
FOR EACH PATH WITH TOTALS

	Campsite	Alpha	Beta
On-path	8:22	22:8	22:8
Off-path	28:2	26:4	28:2
Totals	36:24	48:12	50:10

Dating the samples involved counting the annual growth rings inward from the latest year's growth to the growth ring which corresponded to the scar or reaction wood which was present for each sample. The spruce samples could generally be dated without the use of any magnification except for those samples having a small diameter. Unlike the spruce samples, the aspen samples require the use of a stain to highlight the annual growth rings and the use of magnification to differentiate between them. The inability to date the aspen samples in the field insures the lack of any bias in sampling. The samples were stained with a solution of 4 percent pentachlorophenol wood preservative mixed with mineral spirits after shaving the sanded surface to assure that the rings could be counted accurately as described by Trujillo (1975).

Data Analysis

A large number of the samples showed some form of morphological response occurring in 1973. The total on-path samples showing scars or reaction wood in 1973 was 52 compared to 18 for the off-path samples. Alpha and Beta paths each had 14 on-path samples showing response dates in 1973. Alpha path had four on-path samples with response dates in 1969 and Beta path had four on-path samples with response dates in 1977. Campsite path had no notable response dates except for 1973 which corresponds to observations by Salisbury (1983).

The date of 1973 in the samples was used to determine if a significant difference occurred between the reaction dates recorded in on-path and off-path samples for each of the paths. Because a low number of samples were acquired for comparison, the Chi-square statistic was derived from Contingency Table Analysis. All comparisons were tested at a 0.01 level of acceptance meaning that a 99 percent probability of making the correct interpretation exists. Fifteen samples were collected in each zone with 60 samples acquired for each path (Table II).

Three comparisons were assessed with the data represented in Table II. These included:

1. Comparison of all four zones for each path examined (Figure 7a).
2. Comparison of the totals of all four zones for each of the paths examined (Figure 7b).
3. Comparison of the total on-path samples with the total off-path samples of all three paths combined (Figure 7c).

Each comparison assessed the null hypothesis that no significant difference exists between the date of morphological responses caused

TABLE II
 NUMBER OF SAMPLES WITH MORPHOLOGICAL RESPONSES IN 1973
 N=15 SAMPLES FOR EACH ZONE

	Off-Path	On-Path
"Campsite Path"		
Up-Slope	3	11
Run-Out	3	13
"Beta Path"		
Up-Slope	2	5
Run-Out	4	9
"Alpha Path"		
Up-Slope	5	9
Run-Out	1	5

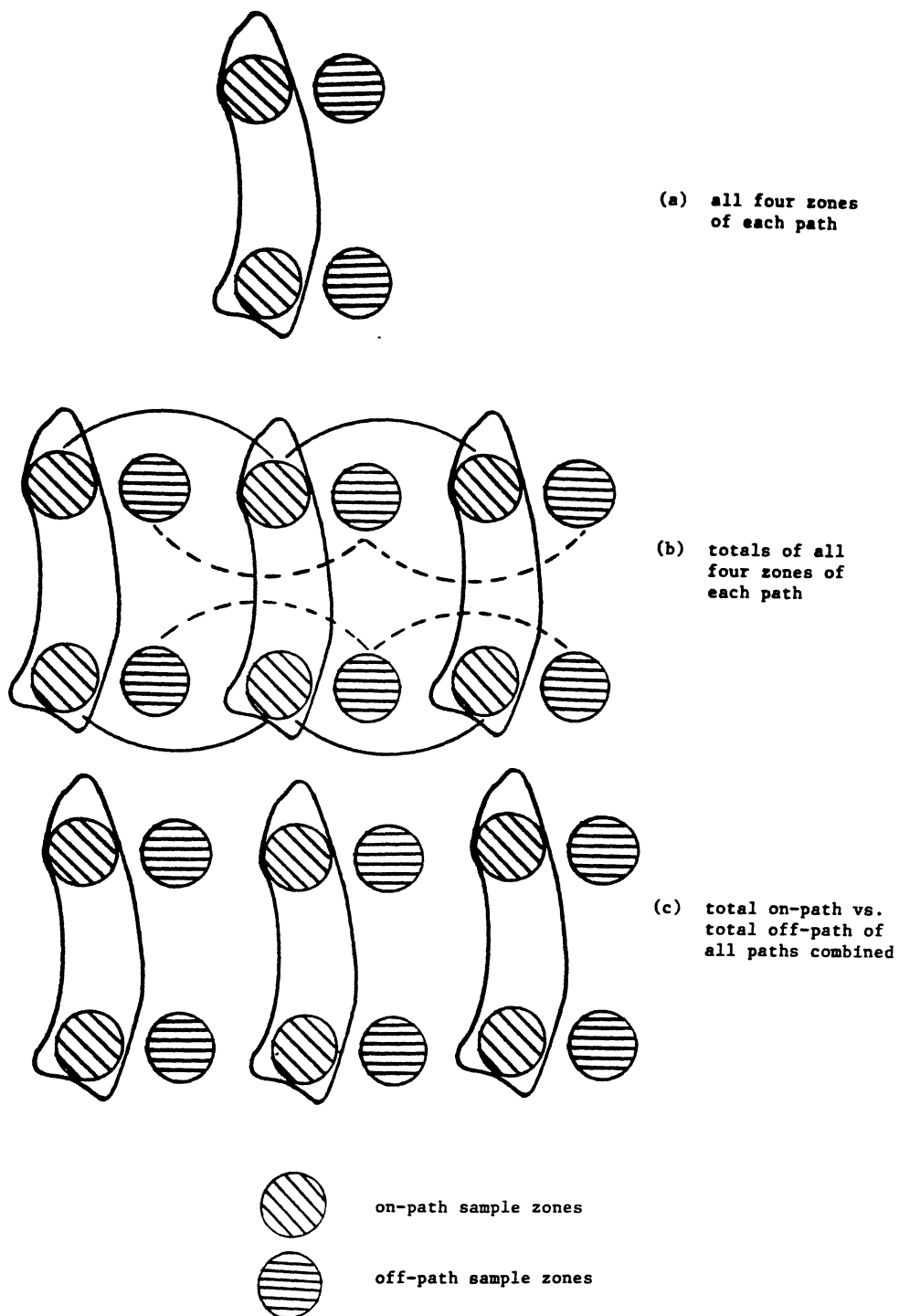


Figure 7. Comparisons of Sample Areas

by debris flow of the avalanches in the on-path zones and the date of morphological responses caused by other natural processes which occur in the off-path zones. The results of these comparisons are the focus of the following section.

Presentation of the Data With an Interpretation

The first comparison tested the null hypothesis: (H_0) no significant difference exists in the amount of morphological responses from 1973 for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones. This comparison was made for each of the three paths. The results are as follows:

Test #1 "Campsite" Avalanche Path

H_0 : no significant difference exists in the amount of morphological responses from 1973 for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones for the "Campsite" avalanche path.

H_a : a significant difference exists in the amount of morphological responses from 1973 for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones for the "Campsite" avalanche path.

Examination of the off-path samples for both the up-slope and run-out zones revealed that only three samples in each zone showed morphological responses in 1973. The on-path samples showed more morphological responses in 1973 for both the up-slope and run-out zones. In the case of the up-slope/on-path zone, 11 of the 15 samples showed morphological

responses in 1973. For the run-out/on-path zone an even greater number, 13 of 15 samples, showed evidence of morphological responses in 1973. Only 20 percent of the off-path samples showed a morphological response in 1973 compared to 80 percent for the on-path samples.

When tested with the Chi-square statistic, the calculated χ^2 value equaled 20.3 with 1.0 degrees of freedom. This value, greater than the tabled value, requires the rejection of the null hypothesis (H_o) and the acceptance of the alternate hypothesis (H_a) that a significant difference exists in the amount of morphological responses in 1973 for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones (Table III). In the case of the data compiled from the "Campsite" avalanche path a significant difference exists in the amount of morphological responses which occur on-path as compared to that which occurs off-path.

Test #2 "Beta" Avalanche Path

H_o : no significant difference exists in the amount of morphological responses in 1973 for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones for the "Beta" avalanche path.

H_a : a significant difference exists in the amount of morphological responses in 1973 for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones for the "Beta" avalanche path.

For this comparison 15 samples were collected in each of the four zones (Figure 7a) related to the "Beta" path. Only two of 15 samples showed morphological responses from some event in 1973. A slightly

TABLE III

TESTS OF HYPOTHESIS I: NUMBER OF MORPHOLOGICAL RESPONSES IN TREES
IN 1973 FOR EACH ZONE OF PATHS

Test #1

Campsite Path

Off-Path

On-Path

Up-Slope

3

11

Run-Out

3

13

samples each zone = 15

total # samples = 60

$\chi^2 = 20.3$

DF = 1.0

= 0.01 = 6.64

Reject H_0 accept H_a - significant difference exists

Test #2

Beta Path

Off-Path

On-Path

Up-Slope

2

5

Run-Out

4

9

samples each zone = 15

total # samples = 60

$\chi^2 = 28.4$

DF = 1.0

= 0.01 = 6.64

Reject H_0 accept H_a - significant difference exists

Test #3

Alpha Path

Off-Path

On-Path

Up-Slope

5

9

Run-Out

1

5

samples each zone = 15

total # samples = 60

$\chi^2 = 28.8$

DF = 1.0

= 0.01 = 6.64

Reject H_0 accept H_a - significant difference exists

greater value exists for the run-out/off-path zone with four of 15 samples showing morphological responses occurring in 1973. The on-path samples showed more morphological responses in 1973 for both the up-slope and run-out zones. In the up-slope, on-path zone, five of 15 samples showed morphological responses in 1973. A greater number occurred in the run-out, on-path with nine of 15 having morphological responses in 1973. Only 10 percent of the off-path samples showed evidence of morphological responses in 1973 compared to 23 percent for the on-path samples.

When tested with the Chi-square statistics, the X^2 value was equal to 28.4 with one degree of freedom. This value was greater than the tabled value. The null hypothesis (H_o) is, therefore, rejected in favor of the alternate hypothesis (H_a) that a significant difference exists in the amount of morphological responses from one year (1973) for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones (Table III). Therefore, a significant difference exists in the amount of morphological responses which occur on-path as compared to that which occurs off-path for the "Beta" avalanche path.

Test #3 "Alpha" Avalanche Path

H_o : no significant difference exists in the amount of morphological responses in 1973 for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones for the "Alpha" avalanche path.

H_a : a significant difference exists in the amount of morphological responses in 1973 for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones for the "Alpha" avalanche path.

In the up-slope, off-path zone, five of 15 samples showed morphological responses in 1973. Only one of 15 samples in the run-out, off-path zone showed morphological responses occurred in 1973. The on-path samples, once again, had more morphological responses in 1973 for the up-slope and run-out zones. On the up-slope, on-path zone, nine of 15 samples showed morphological responses in 1973, while the run-out zone samples had morphological responses in five of 15 samples. Similar to "Beta" path, "Alpha" path had 10 percent of the off-path samples showing a morphological response occurring in 1973 compared to 23.3 percent for the on-path samples.

The Chi-square value for "Alpha" path, 28.8, with one degree of freedom, was greater than the tabled value. This requires the rejection of the null hypothesis (H_0) and allows the acceptance of the alternate hypothesis (H_a) that a significant difference exists in the amount of morphological responses from one year (1973) for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones (Table III). Therefore, a significant difference exists in the amount of morphological responses which occur on-path as compared to that which occurs off-path for the "Alpha" avalanche path.

In summary, these comparisons proved three points. First, a greater number and thus a higher percentage of the on-path samples showed evidence of the avalanches that occurred in 1973. Second, the Contingency Table Analysis, showed that the trees on the three paths

had a significantly different number of morphological responses in 1973 compared to the off-path zones. All three null hypothesis were rejected. Clearly, the processes causing morphological responses in the trees on-path are significantly different from the processes causing morphological responses in the trees located in the off-path zones. The effect of avalanches on trees is site specific.

The second analysis assessed is the difference in morphological responses between the on-path, up-slope and run-out zones was significantly different than the off-path, up-slope and run-out zones when the values of all three paths were combined. The hypothesis states:

H_0 : no significant difference exists in the amount of morphological responses in 1973 for the on-path, up-slope and run-out zones are compared with the off-path, up-slope and run-out zones when the values for each path are combined.

H_a : a significant difference exists in the amount of morphological responses in 1973 for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones when the values for each path are combined.

For this comparison 45 samples were employed from the four zones (Figure 7b). The values for the three paths were: 10 samples showed morphological responses in 1973 for the off-path, up-slope zones and eight samples for the off-path, run-out zones. In contrast, a greater number of samples showed morphological responses in 1973 for the on-path zones. Of the 45 on-path, up-slope samples, 25 had morphological responses occurring in 1973 and 27 of the on-path, run-out samples exhibited responses in the same year. Twenty percent of the combined

off-path samples had morphological responses in 1973 compared to 57.7 percent for the combined on-path samples.

The Chi-square value for this comparison 83.73 with 1.0 degrees of freedom, was greater than the tabled value. The null hypothesis (H_0) was rejected in favor of the alternate hypothesis (H_a) (Table IV). In this comparison of the combined values for the three paths a significant difference exists in the number of morphological responses in 1973 which occurred on-path and those which occurred off-paths.

TABLE IV

TEST OF HYPOTHESIS II: NUMBER OF MORPHOLOGICAL RESPONSES IN TREES
IN 1973 ON EACH ZONE OF PATHS COMBINED

	Campsite + Alpha + Beta	
	Off-Path	On-Path
Up-Slope	10	25
Run-Out	8	27
# samples each zone $15 \times 3 = 45$		
total # samples = 180		
$\chi^2 = 83.73$		
DF = 1.0		
= 0.01 = 6.64		
Reject H_0 accept H_a - significant difference exists		

The third analysis assessed is the difference between the combined on-path samples and off-path samples of all three paths was significant.

This test is perhaps the most conclusive of the comparisons between the on-path and off-path samples because it is a test of more than one avalanche occurrence. The hypothesis is:

H_0 : no significant difference exists in the number of morphological responses in 1973 from the combined on-path samples compared with the combined off-path samples for all three avalanche paths.

H_a : a significant difference exists in the number of morphological responses from the combined on-path samples compared with the combined off-path samples for all three avalanche paths.

This comparison utilized 30 samples for each of the on-path and off-path zones of the three paths (Figure 7c) for a total of 180 samples. Fifty-two on-path samples had morphological responses in 1973 and 18 off-path samples exhibited responses in the same year. Twenty percent of the off-path samples had morphological responses in 1973 and 57.7 percent of the on-path samples responded in the same year.

The Chi-square value for this comparison was 75.86 with 2.0 degrees of freedom. This value was greater than the tabled value. This requires the rejection of the null hypothesis (H_0) and allows the acceptance of the alternate hypothesis (H_a) that a significant difference exists in the number of morphological responses in trees in one year (1973) for the on-path, up-slope and run-out zones as compared with the off-path, up-slope and run-out zones (Table V).

To summarize the findings of the comparisons: in all cases a larger percentage of the on-path samples had morphological responses in 1973 compared to the off-path samples. Though the difference between them was slight in some cases (i.e. comparison I for "Beta" path) Contingency Table Analysis proved that this difference was

TABLE V

TEST OF HYPOTHESIS III: NUMBER OF MORPHOLOGICAL RESPONSES IN TREES
IN 1973 OF ON-PATH VS OFF-PATH ZONES FOR EACH PATH

	Campsite + Alpha + Beta	
	Off-Path	On-Path
Campsite	6	24
Beta	6	14
Alpha	6	14
# samples each zone = 30		
total # samples = 180		
$\chi^2 = 75.86$		
DF = 2.0		
= 0.01 = 9.21		
Reject H_0 accept H_a - significant difference exists		

significant. All comparisons allowed for the rejection of the null hypothesis and the acceptance of the alternate hypothesis when tested at the 0.01 level of acceptance. From these differences, it is safe to conclude that different processes actually cause the morphological responses in the two areas. In the case of the on-path samples, the morphological responses are a result of the impact from avalanches, therefore, a large percent of samples exhibit morphological responses from those events.

It is also safe to assume that few trees, if any, are affected by avalanche debris in the off-path areas which parallel the avalanche paths. Morphological responses in the same year, however, indicate that other processes, unrelated to the activity of the avalanches, can stimulate morphological responses in trees. These other processes can include such events as bear scratchings, deer rubs, wind damage and the resulting impact from trees falling into each other in the more densely vegetated off-path zones. With this in mind, it should be apparent that when sampling trees for evidence of avalanche occurrence, the sampling will give a more reliable date of the event when taken either on or immediately bordering the path than samples acquired further from the apparent swath which results from avalanche events.

CHAPTER V

CONCLUSIONS

Conclusions of This Study

The purpose of this thesis was to test the validity of using morphological responses in trees to date the occurrence of avalanches and to show that all morphological responses may not be avalanche-induced. Trees in the on-path and off-path zones were sampled for the number of morphological responses in a given year (1973). Contingency Table Analysis was used to determine if a significant difference existed in the number of on-path and off-path samples that had morphological responses occurring in a given year. A significant difference did exist between the number of morphological responses for the on-path and off-path zones on each of the three avalanche paths examined. By showing that the difference does exist, proves that morphological responses in trees can be used to define avalanche and non-avalanche areas at a particular time. It follows, that this permits development of a chronology of the processes which affect each particular site as stated by Potter (1969).

Although sample size was limited to 180 samples this number was an appropriate sample for evaluation by the Chi-square test. In each comparison the null hypothesis that 'no significant difference exists between the number of morphological responses in 1973 for on-path samples when compared to off-path samples', was rejected and the

alternate hypothesis that: 'a significant difference exists between the number of morphological responses in a given year for on-path samples when compared to off-path samples,' was accepted.

These conclusions gave evidence that: (1) a significant difference exists in the number of morphological responses in a given date in the on-path zones as compared with the off-path zones; (2) differences exist in the processes which cause morphological responses in trees for the two zones.

These processes include the impact from trees and limbs which fall because of wind, snow, or deterioration from age. Additional processes which cause morphological responses include impact from unconsolidated rock, lightning strike, fire, scratchings from bear, or antler rubs from elk and deer.

Drawing from these conclusions it can be stated that the use of scars and reaction wood at callous margins to date the occurrence of snow avalanches in sub-alpine regions is a valid and accurate means to develop a chronology of the events.

Suggested Research Utilizing Dendrochronology

This is the first study to prove that:

1. Significant differences exist in the numbers of morphological responses, in a given year, to trees in on-path zones of snow avalanche paths when compared to off-path zones.

2. The processes which cause the scarring differ in the two zones.

These conclusions were derived from samples collected in one study area; they may not hold true in other locations where conditions may vary or where the plant or tree species differ from those present in the

Huerfano Valley of Colorado. For this reason other studies need to be done in different locations and utilizing other tree species, rather than generalizing from the species in this study to all other species.

Other considerations should also be used in future studies, such as, the size or magnitude of different avalanches and for different types of avalanches (i.e., wet snow avalanches compared to dry snow avalanches or avalanches confined to gullies compared to non-confined avalanches). These comparisons may help to establish guidelines as to how large or small an avalanche occurrence must be before similar results may be evident. Similar comparisons should also be made for geomorphologic processes such as mass-wasting, debris avalanches, glacial fluctuations, and flooding along with other natural processes such as fires. Such studies can provide information concerning the use of tree-ring dating as a technique to reconstruct a chronology of natural processes.

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APPENDIX

RESPONSE DATES AND SPECIES FOR "CAMPSITE",
"BETA" AND "ALPHA"
PATH SAMPLES

"CAMPSITE" PATH
Response Dates and Species

Up-Slope

Off-Path			On-Path	
1	1960	aspen	1973	spruce
2	1956	aspen	1977	aspen
3	1951	aspen	1973	spruce
4	1964	aspen	1973	spruce
5	1954	aspen	1973	spruce
6	1960	aspen	1959	aspen
7	1960	aspen	1973	spruce
8	1973	aspen	1950	aspen
9	1973	aspen	1973	spruce
10	1975	aspen	1973	spruce
11	1962	aspen	1973	spruce
12	1968	aspen	1973	spruce
13	1977	aspen	1976	spruce
14	1960	aspen	1973	spruce
15	1973	aspen	1973	spruce

Run-Out

1	1968	aspen	1973	spruce
2	1970	aspen	1973	spruce
3	1977	aspen	1970	aspen
4	1978	aspen	1973	aspen
5	1978	spruce	1973	aspen
6	1967	aspen	1973	spruce
7	1980	aspen	1973	spruce
8	1966	spruce	1973	spruce
9	1978	aspen	1973	spruce
10	1978	aspen	1973	spruce
11	1973	aspen	1973	aspen
12	1973	aspen	1964	aspen
13	1973	aspen	1973	spruce
14	1980	aspen	1973	spruce
15	1980	aspen	1973	spruce

"BETA" PATH
Response Dates and Species

Up-Slope

Off-Path			On-Path	
1	1978	aspen	1973	spruce
2	1978	aspen	1973	spruce
3	1979	aspen	1960	spruce
4	1966	spruce	1968	aspen
5	1969	aspen	1975	aspen
6	1977	aspen	1970	aspen
7	1977	aspen	1977	aspen
8	1968	aspen	1973	aspen
9	1956	aspen	1977	aspen
10	1976	aspen	1973	spruce
11	1973	aspen	1954	spruce
12	1964	aspen	1954	spruce
13	1980	aspen	1977	aspen
14	1978	spruce	1932	spruce
15	1973	aspen	1973	spruce

Run-Out

1	1975	aspen	1973	aspen
2	1956	aspen	1970	aspen
3	1977	aspen	1973	aspen
4	1970	aspen	1956	aspen
5	1973	aspen	1973	aspen
6	1973	aspen	1973	aspen
7	1973	aspen	1982	aspen
8	1968	aspen	1973	aspen
9	1966	aspen	1981	aspen
10	1973	aspen	1977	aspen
11	1977	aspen	1973	aspen
12	1980	aspen	1973	aspen
13	1979	apsen	1973	aspen
14	1972	aspen	1962	apsen
15	1977	aspen	1973	aspen

"ALPHA" PATH
Response Dates and Species

Up-Slope

Off-Path			On-Path	
1	1973	aspen	1954	spruce
2	1977	aspen	1973	spruce
3	1973	aspen	1973	spruce
4	1961	aspen	1973	spruce
5	1971	spruce	1973	spruce
6	1971	spruce	1973	spruce
7	1973	aspen	1973	aspen
8	1979	aspen	1975	aspen
9	1970	aspen	1958	aspen
10	1969	aspen	1954	aspen
11	1969	spruce	1964	spruce
12	1973	spruce	1969	aspen
13	1973	aspen	1973	aspen
14	1971	aspen	1973	aspen
15	1963	aspen	1973	spruce

Run-Out

1	1973	aspen	1973	aspen
2	1977	aspen	1979	aspen
3	1978	aspen	1979	aspen
4	1958	aspen	1979	aspen
5	1979	aspen	1969	aspen
6	1966	aspen	1969	aspen
7	1977	aspen	1973	aspen
8	1981	aspen	1978	aspen
9	1975	aspen	1980	aspen
10	1975	aspen	1964	aspen
11	1978	aspen	1973	aspen
12	1980	aspen	1973	aspen
13	1979	aspen	1969	aspen
14	1978	aspen	1973	aspen
15	1976	aspen	1977	aspen

2 VITA

Carl Leon Bryant

Candidate for the Degree of

Master of Science

Thesis: THE MORPHOLOGICAL RESPONSES OF TREES TO AVALANCHES: A
COMPARISON OF ON-PATH VS OFF-PATH RESPONSES

Major Field: Geography

Biographical:

Personal Data: Born in Chicago, Illinois, August 3, 1956, the
son of Mr. and Mrs. Carl L. Bryant.

Education: Graduated from MacArthur High School, Irving, Texas,
in May, 1974; received Bachelor of Science degree in
Geography from Oklahoma State University in July, 1981;
completed requirements for the Master of Science degree
at Oklahoma State University in December, 1985.