1558

THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Civil Engineering

Final Report

CREEP MOVEMENT AND SOIL MOISTURE STRESS IN FORESTED VS. CUTOVER SLOPES: RESULTS OF FIELD STUDIES

Donald H. Gray

DRDA Project 012577

supported by:

NATIONAL SCIENCE FOUNDATION
GRANT NO. ENG 74-02427
WASHINGTON, D.C.

administered through:

DIVISION OF RESEARCH DEVELOPMENT AND ADMINISTRATION
ANN ARBOR, MICHIGAN

August 1977

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Concluded)

ABSTRACT

Evidence for a cause and effect relationship between clear-cutting and accelerated mass erosion is reviewed. Clear-cutting is a timber harvesting procedure commonly employed on forest lands in many parts of the United States. The report describes the results of 8-years of creep monitoring and soil moisture stress measurements in forested and clear-cut slopes. The field data was obtained from instrumented sites located on steep mountain slopes of the Cascade Range in Central Oregon; the Klamath Mountains of Northern California; and the North Cascade Range of Washington.

Trees enhance the strength and stability of soil on steep slopes mainly through mechanical reinforcement by the root system and through soil moisture depletion by transpiration. Large scale removal or cutting of trees on steep slopes, on the other hand, tends to increase rates of mass-erosion or mass-soil movement. An emerging concensus in the published literature supports this conclusion as do the results of the study reported herein.

Two types of monitoring studies were established at the field sites, viz., "side-by-side" comparisons of forested and adjacent cutover areas and "before-and-after" comparisons at a single site, initially forested and subsequently clear-cut. Creep rates were generally higher in cutover or clear-cut areas as opposed to adjacent forested areas. Creep rates also tended to increase at sites which were initially forested and were subsequently clear-cut. Soil creep functions as a primary or initial link in the natural transport of soil and rock downslope. Acceleration in creep rates ultimately results in increased rates of mass-erosion and sedimentation.

Removal of slope vegetation tended to produce wetter conditions in the instrumented slopes. Wetter soil conditions are consistent with observed increases in creep rate. Creep

ABSTRACT (Concluded)

rates are also strongly influenced by precipitation patterns which likewise affect the moisture regime in the soil. In this regard, the far West has been afflicted with consecutive years of drought which coincided with the post clear-cutting monitoring period at several of the sites. Even so, increases in creep rate were still detected. It is highly recommended, however, that monitoring of these sites continue in order to observe the creep response under similar climatic conditions following clear-cutting.

I. INTRODUCTION

A storm of controversy has swirled about the practice of clear-cutting, a timber harvesting procedure widely employed in many parts of the United States. This practice became the focus of hearings on management practices in national timberlands held by the U. S. Senate Committee on Interior and Insular Affairs in Washington, D.C. in 1971. The record of these hearings (U. S. Senate Subcommittee on Public Lands, 1971) provides a wealth of background information on this controversial issue.

The underlying purpose of the study described herein was to examine only one facet of the clear-cutting controversy, viz., its impact on the stability of natural slopes. Stability in this case refers to the deep seated stability of slopes, i.e., resistance to mass wasting rather than surficial erosion. A specific goal of the study was to examine creep rates and soil moisture stress in forested as opposed to cutover slopes.

Soil creep functions as a primary link in the natural transport of soil and sediment to streams by mass wasting processes. Creep, a slow downhill movement of the soil mantle, tends to destabilize midslope areas. Accelerated creep triggers slump-earth flows which may constrict drainage channels. This in turn can lead to debris slides and torrents which scour channel bottoms and deposit debris downstream. Increased creep rates thus result ultimately in increased rates of mass wasting and downstream sedimentation.

Soil moisture stress affects not only creep rate but is also a critical parameter affecting the stability of slopes against catastrophic failure or sliding. Slope vegetation depletes soil moisture by the process of transpiration and it also affects the soil moisture regime by interception. Woody vegetation further influences the stability of slopes by root reinforcement and buttressing as described later in this report.

The study in question was initiated in the summer of 1968; before the practice of clear-cutting was subjected to intense public debate. Background information and preliminary analyses on the impact of clear-cutting on the stability of slopes was published in earlier reports by Gray (1970, 1973). A fairly detailed literature survey, theoretical discussion, and description of field research methods can be found in these earlier publications. In addition to field studies a laboratory, hydrologic investigation into the effects of vegetation removal was also undertaken. This latter study was carried out with a tilting soil bin simulating natural slopes at the University of Michigan Botanical Gardens. Results of this investigation were reported by Gray and Brenner (1970).

The purpose of the present report is to discuss and analyze the results of field studies carried out at three separate sites in the Pacific Northwest. The sites in question are located in Northern California, Central Oregon, and Northwest Washington. All of these sites had prior records of slope instability of one form or another. Slopes were instrumented at these sites in order to monitor changes in downslope movement (or creep rate) and soil moisture stress following clear-cutting.

Clear-cutting, it should be pointed out, is a silvicultural or harvesting procedure in which all timber over a certain minimum diameter is felled and removed. This method is normally employed in Douglas fir and redwood harvesting in the Western states. While no forester would equate clear-cutting with deforestation; the two are virtually synonymous when large scale clear-cutting is carried out in mature, even age stands of timber. Evidence of this fact is visible in many clear-cut sites in Washington, Oregon, and California. Figure 1 is a photograph of only one of several clear-cut sites observed by the author--illustrating complete denudation.

Post clear-cutting data is now available from all the instrumented sites which makes it possible to draw some tentative conclusions from the field study. Unfortunately the post clear-cutting period also coincided with consecutive years of record drought in the far West. This means that the sites in their denuded or cutover condition have not been exposed to the same climatic regime. The ideal situation would have been at least a year of post-cutting precipitation equal to the largest, annual pre-cutting rainfall. On the other hand, there is also "side-by-side" data available from sites in Oregon and Washington to permit behavioral comparison of forested with adjacent cutover areas. A "side-by-

Figure 1. View of clear-cut site, Happy Camp Ranger District, Klamath National Forest.

side" type study eliminates the problem of variable climate encountered in a sequential or "before-and-after" study, but it raises the question of site similarity. Finally, it should be noted that if creep rates increase significantly after clear-cutting in a "before-and-after" study inspite of dry years, then it can be reasonably inferred that woody vegetation removal does in fact accelerate creep and destabilize slopes because wet years should accelerate creep rates further yet.

II. REVIEW OF PAST WORK

A. EFFECT OF TIMBER HARVESTING OPERATIONS ON THE STABILITY OF SLOPES

Evidence for a cause and effect relationship between mass wasting and timber harvesting was reviewed in previous reports by Gray (1970, 1973). As noted in these earlier reports there was little prior published information in scientific or engineering journals on the effect of logging operations on the stability of slopes. The picture has changed markedly in recent years, however, as increasing numbers of studies and analyses on this subject have been reported in the technical literature. The emerging concensus in these studies is that clear-cutting and timber harvesting operations can and do accelerate mass wasting and erosion on steep, mountain slopes.

One of the earliest studies was conducted by Bishop and Stevens (1964) on landslides in logged areas in southeast Alaska. Bishop and Stevens noted a significant increase in both frequency of slides and size of area affected by slides after logging. They attributed the destruction to interconnected root systems by gradual decay as a principal cause of sliding. A later study by Wu (1976) on Prince of Wales Island in southeast Alaska tends to corroborate these earlier findings. Wu calculated the factor of safety against sliding of both forested and adjacent cutover slopes. The latter had lower factors of safety and in general were less stable because of loss of rooting strength and higher piezometric levels.

Recent studies (Bailey, 1971; Rice and Krammes, 1970; Swanson and Dyrness, 1975; Dodge *et al*, 1976; Swanston and Swanson, 1976) all show a cause and effect relationship between timber harvesting and slope instability. Steep, metastable slopes underlain by weak rock and soils are particularly sensitive to disturbances by man such as road building, clear-cutting, and vegetation manipulation. Many investigators (Dyrness, 1967; Gonsior and Gardner, 1971; and USDA, 1971) maintain that road building associated with logging plays the dominant role in slope stability problems. These same investigators concede, however, that timber harvesting *per se* on steep slopes, with subsequent destruction of stabilizing root systems can contribute to occurrence of shallow landslides. After analyzing past data on relative impacts of clear-cutting as opposed to road construction, Swanston and Swanson (1976) conclude that in many instances both activities contribute about equally to the total level of accelerated mass wasting.

The effect of vegetation manipulation or conversion of brush to grass cover has been investigated by Bailey and Rice (1969) and Rice *et al* (1969). Their study was conducted in the San Dimas Experimental Station in the San Gabriel Mountains in Southern California. They noted that the occurrence of slips was inversely related to the size and density of the slope vegetation. Conversion from brush to grass resulted in a sevenfold increase in shallow soil slips during the storms of November and December 1965.

A theoretical basis or framework for analyzing the effect of vegetation removal or clear-cutting on the stability of slopes has been presented by Gray (1970), Brown and Sheu (1975), and Wu (1976). The contribution of tree roots to shear strength along a potential sliding surface or the influence of transpiration on soil moisture stress can be taken into account in these analyses. A rational or systematic basis is thus available for comparing the stability of slopes in a forested vs. cutover condition.

B. ROLE OF WOODY VEGETATION IN STABILIZING SLOPES

1. Stabilizing Mechanisms

There are five principal ways in which trees or woody vegetation are likely to affect the deep seated stability of slopes, viz.,

1. By mechanical reinforcement from roots
2. By soil moisture depletion resulting from transpiration
3. By surcharge from the weight of the trees
4. By wind throwing or root wedging
5. By "soil arching" or buttressing action

All of these mechanisms except the last, i.e., buttressing action, were investigated in detail by Brown and Sheu (1975) who showed that the first two were probably the most important. Surcharge from the weight of trees can have either a beneficial or adverse effect upon stability depending on circumstances, but in any event plays only a minor role. Wind throwing has an adverse influence on stability but likewise plays a minor role (Brown and Sheu, 1975). Buttressing or soil arching action from tree trunks may actually be an important stabilizing mechanism particularly in sandy slopes. This latter mechanism is presently being investigated by Gray (1976).

2. Effect of Tree Roots on Soil Shear Strength

A critical factor in evaluating the effect of clear-cutting on the stability of slopes is the role of plant roots on soil shear strength. Shear strength is the parameter which controls the resistance of a soil to sliding; the weaker a soil the more susceptible it will be to sliding.

Endo and Tsuruta (1969) determined the reinforcing effect of tree roots on soil shear strength by running large scale direct shear tests on soil pedestals containing live tree roots. A schematic diagram of their test procedure is shown in Figure 2. The shear strength of the soil tested was found to increase directly with the bulk weight of roots per unit volume of soil. An empirical relation of the following form was obtained.

$$\Delta s_R = a(R + b) \tag{1}$$

where Δs_R = increase in shearing strength

R = root density

a and b = empirical constants

The shear strength at any depth in a soil layer with roots can be found by adding the shear strength increase Δs_R to the usual Coulomb expression for shear strength. This leads to the following equations:

$$s_t = c_m + \sigma \tan \phi \quad (2)$$

$$c_m = \alpha + \beta R \quad (3)$$

where s_t = total shear strength, kg/cm^2

σ = normal stress, kg/cm^2

ϕ = angle of internal friction of the soil

c_m = a modified cohesion intercept to account for root reinforcement

α and β = empirical constants

Calculations from data on 49 different plots showed that $\alpha = 102\ kg/cm^2$, $\beta = 0.094$, and $\phi = 33°$. The percent increase in shear strength can be found by dividing Equation (1) by (2) with R = 0 in the latter. This yields the following expression:

$$\%\ \text{increase} = \frac{\Delta s_R}{s_{R=0}} \times 100 \quad (4)$$

Equation (4) is shown plotted in Figure 3 for various values of R and σ. The curves show that root reinforcement is especially significant at low normal stresses or for shallow soil layers.

Manbeian (1973) likewise investigated the effect of plant roots on the shear strength of soil. He used a direct shear machine for this purpose which could accommodate large diameter soil samples containing roots of living plants. Only the effects of herbaceous plant roots (alfafa, barley, and sunflower) were investigated. Manbeian's results showed that both peak and residual shear strength were generally increased by as much as 2 to 4 times, respectively in soil specimens

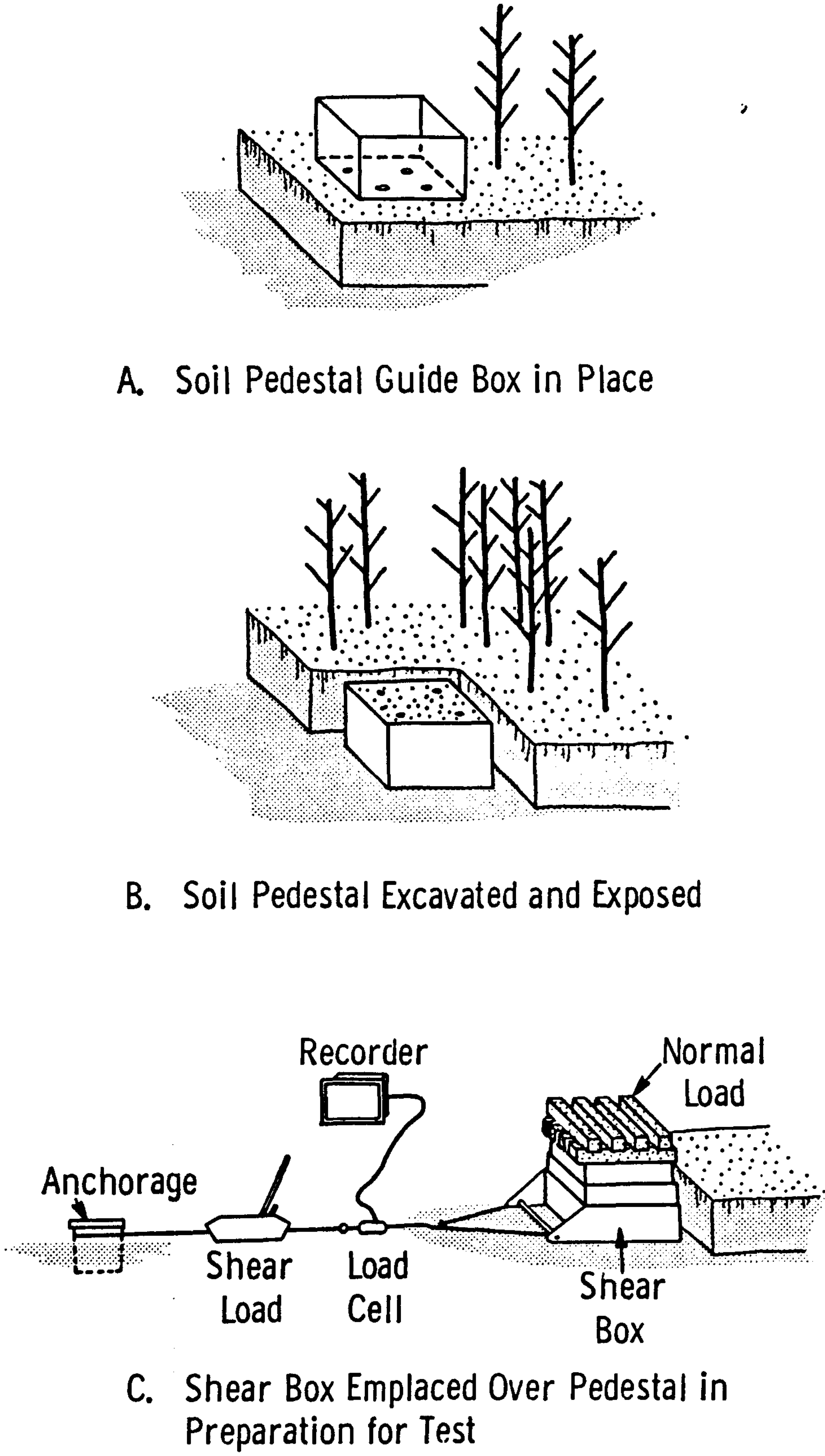

Figure 2. Schematic diagram of in situ shear tests on soil pedestals containing plant roots (after Endo and Tsuruta, 1969).

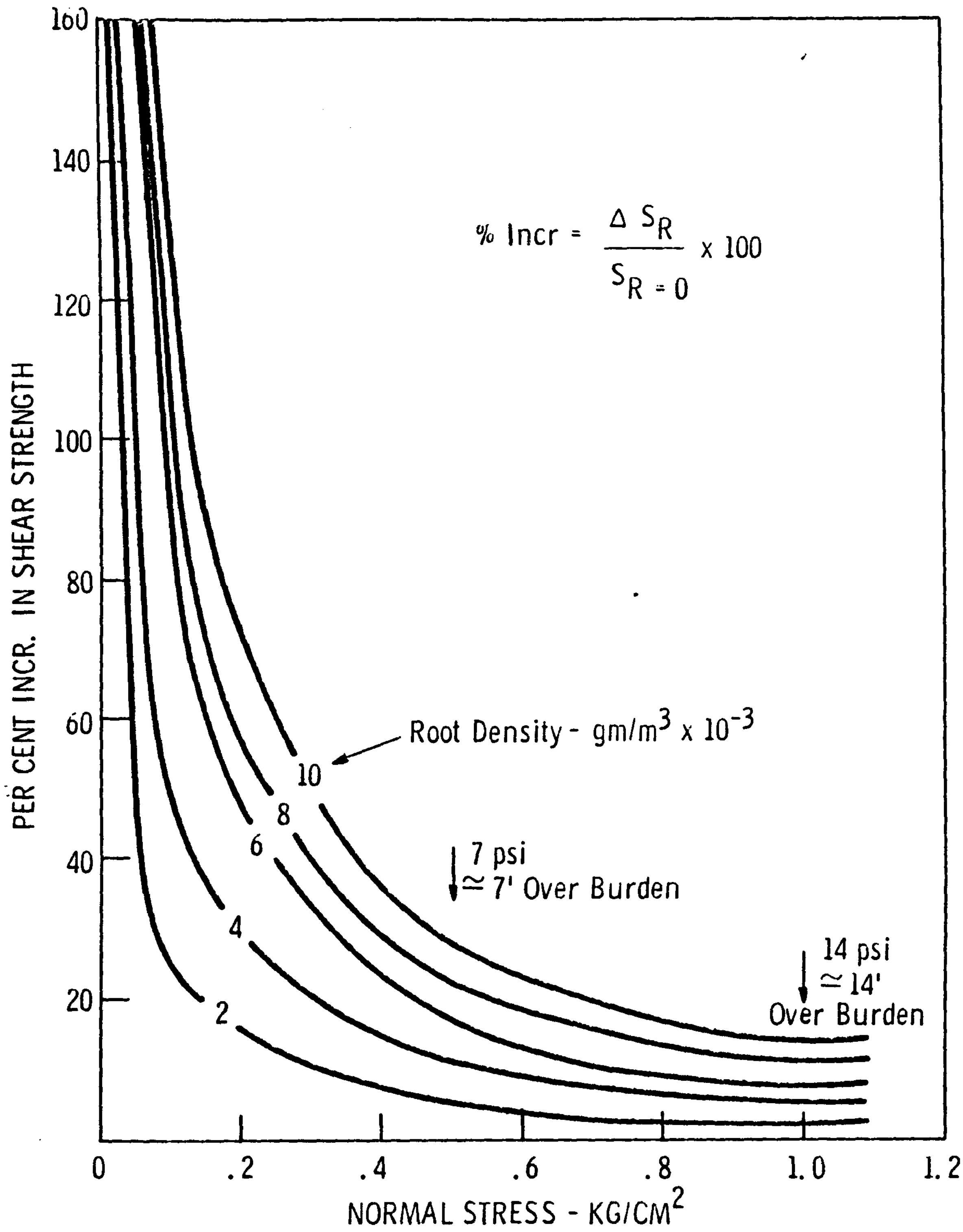

Figure 3. Increase in shear strength as a function of root density and normal stress (after Endo and Tsuruta, 1969).

containing roots.

Manbeian concluded from his tests that the degree of contribution of roots to strength is a function of combined effects of root density, size, root tensile strength, root morphology, and plant type. Duration of the contribution was dependent on whether plants were perennial or annual, and on the rate of root decay. The author did not attempt, however, to delineate these functional relationships nor did he carry out any tests with woody plants, i.e., shrubs or trees.

Wu (1976) has proposed a simple model to take into account the contribution of root tensile strength to soil shear strength. A root's contribution to shear strength according to this model is given by the expression

$$\Delta s_R = t_R \ (\cos \theta \tan \phi + \sin \theta) \tag{5}$$

where θ = the shear strain or distortion

t_R = tensile resistance of roots per unit area of soil

This model assumes the roots break in tension rather than failing by pull out. The expression in parentheses was shown by Wu to be relatively insensitive to the value of θ, and was approximately equal to 1.2 for the range of θ considered (viz., 48 to 72 degrees). Hence, the contribution to shear strength is nearly constant and is dependent essentially on the tensile strength of the roots. Furthermore, this contribution can be treated as an equivalent cohesion not affected by nor affecting the friction angle. The model is therefore consistent with experimental studies which show that reinforcement has little effect on the internal friction angle of soils.

Burroughs and Thomas (1976) have recently obtained detailed data on the tensile strength of roots of both Rocky Mountain and Pacific Coast species of Douglas fir. Tensile strength of the roots was determined as a function of both age after cutting and root diameter for both species. A pronounced decrease in root strength with time was observed with the decline being more rapid in the Pacific Coast species as shown in Figures 4 and 5 respectively. Data was also supplied on the size distribution and root density in the ground for these two species. With this type of information it should now be possible to make fairly accurate predictions about the impact of clear-cutting on slope stability over time at least insofar as the effect on shear strength is concerned.

Other investigators have also looked into the role and effectiveness of tree roots in stabilizing soil on steep slopes and the time required for root decay to cause instability (Bishop and Stevens, 1964; Swanston, 1969; Swanston and Walkotten, 1970; Rice and Krammes, 1970; and Gray, 1974). In general these investigators credit tree roots with increasing the stability of soil mantles on steep slopes to varying extent. The reinforcing effect is believed to be more significant in the case of shallow soils (Rice and Krammes, 1970) and in cases where roots penetrate the soil profile into joints and fractures in bedrock (Swanston, 1969).

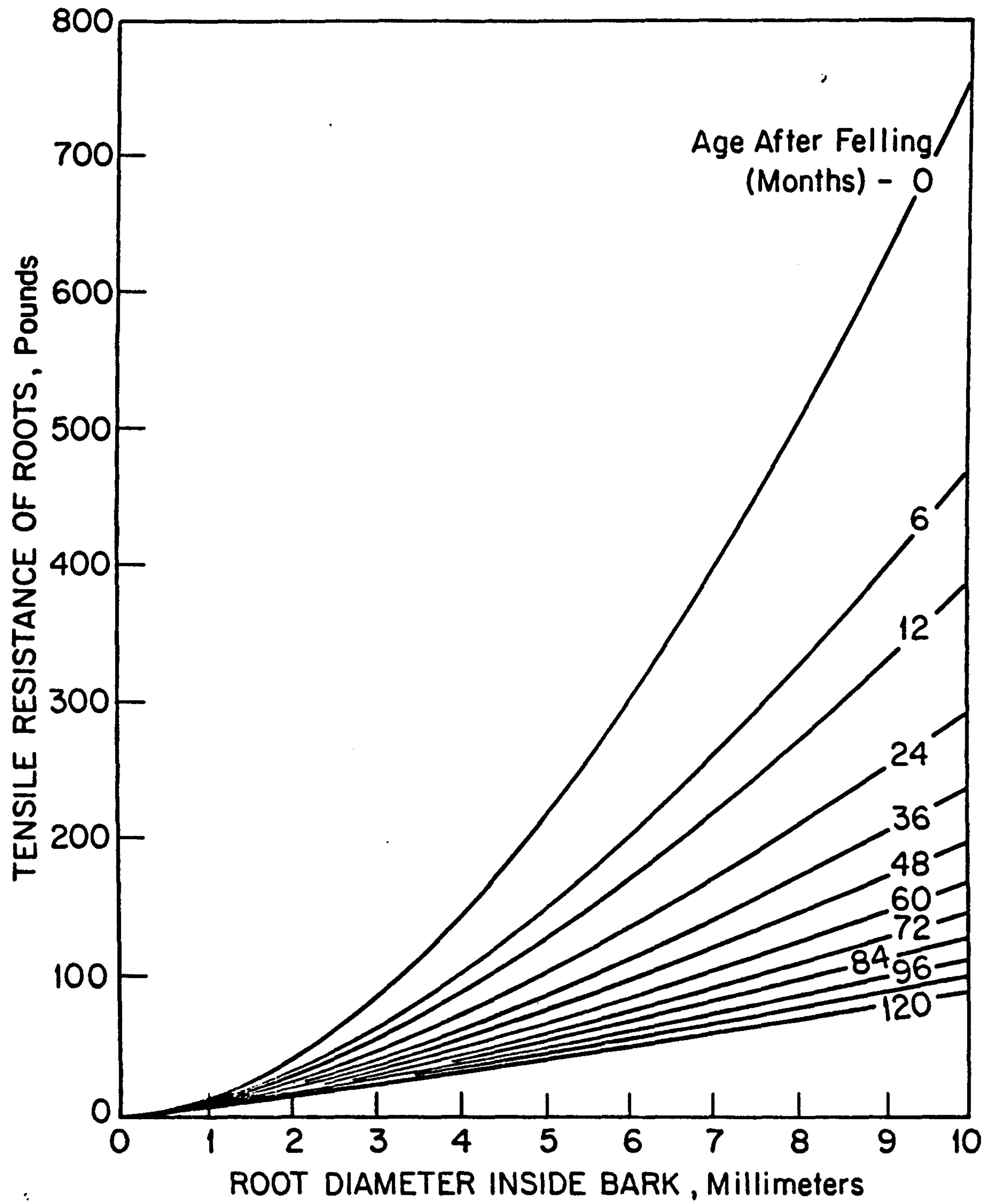

Figure 4. Tensile strength of roots of coastal Douglas fir as a function of time after felling and size of root (after Burroughs and Thomas, 1976).

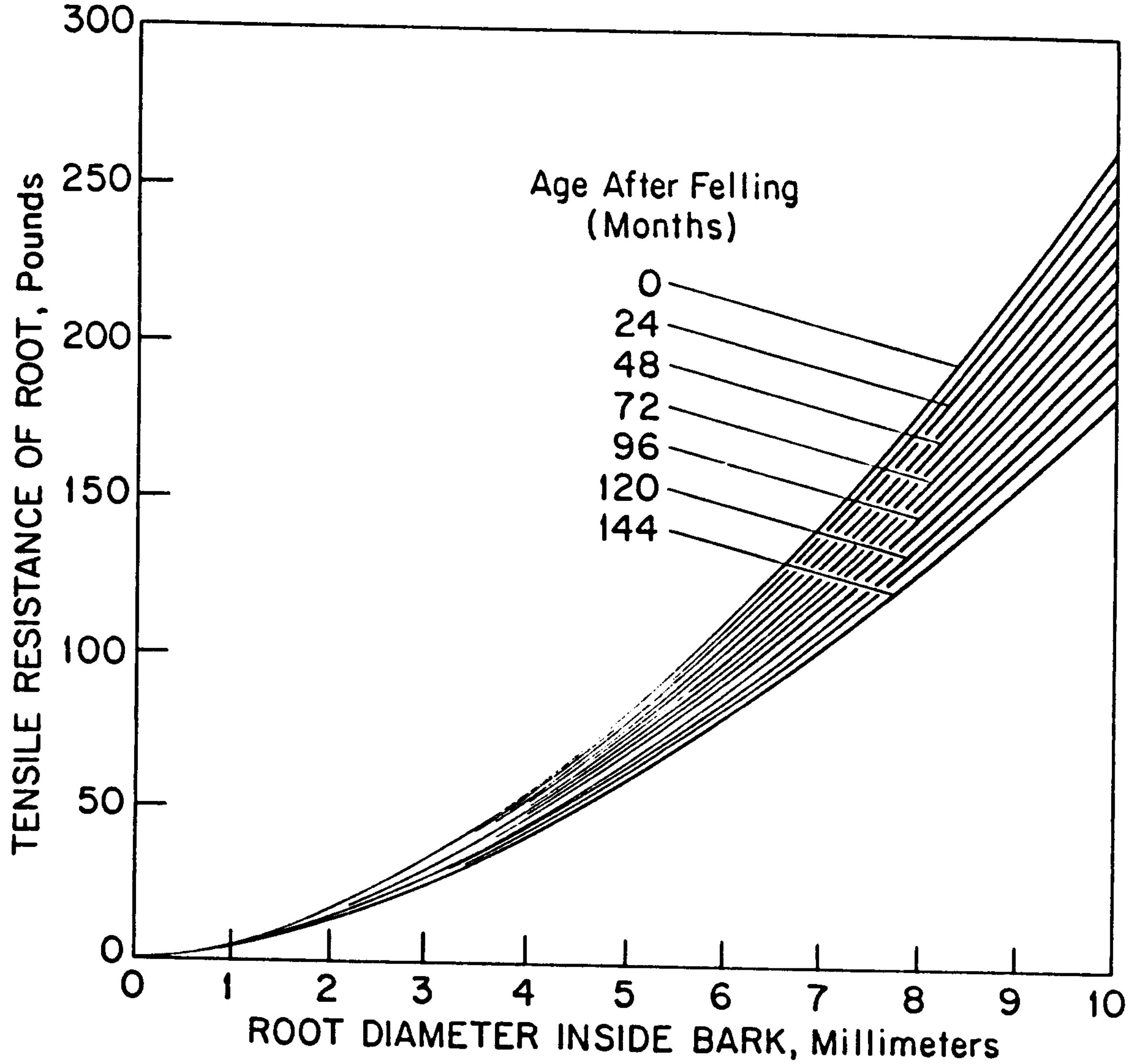

Figure 5. Tensile strength of roots of Rocky Mountain Douglas fir as a function of time after felling and size of root (after Burroughs and Thomas, 1976).

Swanston excavated tree stumps hydraulically in order to determine the distribution of tree roots in a slope. A good idea of the root morphology and potential for soil reinforcement is shown diagramatically in Figure 6 from the work of Curtis (1964). A photo of the exposed root system of a Ponderosa pine in a roadcut is shown in Figure 7. The remarkable vertical roots and extensive lateral root system have helped to buttress and stabilize the road cut shown in the photo.

To the extent that live tree roots provide reinforcement; conversely, dead roots will cause loss of strength and resulting instability. Bishop and Stevens (1964) and Swanston and Walkotten (1970) conclude that the effectiveness of rooting as a factor in soil shear strength decreases with age and that soils on oversteepened slopes reach their minimum effective strength due to root anchorage approximately five years after cutting. This conclusion is based on observations of slopes supporting old growth Sitka spruce--western hemlock stands of timber.

Rice and Krammes (1970) suggest a more slowly deteriorating site (with respect to landslides) following logging. Their view is supported by observations of logged areas in the north coast of California. The authors present interesting photographic evidence of site deterioration commencing and accelerating some fifteen years after logging. Root strength decline after tree felling is probably species and site dependent. The results of laboratory strength tests on

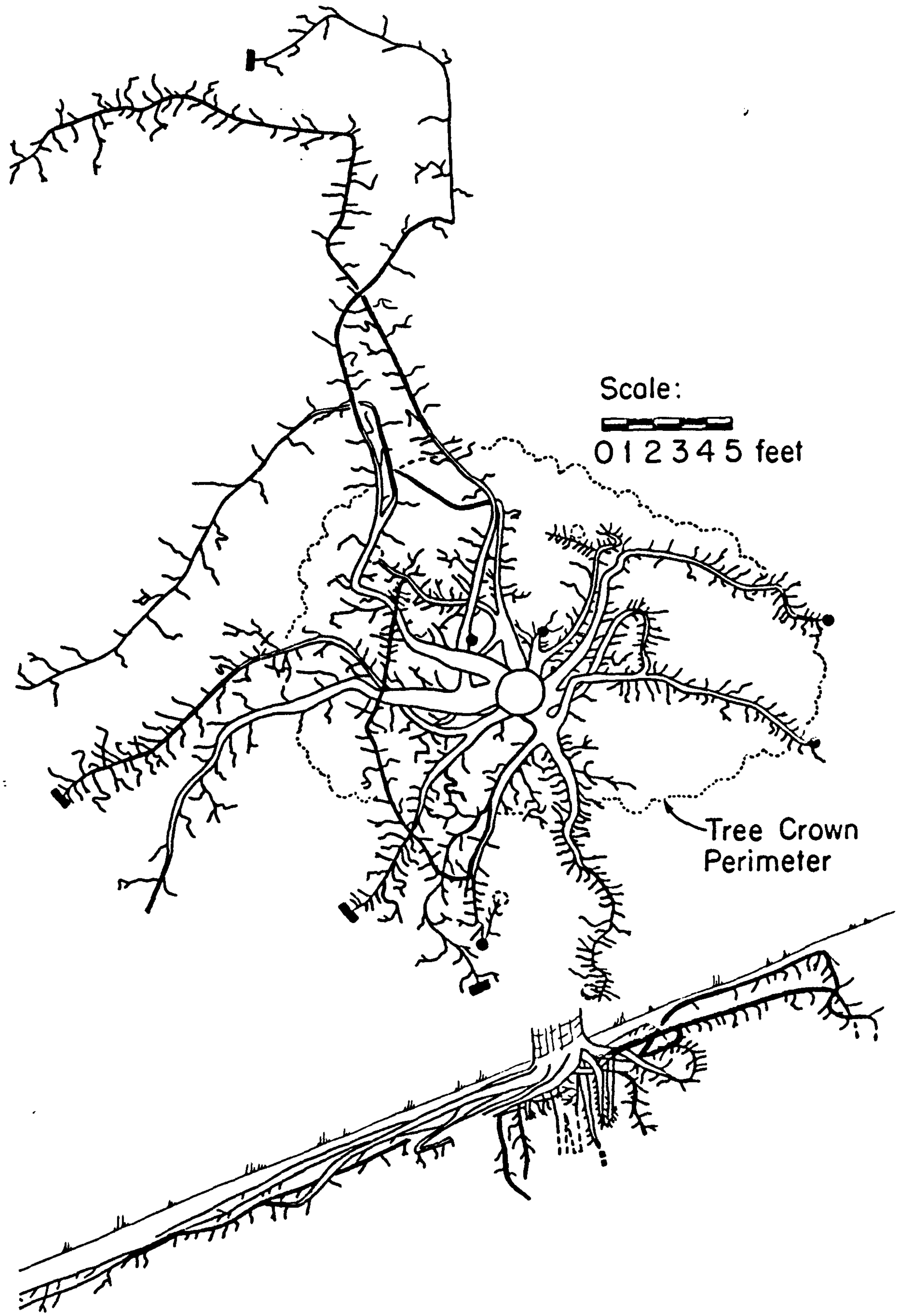

Figure 6. Root structure and morphology of a 60-year old Ponderosa pine (after Curtis, 1964).

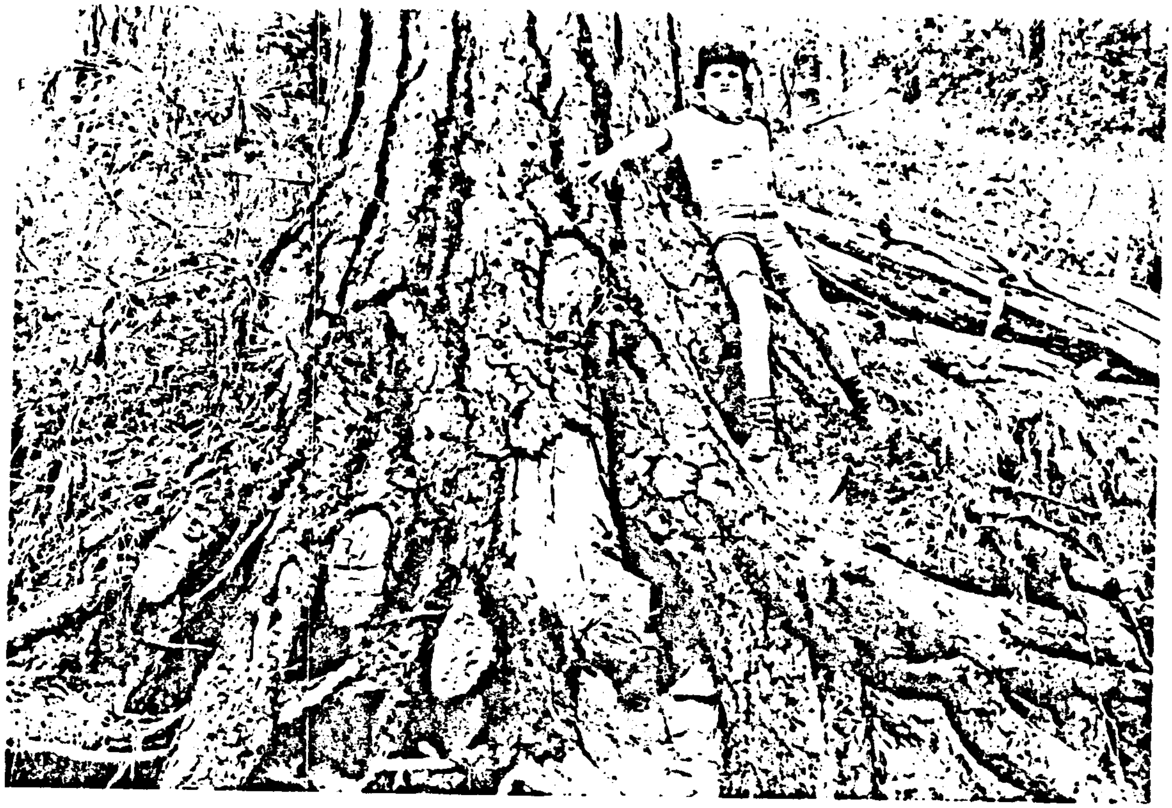

Figure 7. Root system of a Ponderosa pine exposed in a road cut, Boise National Forest, Idaho.

Douglas fir decreases 50 percent in 1 year. Four years after felling, a 1 cm root has lost 75 percent of its fresh strength. A 1-cm diameter Rocky Mountain root, on the other hand, lost only 10 percent of its fresh strength four years after felling.

3. Hydrologic Influence of Vegetation on Stability

It is well established that high precipitation and storm activity are strongly correlated with landsliding and other mass-wasting events in steep slopes (Fredriksen, 1965; Flaccus, 1959; and Swanston, 1969). The influence of precipitation on landslide occurrence derives from its relation to ground water movement and soil moisture stress (Swanston, 1967; Bailey and Rice, 1969; Gray, 1970; and Gray and Brenner, 1970).

It is also well established that trees deplete soil moisture through transpiration (Bethlahmy, 1962; Patric *et al*, 1968; Gray and Brenner, 1970). Soil moisture depletion by transpiration thus leads to drier soils and longer recharge times which in turn improves shear strength and stability. The role of *transpiring** vegetation in preventing landslides in actual practice has been subject to differing interpretations. Gray (1970) argued that forested slopes which tend to be drier may be able to tolerate a storm of greater intensity or duration before a critical, saturated condition develops. Rice and Krammes (1970) maintain that the importance

*A distinction is made here between the role of transpiration and the contribution to shear strength from root reinforcement.

of the role that transpiring vegetation plays in the occurrence of landslides depends upon climate. They believe that this contribution is probably negligible in climates where precipitation greatly exceeds potential evapo-transpiration. On the other hand, in more arid climates, where substantial moisture deficits develop each summer, differential use of water by different types of plant cover may significantly affect the occurrence of landslides.

Wu (1976) developed a simulation model to predict the groundwater regime (pore pressure) of slopes based on precipitation history, evapotranspiration, and infiltration characteristics of the site. This model was used in conjunction with a stability analysis to predict statistically the probability of slope failure for a particular site - forested or cutover - on the basis of past rainfall records. Alternatively, the analyses could be used to determine the steepest slope that could be clear-cut without incurring a risk or probability of failure greater than some predetermined value.

C. SOIL CREEP AND ITS SIGNIFICANCE

Soil creep is a slow, downslope movement or plastic deformation of soil on a slope. Soil creep does not necessarily mean slope failure; in fact, some investigators (Wilson, 1970) maintain it is difficult to differentiate between plastic deformation (creep) and incipient failure.

Other investigators (Saito and Uezawa, 1961) disagree, suggesting that it is possible to forecast slope failure by measuring surface creep rates. Saito and Uezawa show from field measurements and model experiments that the strain (or creep) rate in a mass of soil will increase rapidly just before failure occurs. Ter-Stepanian (1963) showed from a theoretical analysis that the down slope creep rate of an inclined soil layer was exponentially related to the piezometric level in the slope. As the soil layer neared full saturation the creep rate not only tended to accelerate markedly, but the factor of safety against slope failure also approached unity.

Measurements and analysis by Saito and Uezawa (1961) showed that "creep rupture life" or time to failure of a soil is realted to creep rate as follows:

$$\log t_R = C - m \log \varepsilon \tag{6}$$

where t_R = creep rupture life

ε = strain (or creep) rate

m and C = constants

This relationship was found to be valid over a wide range of strain rate (10^{-3} to $10^3 \times 10^{-4}$/min) and was independent of the type of soil or testing method. The slope "m" of this equation on log-log paper was very close to unity (0.916). Setting the constant "m" equal to unity reduces the equation to the simple form:

$$t_R \varepsilon = \text{constant} \tag{7}$$

Therefore, creep rupture life or time to failure is inversely proportional to strain rate. This relationship was shown to be applicable to full scale field experiments on slope failure. Creep rates may thus be used as an indicator of the long term stability of slopes and any acceleration in creep rate used as a precursor of potential instability or slope failure.

Wilson (1970) in his Terzaghi lecture on ground movements related to instability noted that the most significant factors affecting creep rate are slope angle, type of soil, and amount and frequency of rainfall. The latter factor controls the piezometric level or soil moisture stress in a slope. Ter-Stepanian (1963) explicitly recognized the dependence of creep rate on these factors in his theoretical equations. In addition, he included the effect of surcharge on creep rate. Figure 8 is a schematic diagram of the creep model used by Ter-Stepanian, and Figure 9 is a plot of the creep equations showing creep rate as a function of piezometric level and slope surcharge.

Trees or vegetation can be expected to affect creep rates through their influence on soil moisture stress and soil characteristics. Clear-cutting results in a decline of root strength which in turn affects soil shear strength. Reduced evapotranspiration following clear-cutting may result in wetter conditions (Gray, 1970; Rothacher, 1971) and a greater duration of the annual period of creep activity; thereby, increasing the annual creep rate.

Another important aspect of soil creep is its contribution to general lowering or degradation of the land. Soil creep is an ubiquitous form of downslope movement in humid

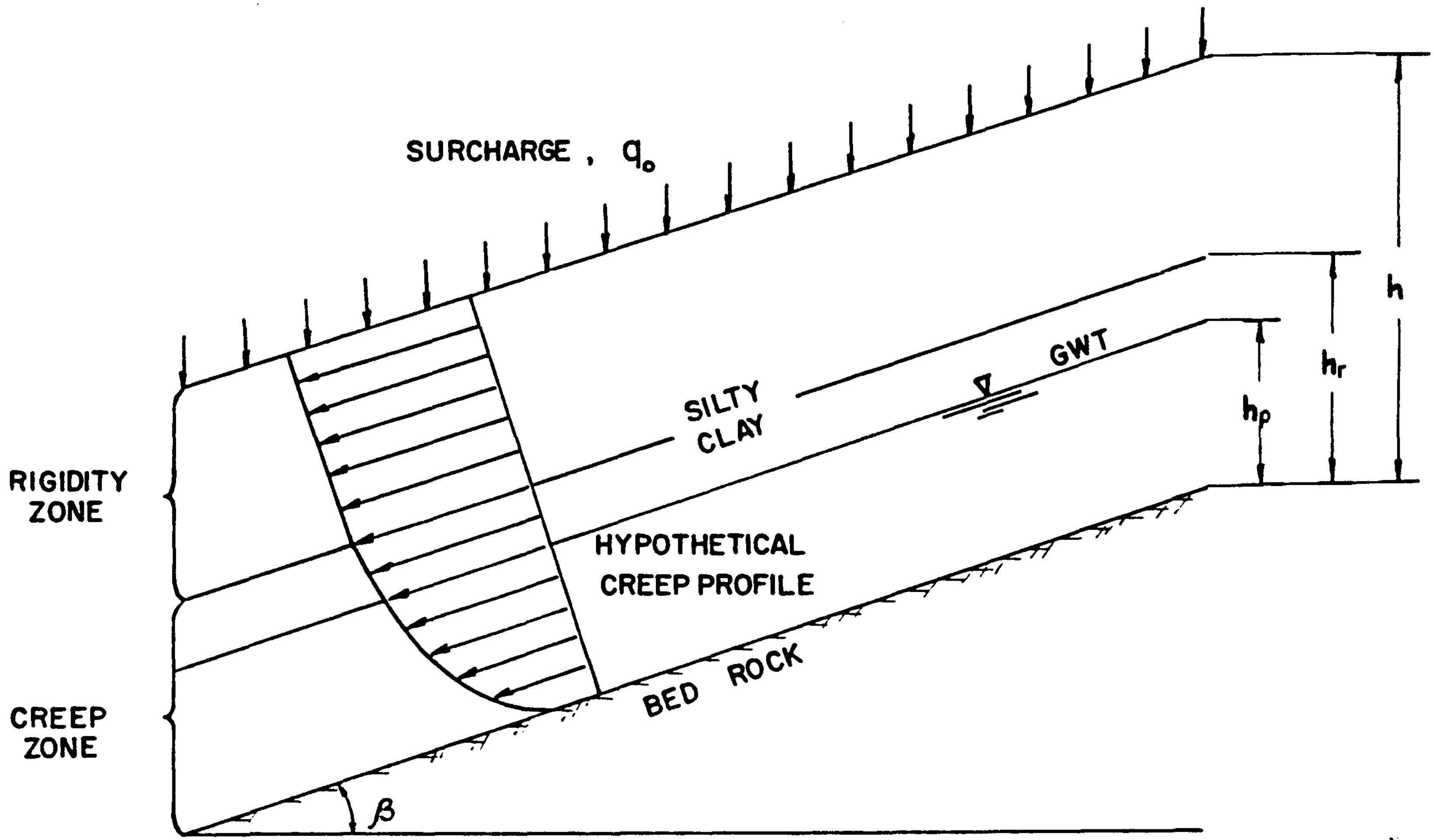

Figure 8. Schematic representation of slope geometry.

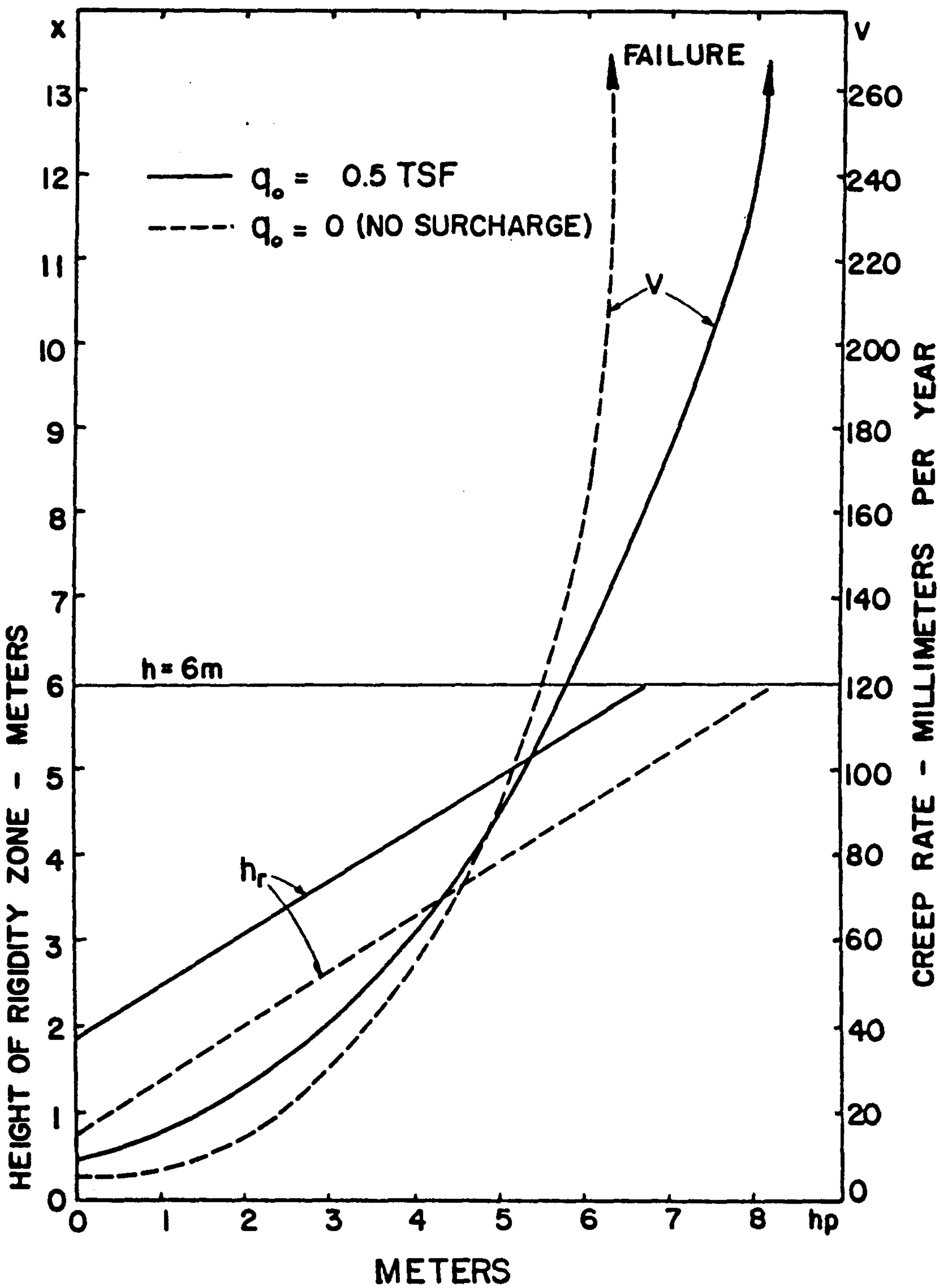

Figure 9. Surface creep rate as a function of piezometric level and surcharge (from Ter-Stepanian, 1963).

climates. Kojan (1969) has measured an average downhill velocity of about 11 mm/year (0.44 in/yr) on an average slope of about 17° in the Northcoast Ranges of California. Swanston (1969) cites a rate of approximately 6.4 mm/yr (0.25 in/yr) in the top 6-12 inches of soil in southeast Alaska. Creep studies (Wilson, 1970) carried out in Western Washington indicate a surface creep rate of approximately 8.1 mm/yr (0.32 in/yr) averaged over a 10-year period. This rate was measured in a 25-foot section of a moderately compact, silty glacial morraine overlying phyllite bedrock. Schumm (1967) measured rates of surficial rock creep on barren hillslopes in Western Colorado on the order of 51 mm/yr (2 in/yr) for slope angles of 30 degrees.

Swanston and Swanson (1976) have monitored creep rates in slopes underlain by different geologic materials in the western Cascade Range and Coast Ranges of Oregon and Northern California. Results of their study shown in Table 1 indicate rates of movement between 7.1 and 15.2 mm/yr. The zone of most rapid movement usually occurred at or near the surface, although a zone of maximum displacement was often observed at depths associated either with incipient failure planes or zones of ground water movement. At many sites movement took place primarily during the rainy season when maximum soil-water or piezometric levels occur. In contrast, creep tended to remain constant throughout the year at sites where the water table did not undergo significant seasonal fluctuations. This finding by Swanston and Swanson is consistent with

TABLE 1 - Examples of Measured Rates of Natural Creep on Forested Slopes in the Pacific Northwest (from Swanston and Swanson, 1976)

Location	Parent Material	Depth of significant movement (m)	Maximum downslope creep rate: At the surface (mm/yr)	Maximum downslope creep rate: In zone of accelerated movement (mm/yr)
Coyote Creek South Umpqua River drainage, Cascade Range of Oregon, site C-1	Little Butte Volcanic Series: deeply weathered caly-rich andesitic dacitic volcani-clastic rocks	7.3	14.0	10.9
Blue River drainage-- Lookout Creek H. J. Andrews Exp. Forest, Central Cascades of Oregon, site A-1	Little Butte Series: (same as above)	5.6	7.9	7.1
Blue River drainage IBP Experimental Watershed 10, site No. 4	Little Butte Volcanic Series	0.5	9.0	---
Baker Creek, Coquille River, Coast Range, Oregon, Site B-3	Otter Point Formation: highly sheared and altered clay-rich argillite and mudstone	7.3	10.4	10.7
Bear Creek, Nestucca River, Coast Range, Oregon, site N-1	Nestucca Formation: deeply weathered pyroclastic rocks and interbedded, shaly siltstones and claystones	15.2	14.9	11.7
Redwood Creek, Coast Range, northern Calif., site 3-B	Kerr Ranch Schist: sheared, deeply weathered clayey schist	2.6	15.2	10.4

Ter-Stepanian's (1963) theoretical analysis graphically illustrated in Figures 8 and 9 which show that the downslope creep rate of an inclined soil layer is exponentially related to the piezometric level in the slope.

Kojan (1969) estimated that in the Eel River drainage of California, soil creep was producing about 260 metric tons of sediment per square kilometer of drainage basin. This volume is about 30 percent of the suspended load which Wallis (1965) has estimated for the area. This estimate, furthermore, was based on a conservative downhill velocity of only 6 mm per year for a 2.4-meter thick mantle; a much lower rate than many measured by either Kojan (1969) or Swanston and Swanson (1976).

Summing up: it appears that soil creep is generally the most ubiquitous and persistent of all mass erosion processes. Acceleration in creep rate is a possible precursor of impending slope failure, and increases in creep rate can lead to increased rates of mass wasting and sediment loading to streams. The linkage between these processes is shown schematically in Figure 75. Creep rates are primarily dependent on slope angle, soil characteristics, and soil moisture stress. Trees and vegetation are likely to affect creep rates by modifying the latter two factors. For all of these reasons, field measurements of soil creep before and after cutting are a useful method of assessing the impact of clearcutting and vegetation removal on the stability of slopes.

III. LOCATION AND DESCRIPTION OF FIELD SITES

A. SITE SELECTION CRITERIA

The primary objective of the field research was to investigate the effect of forest clear-cutting on soil moisture stress and on the rate of downslope movement (or creep rate), respectively, in steep slopes. Two approaches are possible in this regard, viz., (1) a "before-and-after" clear-cutting comparison at a single site, (2) a "side-by-side" comparison of a forested and adjacent cutover site.

In order to accomplish this objective the following criteria were established for selection of a site:

1. A history of mass-soil movement or susceptibility to sliding
2. Reasonably steep slopes (> 60 percent)
3. Slopes with a relatively uniform mantle of residual soil some 5 to 20 feet thick overlying an inclined bedrock contact
4. A recently clear-cut area adjacent to a virgin, forested area (both otherwise similar) for a "side-by-side" comparison
5. An area scheduled for clear-cutting in a near future from which reliable base or control data could be obtained for a "before-and-after" comparison
6. Good climatic and weather records
7. Year round accessibility
8. Field personnel available at the site to monitor instruments and take readings when necessary.

On the basis of these requirements three different areas were selected in the Pacific Northwest. Sites in these areas were instrumented during successive summers starting with the H. J. Andrews Experimental Forest, near Blue River, Oregon

(1968 and 1969); U. S. Naval Radio Station at Jim Creek, near Arlington, Washington (1970); and sites in the Klamath National Forest, near Happy Camp, California (1971).

Sites were also reconnoitered at Hubbard Brook Experimental Forest, New Hampshire, and at Zena Creek in the Payette National Forest, Idaho. Both these latter areas had a history of slope instability associated in part with timber harvesting (Flaccus, 1959; Gonsior and Gardner, 1971), but were never instrumented because of logistical problems and other unfavorable site characteristics.

B. H. J. ANDREWS EXPERIMENTAL FOREST, OREGON

1. Location and Topography

The H. J. Andrews Experimental Forest is located in the Cascade Mountains about 40 miles east of Springfield, Oregon, and 5 airline miles north of the McKenzie Highway (U.S. 126) as shown in Figure 10. The entire 15,000-acre drainage of Lookout Creek, in the Willamette National Forest is included in the boundaries of the Experimental Forest. The Experimental Forest was established in July, 1948, and is administered by the Pacific Northwest Range and Forest Experimental Station, U.S. Forest Service.

Three different sites within the Experimental Forest have been instrumented as part of the slope stability studies. These include a clear-cut watershed (No. 1), and two forested watersheds, viz., No. 10 and No. 2-3, respectively. Watershed No. 1 was clear-cut by skyline crane in 1961, Watershed No. 10 was clear-cut in the summer of 1975, and Watershed No.

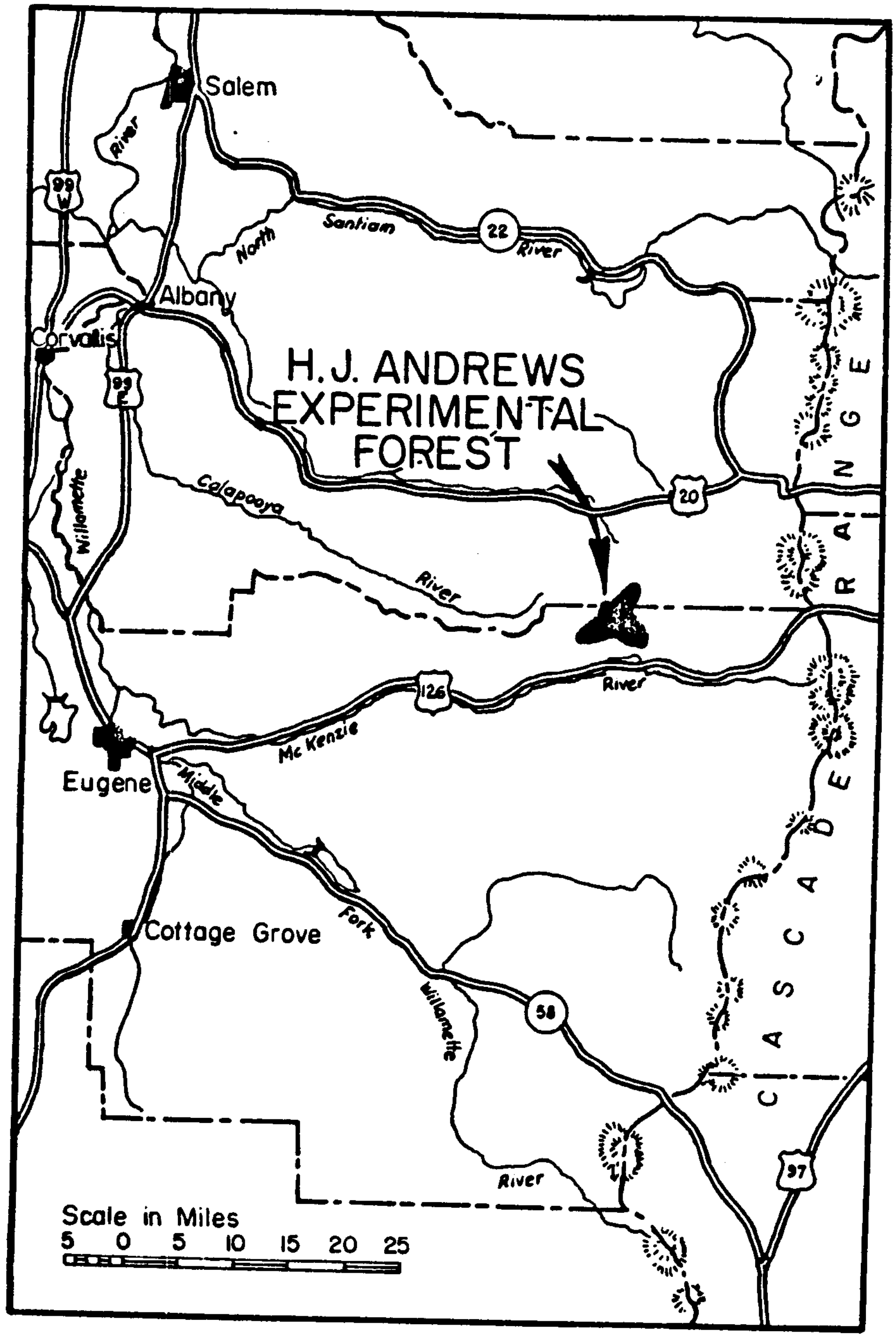

Figure 10. Map location of H. J. Andrews Experimental Forest.

2-3* is a forested slope which has been left undisturbed indefinitely.

The surrounding terrain can be characterized as "ridge and ravine" topography with sharp ridges and steep slopes. Only about one-fifth of the area is in gentle slopes or benches. Elevations within the Experimental Forest vary from about 1500 feet to more than 5000. Rock outcroppings occur frequently in steeper areas of the forest and old lava flows have formed lines of bluffs at some elevation.

The general topography and location of instrumented study sites are shown in Figures 11 and 12. Watersheds Nos. 1 and 10 are approximately 200 acres in size. Study sites on these two watersheds face north and southwest, respectively. Maximum side slopes in each watershed range as high as 100 percent in places; average side slopes in the vicinity of instrumented sites are about 70 percent for all watersheds. Photographs illustrating the nature of the terrain and vegetation in the vicinity of the study sites are shown in Figures 13 to 15.

2. Soils and Geology

The principal soil types found at the H. J. Andrews Experimental Forest are all of volcanic origin. A residual clay loam, formed from andesite and basalt, is common on the steeper slopes and on ridgetops. A residual silty clay loam--

*Watershed No. 2-3 is a forested slope located between Watersheds Nos 2 and 3.

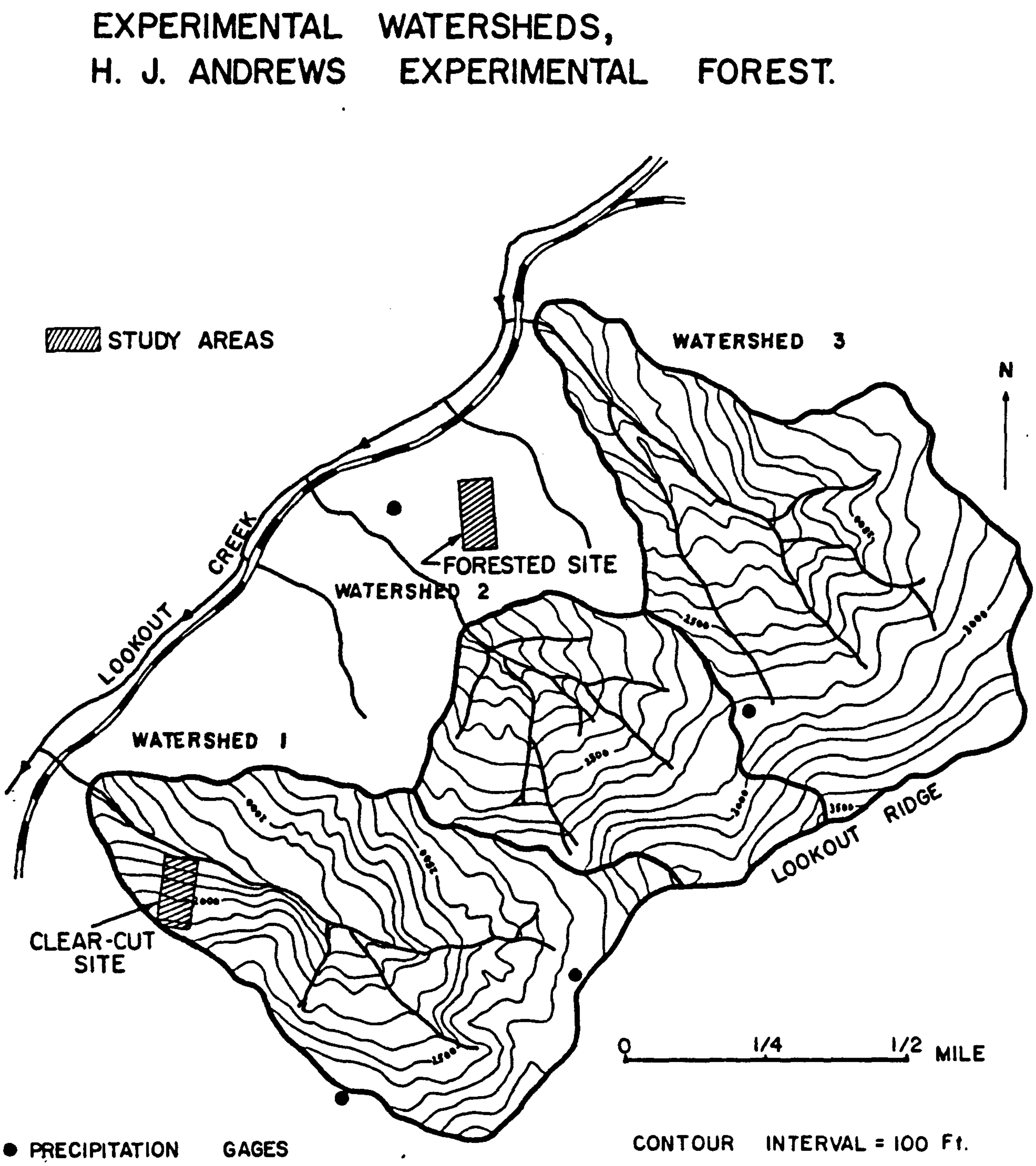

Figure 11. Location of field sites for "side-by-side" comparison of creep movement, H. J. Andrews Experimental Forest.

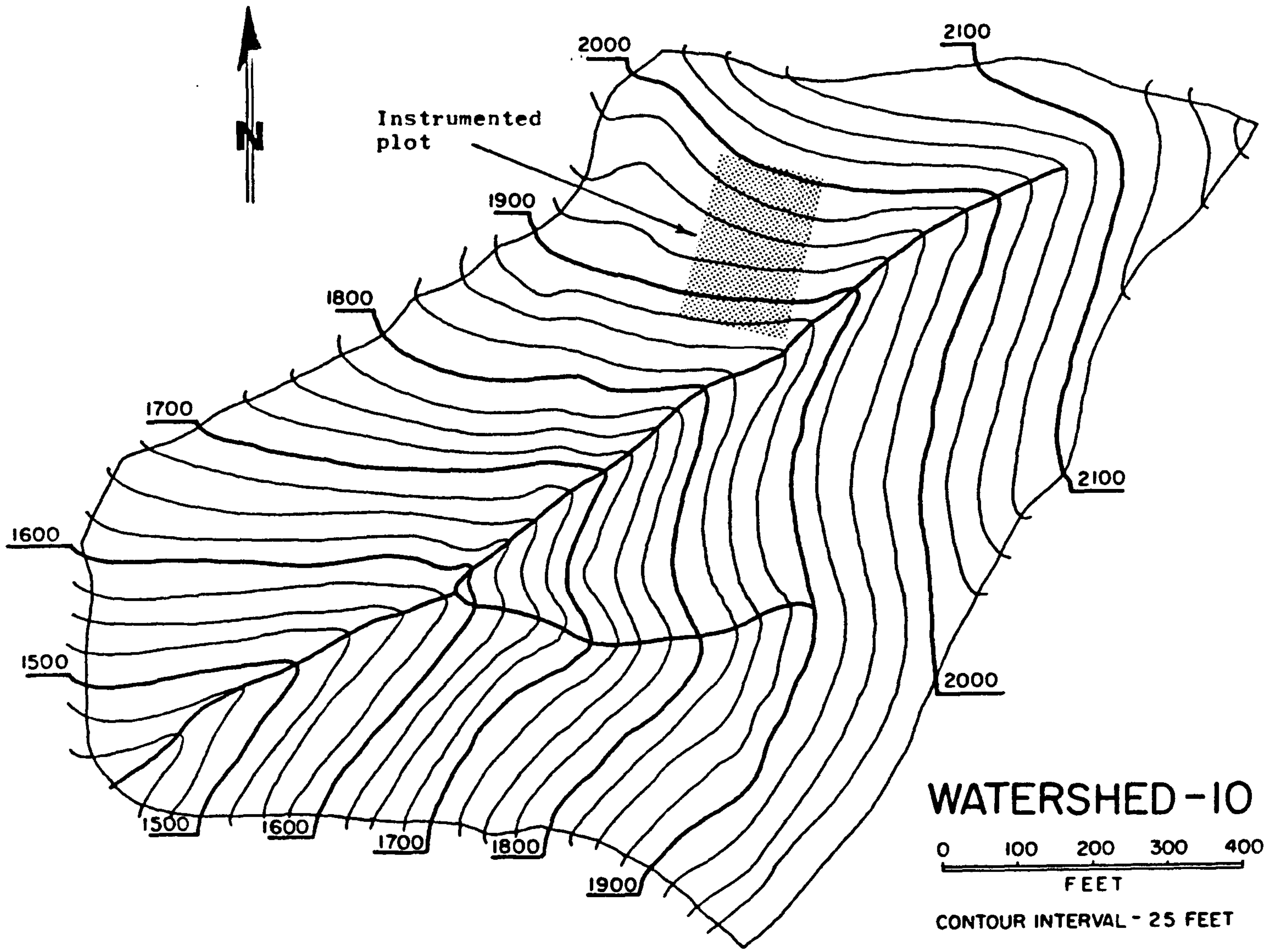

Figure 12. General topography and location of slope instrumentation in Watershed No. 10.

formed from agglomerates, tuff, and breccia--is characteristic of midslope and low-ridge positions. This soil is very unstable and easily disturbed by road construction. The third soil, a clay loam formed from colluvial materials, occupies gentle slopes and benches. All three soil types support forest vegetation and are strongly acid.

Slope instability appears to be strongly correlated with soil type. Dyrness (1967) examined the relationship between mass-movement events and various site factors. He found that mass soil movements occurred much more frequently in areas of pyroclastic rocks (tuffs and breccias) than in areas where the bedrock is comprised of basalt or andesite. In addition, greenish tuffs and breccias appeared to be more unstable than their reddish counterparts. The unstable nature of these materials is even more apparent when one notes that 64 percent of the mass-movements were on greenish tuffs and breccias which make up only 8 percent of the total area. Soil instability is partly related to clay mineralogy. Dominant clay minerals are montmorillonite, kaolinite, and chloritic intergrades. The more unstable soils are those containing montmorillomite as the principal clay mineral (Paeth, 1970).

The instrumented site in Watershed No. 1 is located on largely colluvial material whereas the site in Watershed No. 10 is located on a residual soil derived from tuff. The thickness of soil or depth to bedrock at these sites ranges from 11 to 16 feet.

3. Climate and Hydrology

Precipitation is heavy, varying from 89 inches per year in the lower reaches of Lookout Creek to as much as 140 inches per year along the highest ridges. Rain predominates at the lower elevations, but considerable snowpack develops on the higher slopes. Approximately 82 percent of the annual rainfall on the Experimental Forest occurs from October through March, filling the watershed's natural storage to capacity. Summers tend to be hot and dry with the result that considerable soil moisture depletion (soil water suction) develops in the forested slopes.

4. Vegetation

The predominant forest type, Douglas fir, occurs in a complete range of size classes--from seedlings to large over mature timber. The older age classes, however, are by far the most common. Varying amounts of western hemlock, western red cedar, and sugar pine together with a few hardwood species such as big leaf maple also grow in the forest.

Several understory plant communities have been identified on the forested slopes (Rothacher *et al*, 1967). The type of plant species in these communities reflect the slope and moisture conditions to a considerable extent. A sword-fern community, for example, is found in areas where moisture is abundant. It is located along drainages, on steep north- and east-facing slopes, and in seepage areas. This is the dominant type of vegetation in the instrumented plot in the cutover watershed (No. 1) and it also occurs in parts of the forested watershed (No. 10).

A vine maple-Oregon grape community commonly occurs under a timber stand of variable density and is indicative of a fairly productive site for Douglas fir and hemlock. This understory community is typical of the instrumented plot in the forested watershed (No. 10).

Mature species of Douglas fir were found growing in Watershed No. 10 with a basal diameter of 4 feet or more. Merchantable volumes of timber in these watersheds average 50,000 and 65,000 board feet per acre, and basal areas of all stems 2 inches and over range from 300-500 square feet per acre (Rothacher et al, 1967). Using these figures we calculated (assuming 10 lb per board-ft) that on the average the trees produce a stress of 1000 to 1500 psf immediately beneath their base. When the weight of the trees is spread out over the entire slope, the surcharge drops to 12-15 psf. On the other hand, if the surcharge is calculated according to the procedure adopted by Bishop and Stevens (1964), the stress ranges from 60 to 80 psf. This latter surcharge calculation is based on a density of 100 trees per acre and tree weight distributed over an area of 75 square feet.

Examples of both forested and clear-cut areas are shown in Figures 13 to 15.

5. Slope Stability Problems

Numerous slides and other types of mass-soil movements have occurred on steep slopes in the Experimental Forest. A study of mass-soil movements, particularly those occurring

Figure 13. Typical view of forested slope, Watershed No. 2-3, H. J. Andrews Experimental Forest.

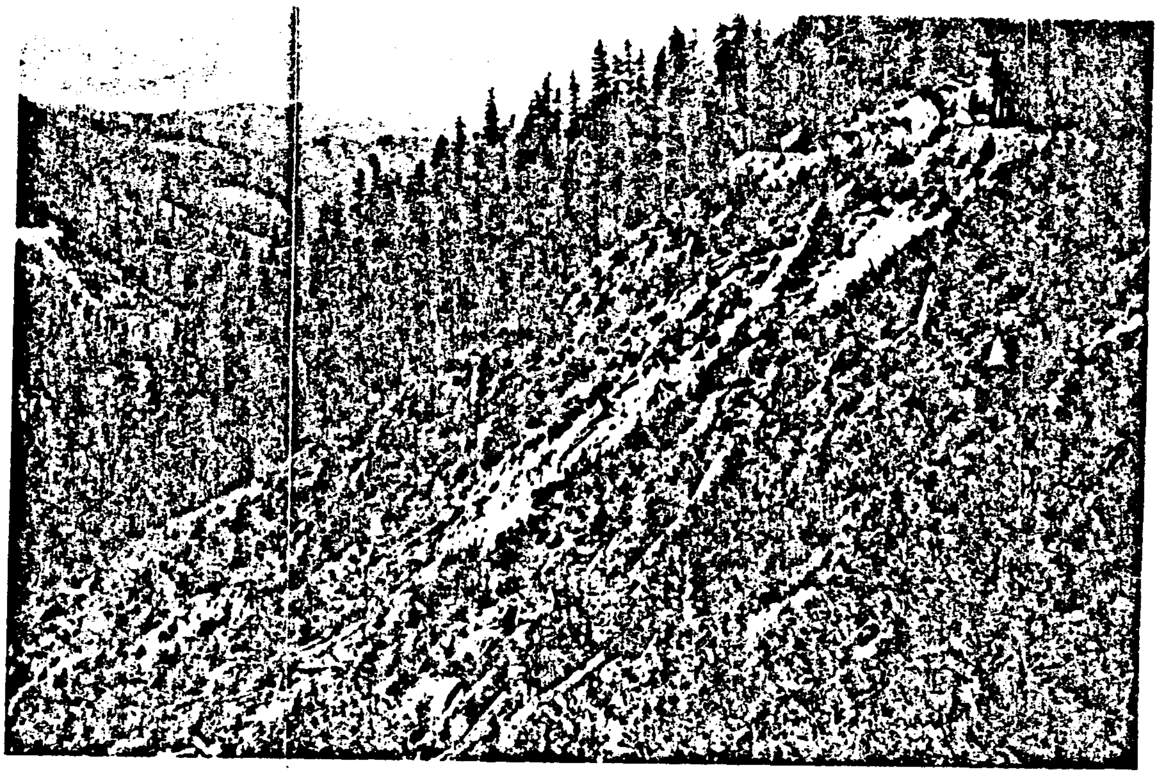

Figure 14. View of clear-cut slope adjacent Watershed No. 10, H. J. Andrews Experimental Forest.

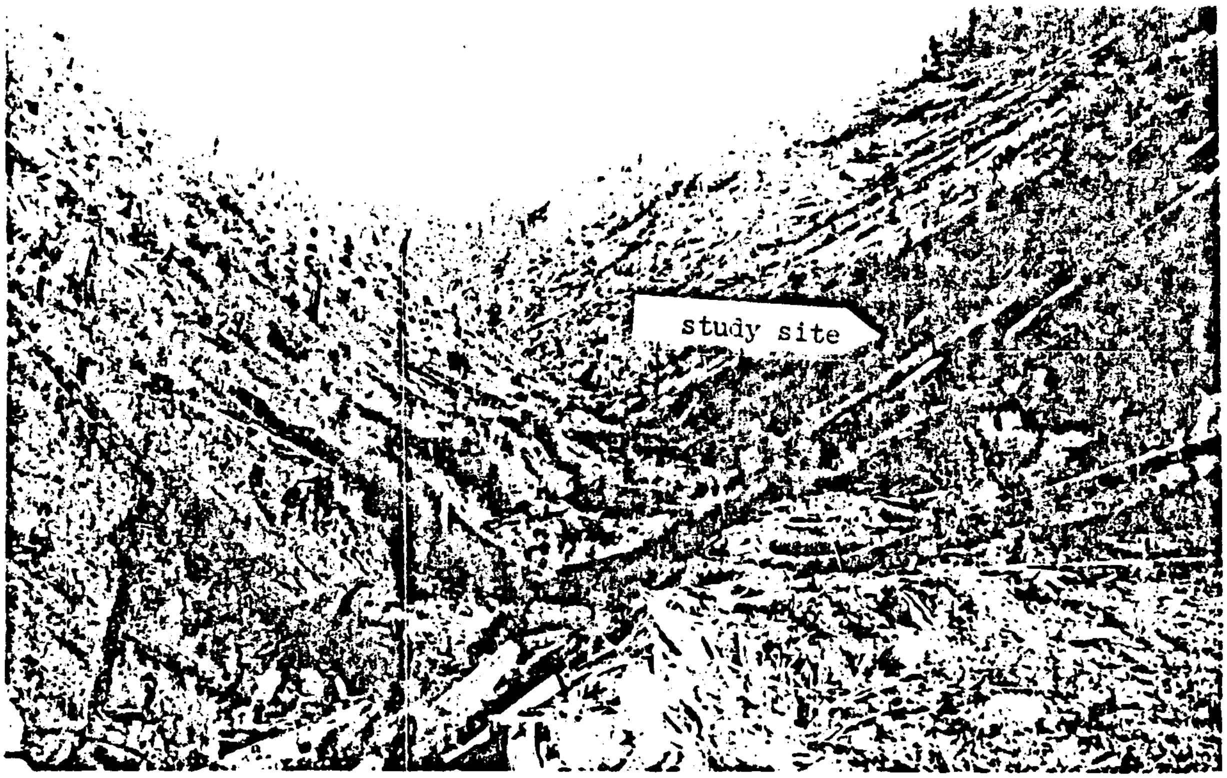

Figure 15. View of clear-cut watershed (No. 1), H. J. Andrews Experimental Forest.

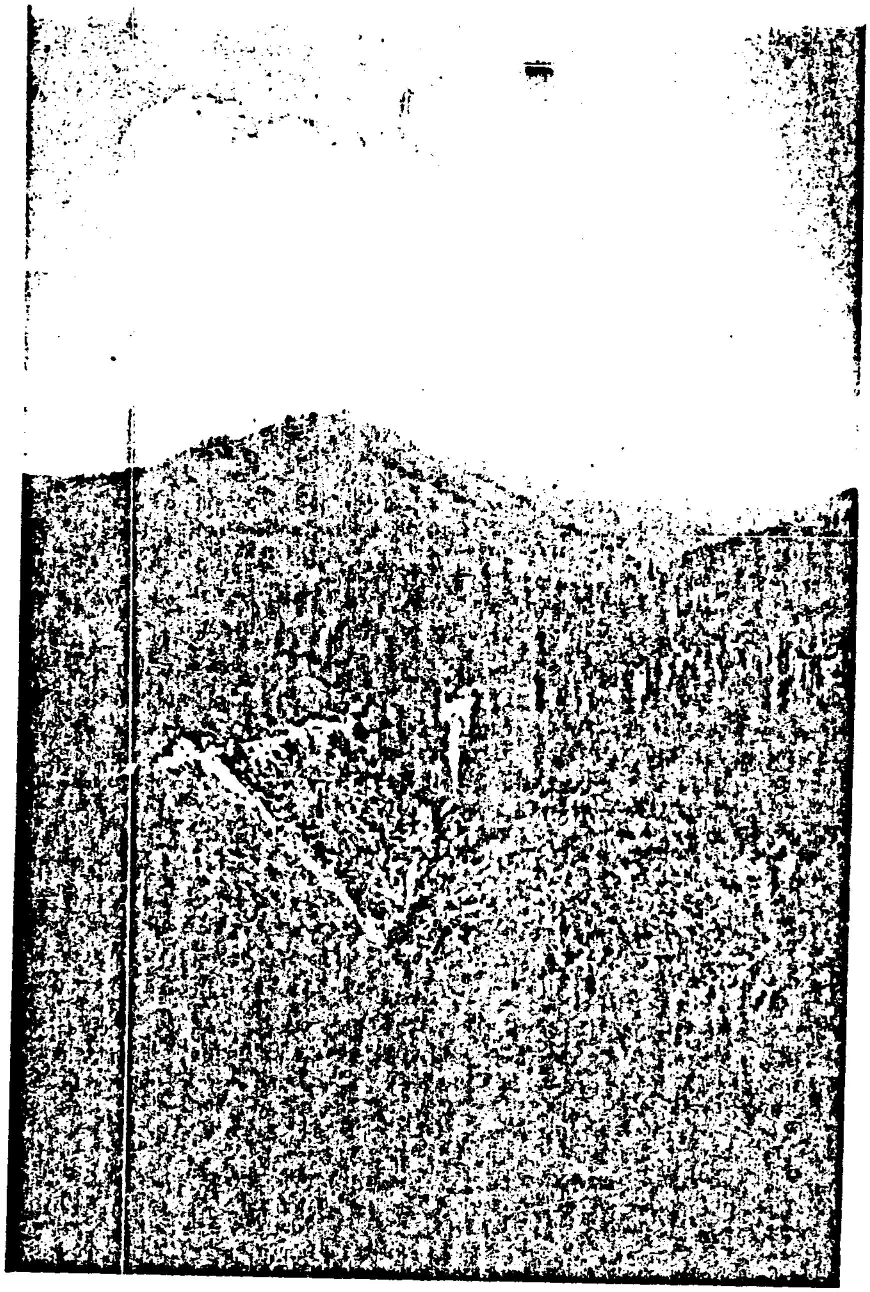

Figure 16. Debris slides in a "logged" and "roaded" slope, H. J. Andrews Experimental Forest.

during severe storms in the winter of 1964-65, was reported by Fredriksen (1965), Dyrness (1967), and Swanson and Dyrness (1975).

Dyrness (1967) described a total of 47 mass movement events. He recorded at each movement site the type of movement, soil characteristics, and general character of the area including such factors as aspect, slope angle, elevation, and prior disturbance by man if any. Earth flows were the dominant type of mass movement followed by slumps.

Dyrness also attempted to assess possible relationships between mass soil movements and certain site characteristics. Several interesting relationships emerged. The influence of roads on mass soil movements was seemingly overwhelming with 126 events per 1000 acres in road areas compared with 0.4 events per 1000 acres in undisturbed areas. Some influence of logging was also observed with a ratio of 3.9 in logged areas compared to 0.4 in undisturbed areas. Swanston and Swanson (1976) point out that the relative impacts of clear-cutting and road construction on the <u>total</u> level of accelerated mass wasting are not clearly reflected in this data. Roads, for example, may indeed accelerate debris-avalanches to a greater extent than clear-cutting, but road right-of-way covers much less of the forest than do clear-cutting units. When road and clear cutting impacts are weighted by area of influence, the two types of forest engineering activities contribute about equally to the total level of accelerated debris-avalanching.

The frequency of mass soil movements was also strongly correlated with soil type as mentioned previously. Other side characteristics correlating with increased frequency of movement included northwest exposure, elevation range 2300 to 2600 feet, and slopes in the range 60 to 70 percent.

C. U. S. NAVAL RADIO STATION, WASHINGTON

1. Location and Topography

This site is located in the watershed of Jim Creek about 12 miles east of the town of Arlington, Washington. The site is characterized by a deep, glacial valley some 8000 feet wide by 2000 feet deep which has been substantially modified in the past by landslides. This valley is bounded to the northeast by Wheeler Mountain and to the southwest by Blue Mountain. The Naval Station is situated in the midst of Mount Baker National Forest. A map showing the location and topography of the site is given in Figure 17.

Because of its favorable topography and location, the site was selected by the U. S. Navy for a major radio communications facility. Two hundred-foot towers were erected on opposite ridges to support an overhead aerial system spanning the valley below. Soon after construction of the antenna system the Navy decided that ground vegetation on the valley sides beneath the antennas was interfering with radio operations. The Navy consequently removed all woody vegetation directly underneath the antennas.

This site was of particular interest because portions of the watershed had not been cutover. This provided a tailor

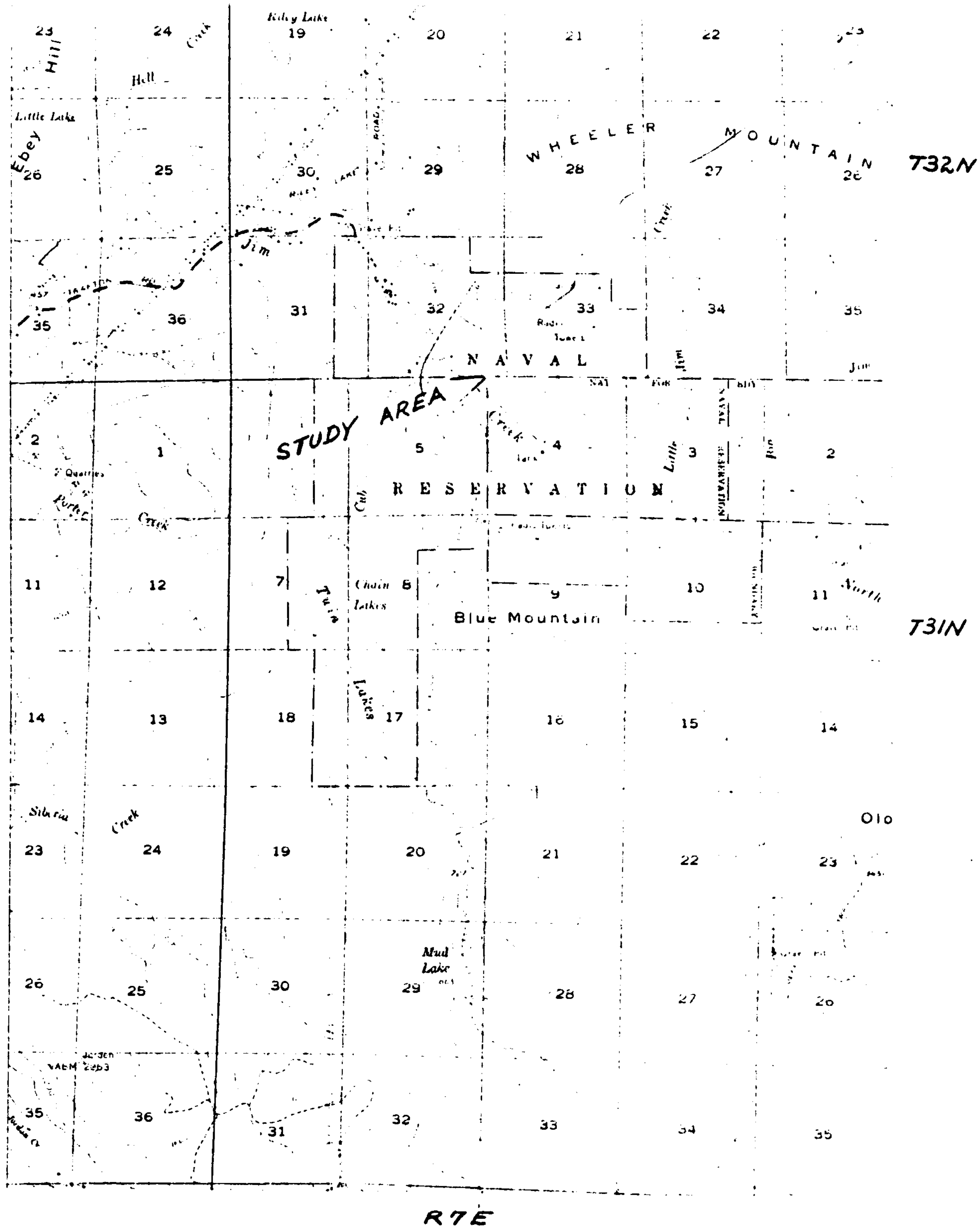

Figure 17. Location of field site at the U. S. Naval Radio Station, near Arlington, Washington (from USGS Granite Falls quadrangle).

made location for a side-by-side comparison of soil moisture stress and creep rates in forested as opposed to adjacent cutover slopes. The extent of timber removal at Jim Creek is shown in the topographic map in Figure 17. A view of a forested and cutover portion of a slope separated by an abrupt tree line on the Wheeler Mountain side of the valley is shown in Figure 18. General views illustrating the topographic features and denudation of valley sides are shown in Figures 19 and 20.

2. Soils and Geology

The bedrock of the site is mostly interbedded graywacke, slate, and phyllite. Surficial deposits in general consist of talus on the upper slopes and deposits of glacial till on the lower slopes. The soils and geology at the site have been described in detail by Crandell and Waldron, 1952; and Waldron, 1954.

Talus deposits are more common to the upper parts of the valley sides above 2000 feet elevation. They typically consist of angular cobbles and boulders in a matrix of sandy silt. Talus slides occur on the upper slopes in winter.

Deposits of glacial till blanket the lower slopes to depths of 25 feet in some places. Soil depths at the instrumented sites are shallow, however, ranging from only 4 to 7 feet.

The fill was deposited as a lateral moraine by a valley glacier. It consists of angular fragments of phyllite, slate, and graywacke in a matrix of well-graded silty sand. Till

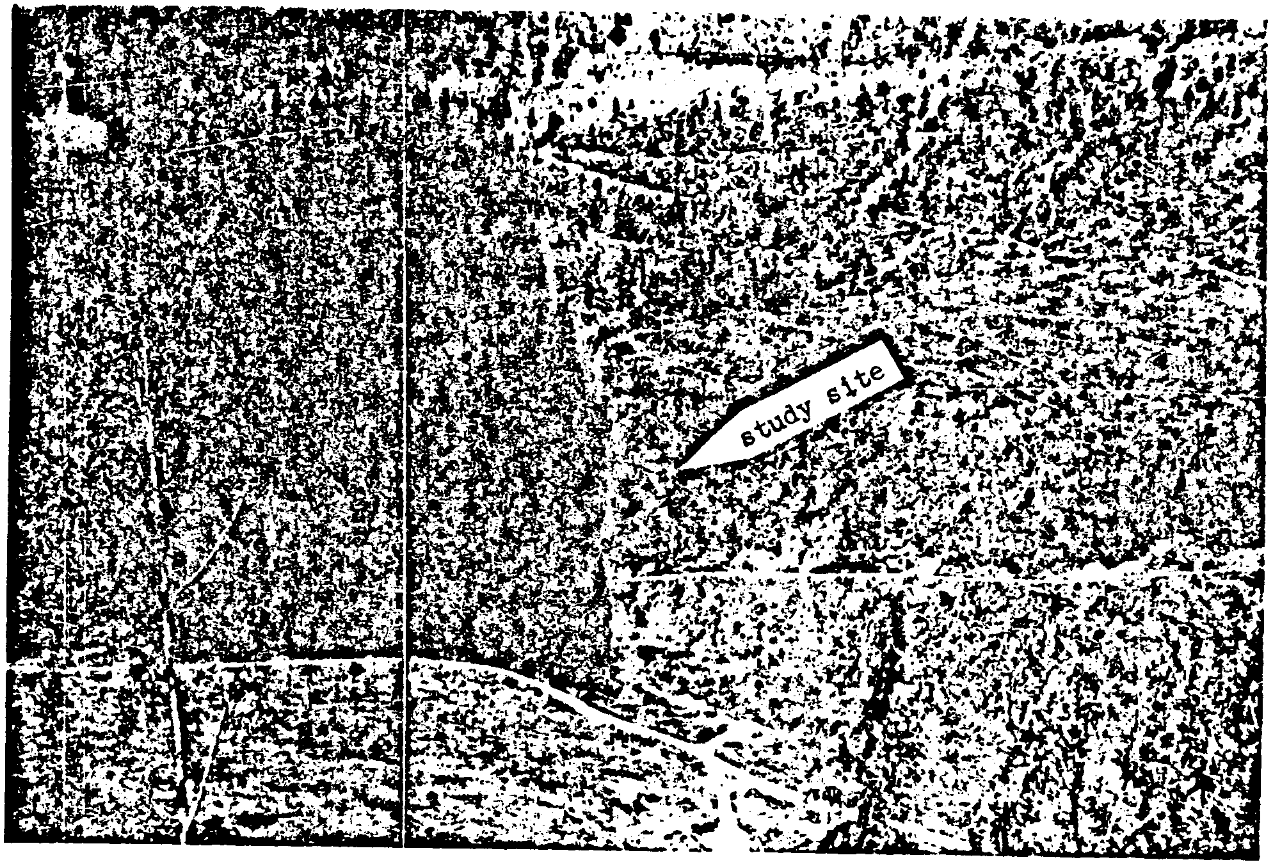

Figure 18. Forested and cutover portions of slopes at the U. S. Naval Radio Station.

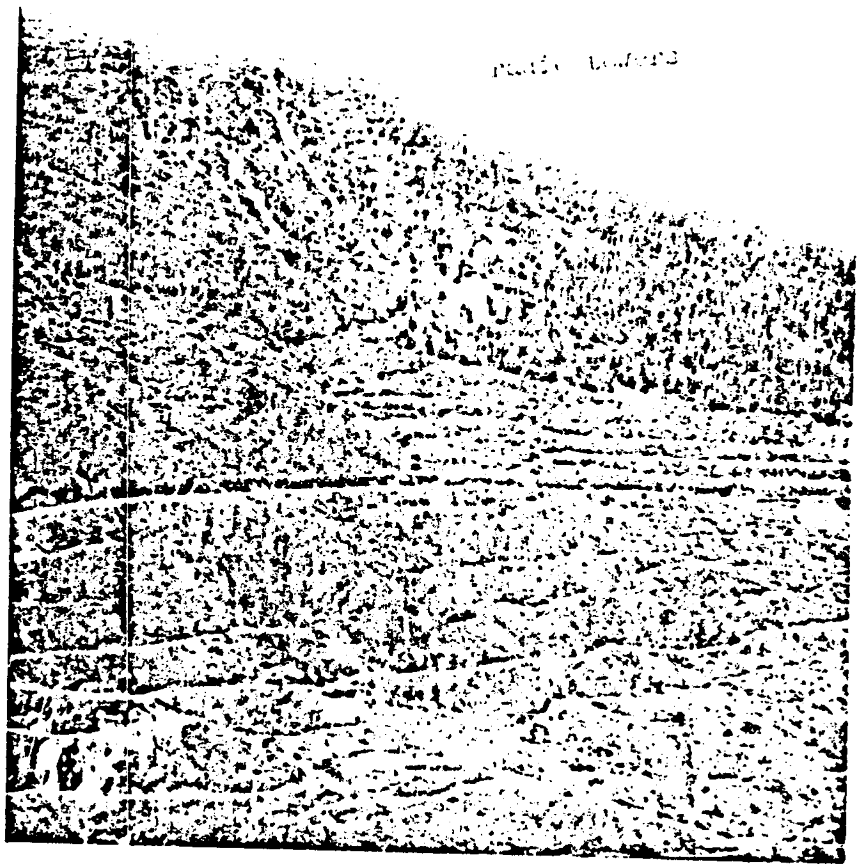

Figure 19. View of cutover slopes on valley sides, U. S. Naval Radio Station.

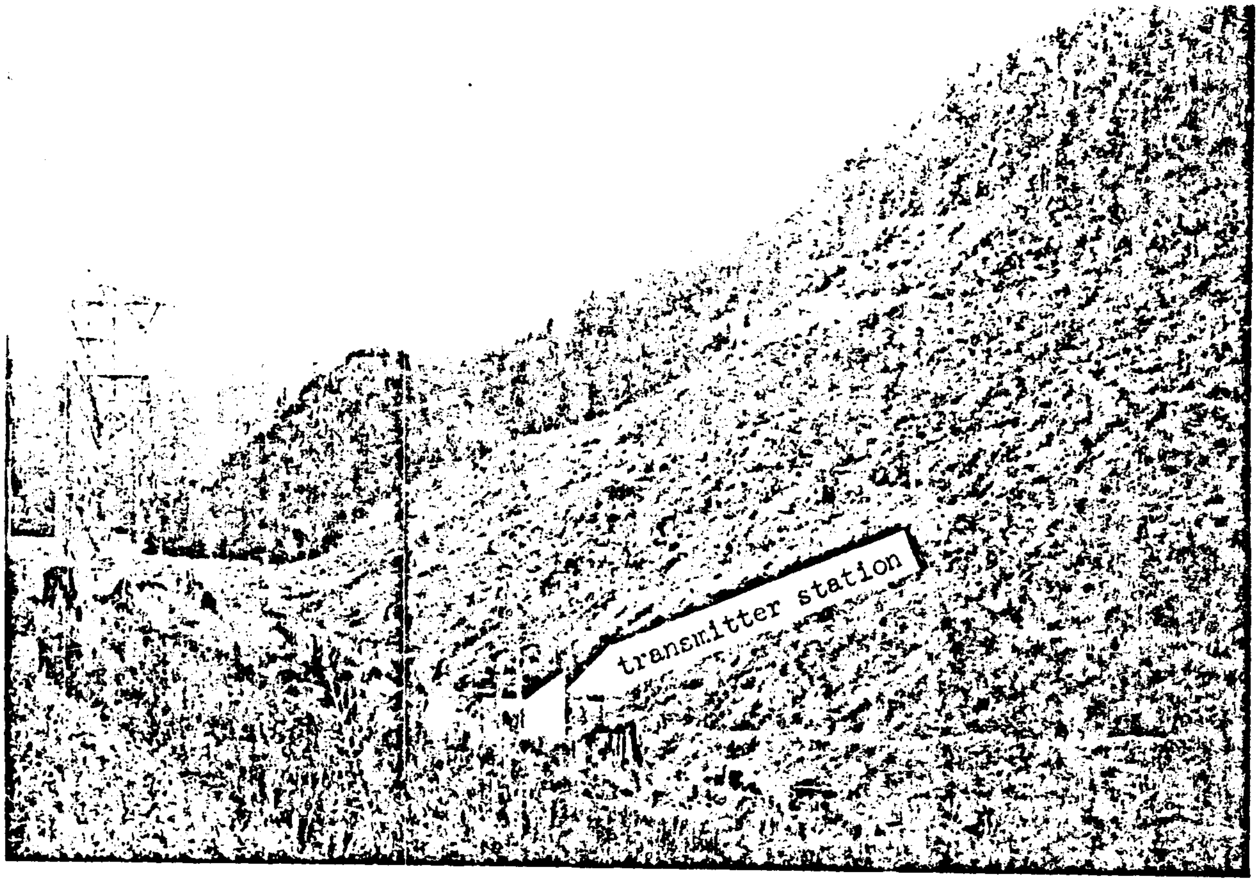

Figure 20. Down valley view showing extent of denudation of slopes at U. S. Naval Radio Station.

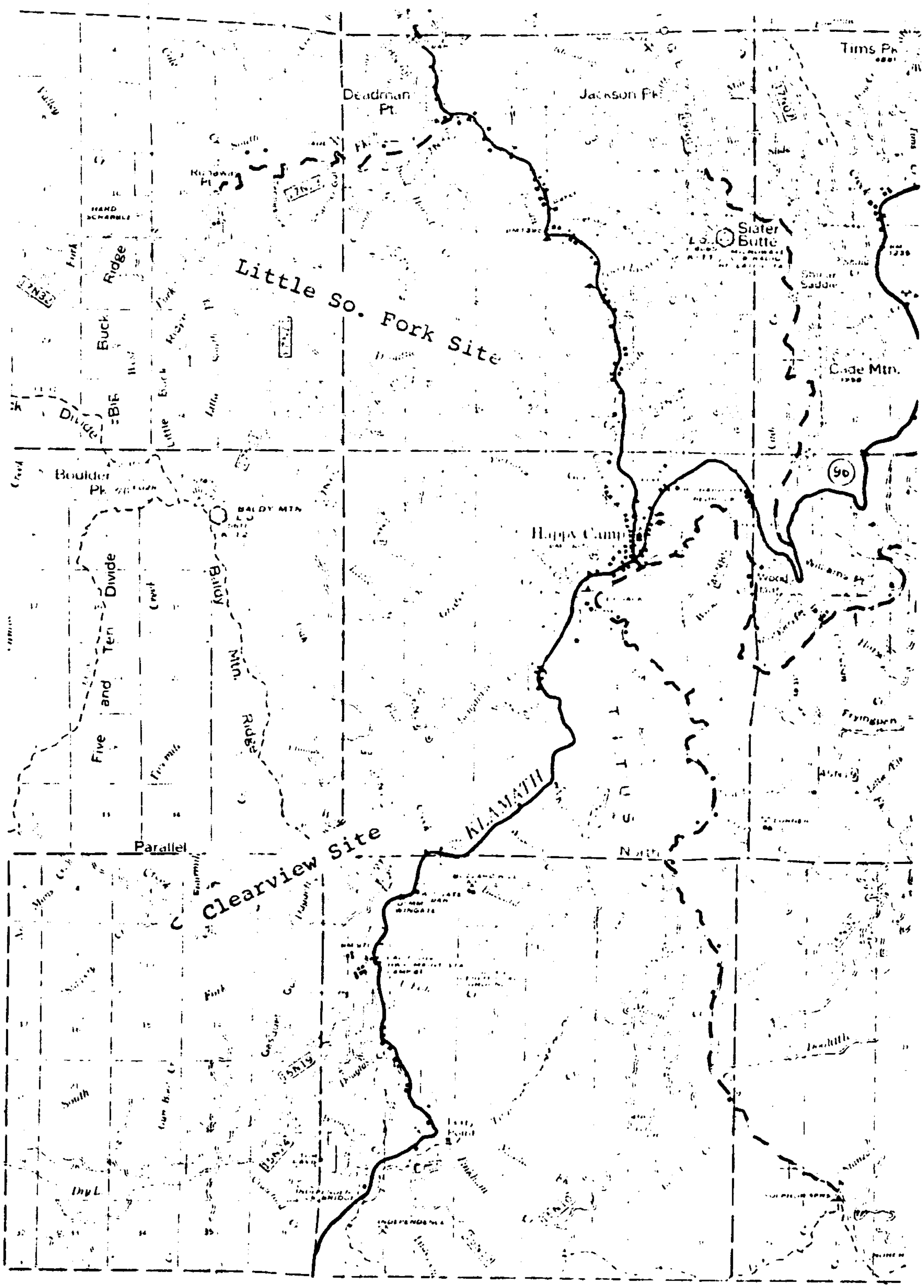

Figure 21. Location of field study sites in the Klamath National Forest (from USFS recreation map, Happy Camp Ranger District).

landslide which was cutover several years ago. The influence of tree removal on the velocity of downslope movement in this slope is unknown because no records on observations were made prior to timber harvesting. Fossil slides often develop deep soils and are relatively stable under modern, climatic conditions. Unfortunately, logging and road construction in the region sometimes reactivates slippage (Hicks and Collins, 1970). The other site in the Little South Fork area (referred to as the Little South Fork annex) is nearly adjacent and is an active slide. It still retains a tree cover, although many trees are canted at extreme angles as a result of deep seated movement. Both these sites were instrumented to obtain an estimate of the extent and rate of deformation in slide areas.

The Clearview sale site was originally forested and was instrumented in 1970 in order to obtain a "before-and-after" comparison of creep rates following clear-cutting. This site was clear-cut during the summer of 1974.

2. Soils and Geology

The geology of the Klamath Mountains is complex; they consist essentially of metamorphic rocks intruded by granitic and ultramatic masses. The metamorphic rocks are mainly schist, phyllite, slate, chert, and marble. The granitic rocks are granodiorite, quartz diorite, and hornblende diorite. Thrust faults, trending north-south and dipping east, separate major lithologic boundaries. Many of the ultramafic bodies were intruded along the thrust faults.

In the Klamath Mountains, the three major rock units, (1) granitic, (2) metamorphic, and (3) ultramafic, are associated with different soil types and these in turn present various stability problems (Hicks and Collins, 1970).

Weathering decomposes and disintegrates granite to a depth of several feet. Weathered granite breaks down readily to sand-and-silt size particles. Granitic terrain is particularly subject to surface erosion and debris flows. Slope stability problems in granitic areas are similar to those described by Gonsior and Gardner (1971) in their study of slope failures in the Idaho batholith.

Among the metamorhpic rocks, the Jurassic Galice formation, composed principally of slate and phyllite, contains numerous landslides. The abandoned site on Condrey Mountain was situated on a decomposed graphitic schist. These graphitic zones are very unstable especially in the presence of water.

Highly fractured and sheared serpentized ultrabasics are a characteristically weak foundation material found throughout the western part of the Klamath National Forest. The Little South Fork sites are underlain by unstable, serpentine soils ranging in depth from 8 to 12 feet.

The Clearview Site is underlain by a thick section of moist gravelly-clay colluvium ranging in depth from 15 to 20 feet. A metamorphic, disintegrated slate comprised much of the rock fragments in this material.

3. <u>Climate and Hydrology</u>

Precipitation in the Klamath Mountains averages about 55 inches per year. This is considerably less than the average for the Washington and Oregon sites, but most of this precipitation falls as concentrated rain during the winter months. Long periods of rain interspersed with high intensities (1 to 2 inches per hour) accentuate the low degree of stability found throughout the Klamath Mountains. Evidence exists (Hicks and Collins, 1970) that clear-cutting on or above a fossil landslide will increase the water content or influx of water into weak landslide material, and this may lead to ground saturation and failure.

4. <u>Vegetation</u>

Like the other study areas, Douglas fir is the dominant species on forested slopes in the region. Incense Cedar and Ponderosa or Yellow Pine are also prevalent. These latter forest species thrive on harsh, serpentine soils, where Douglas fir will not.

5. <u>Slope Stability Problems</u>

The Klamath Mountains portion of the Klamath National Forest (where the study sites are located) is particularly susceptible to mass wasting on a grand scale due to the combination of steep terrain, high precipitation intensity, and a wide range of unstable surficial materials and bedrock. In such a precarious setting, road construction and logging sometimes creates problems.

Dunlap and Moore (1970) have provided a detailed account of serious soil erosion and mass-wasting in the region...most of it associated with logging operations. Hicks and Collins (1970) likewise have described slope stability problems in the area. Four specific situations were discussed by these latter investigators (1) landslides due to road cuts, (2) landslides due to ground water increases in or downslope of clear-cut areas, (3) reactivation of fossil landslides, and (4) debris flows.

IV. SLOPE INSTRUMENTATION

A. MEASUREMENT OF SOIL MANTLE CREEP

The principal objectives of the slope instrumentation were measurement of creep rates and soil moisture stress before and after clear-cutting. This section describes the field instrumentation and procedure used to measure rates of downslope movement or soil mantle creep.

A commercially available inclinometer known as a Slope Indicator was selected for this purpsoe. Inclinometers are used extensively in civil engineering practice to investigate the performance of embankments and to monitor earth movements in natural slopes. These devices basically consist of a pendulum-activated transducer enclosed in a watertight torpedo, which is lowered down a near-vertical casing. The inclination from vertical is measured at successive intervals down the casing. Lateral movements in a slope deflect the casing, thus changing its inclination. Changes in inclination with time can be translated back into a deformation versus depth curve which varies with time. From these curves it is then possible to calculate creep rates in the soil mantle.

The inclinometer (or Slope Indicator) used in the present study has been described in detail by Wilson (1962). It consists of a pendulum-actuated Wheatstone-bridge circuit enclosed in a wheel-mounted torpedo whose azimuth is controlled by vertical grooves formed in the walls of special extruded aluminum casing. The output from the sensing element of the device can be remotely read at a control box at the top of the casing. The control box at the ground surface is connected to the instrument with a multiwire conductor having a stranded steel cable in the center. This cable is used to support the weight of the instrument while it is lowered down the casing. The grooved deformable casing, which comes in sections 5 feet or 10 feet long, is joined together with couplings which are also grooved. A photograph showing the inclinometer, control box, and the top part of the aluminum casing is shown in Figure 22. The sensitivity of the instrument is rated by the manufacturer at one part in 1000, which means a change of inclination of as little as 3 minutes of arc can be detected. This corresponds to a lateral movement of a tenth of an inch in 10 feet.

The precision of the slope indicator was investigated by having a single operator run eight consecutive soundings on a 20-foot deep reference tube installed in flat, level ground at the University of Michigan. The results of these tests were plotted in terms of a cumulative error band or 90 percent confidence limits around the mean reading for both the E-W and N-S grooves. The results of this plot indicated that a profile precision within $\pm$ .003 in/ft is possible provided the data is obtained each time by the same operator carefully following a standardized procedure. The possibility of spurious changes in inclination caused by a shift in the zero or internal reference of the instrument with time was also checked each year. This was done by lowering the instrument down a fixed, reference tube installed in flat, level ground each time before reading the slope tubes. No significant nor systematic changes in inclination of this fixed tube were detected during the eight years of monitoring; hence the instrument zero was assumed to be constant.

The installation of the slope indicator casing is a critical step. It is important that the casing be in effective contact with the surrounding soil so that changes in inclination reflect movements in the entire soil mantle and not just local movement and settlement around the casing as a result of the installation procedure. To insure that this would be the case we adopted the procedure of drilling a slightly oversized hole, inserting the casing, and backfilling the annular space with dry sand. The diameter of the drilled hole was 6 inches, that of the casing, 3 inches.

By using a so-called single grain, air dropping technique it was possible to obtain a backfill with a minimum void ratio (or maximum relative density) which completely occupied the annular space and which could deform, but not compress. This technique of backfilling is one recommended by the manufacturer of the Slope Indicator. It is also a technique of depositing dry sand which has been investigated extensively in the Soil Mechanics Laboratory at The University of Michigan and which has been found consistently and reliably to give minimum void ratios. "Single grain air dropping" and minimum void ratios can be achieved in the field by raining a uniformly graded, dry sand through a sieve with a mesh size slightly larger than the grain size of the sand. Figure 23 is a photograph illustrating a backfilling operation in

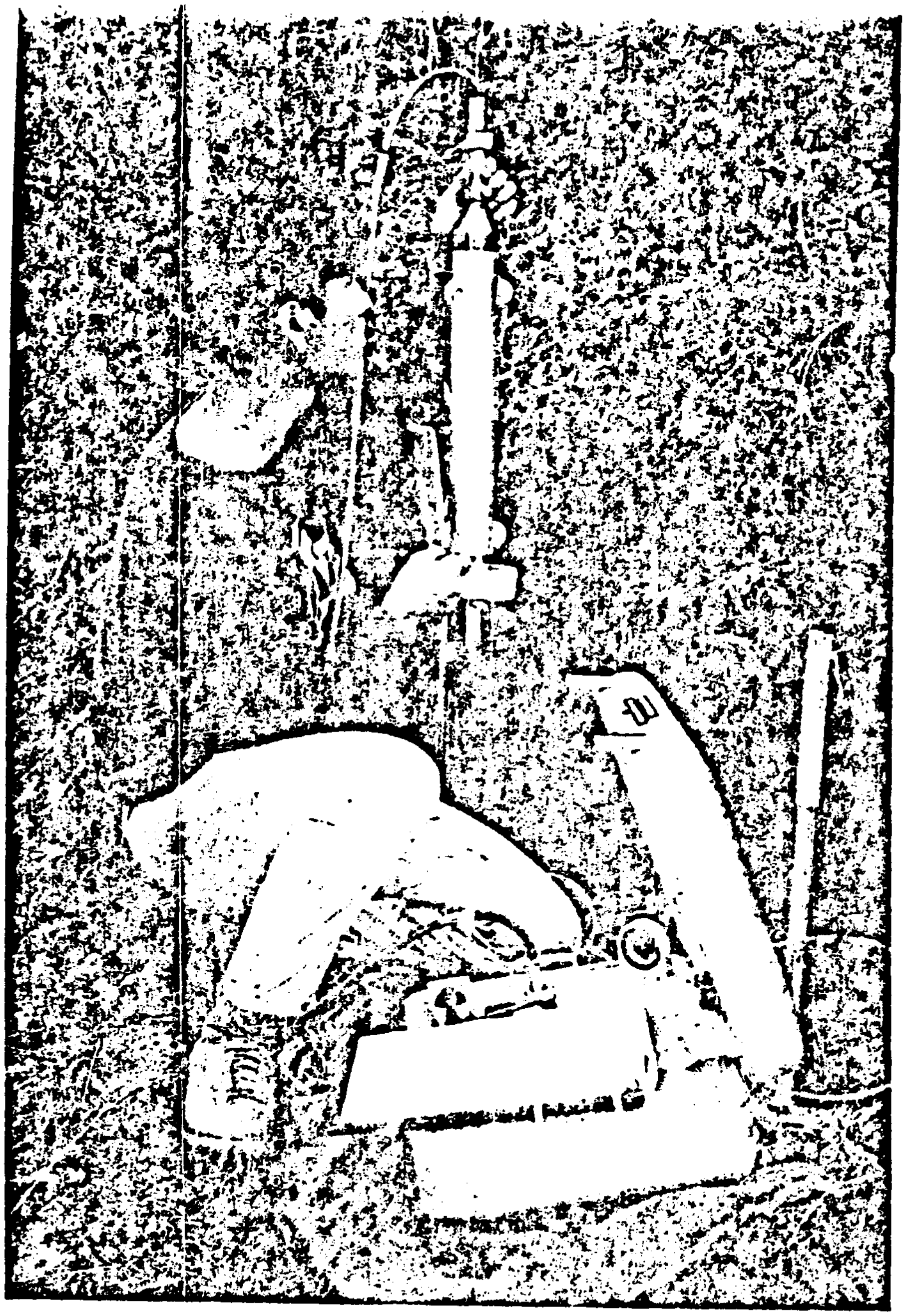

Figure 22. Slope indicator, control box, and top of casing or tubing.

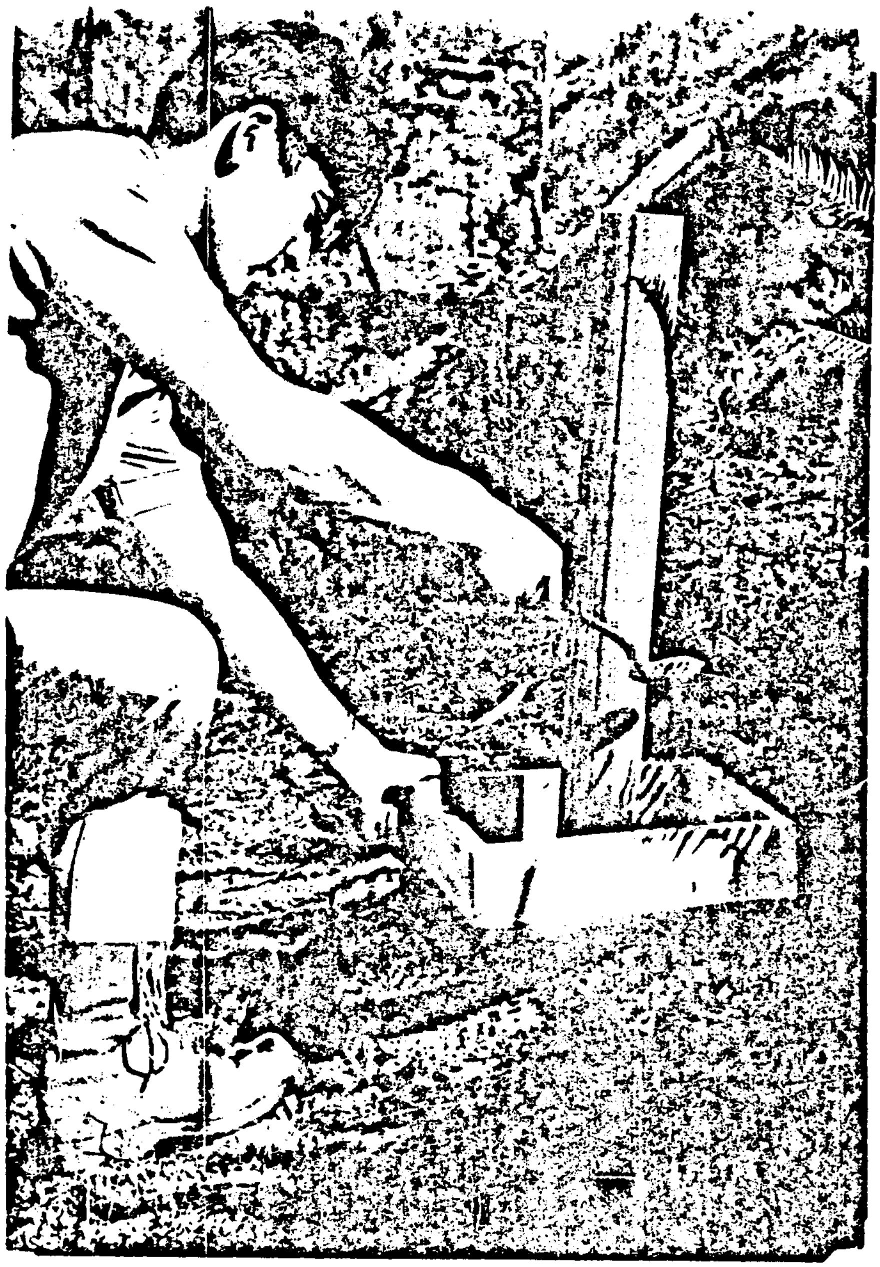

Figure 23. Backfilling around slope indicator casing using the "single grain air dropping" technique.

progress. We used a dry, 30-mesh, Monterey sand for backfilling purposes. It is important that there be no free or standing water in the hole during backfilling.

The holes for the slope indicator casing were drilled using a portable, two-man, gasoline-powered flight auger. The photograph in Figure 24 shows a hole being drilled with this equipment at the field study site in central Oregon. The power auger was used down to a depth of about 10 to 12 feet. Past this depth is was more practical to use a hand bucket auger and accessory drilling tools. We used an Acker drill set for this purpose.

The bottom of the casing was anchored in fractured bedrock. This was achieved by drilling into the fractured bedrock about a foot with a chopping bit and then bailing out the debris. We assume in the data analysis that the bottom of the casing, anchored in the fractured bedrock, remains fixed in place.

There are two sets of longitudinal grooves, perpendicularly opposed to one another, in the casing. One set was always oriented down slope when the casing was installed in the holes. The wheels on the slope indicator torpedo (or instrument housing) track down one set of grooves thus keeping it on a fixed azimuth. By lowering the instrument down the casing in these two mutually perpendicular directions it is possible to obtain the azimuth and magnitude of the maximum horizontal movement.

In the case of those watersheds scheduled for clear-

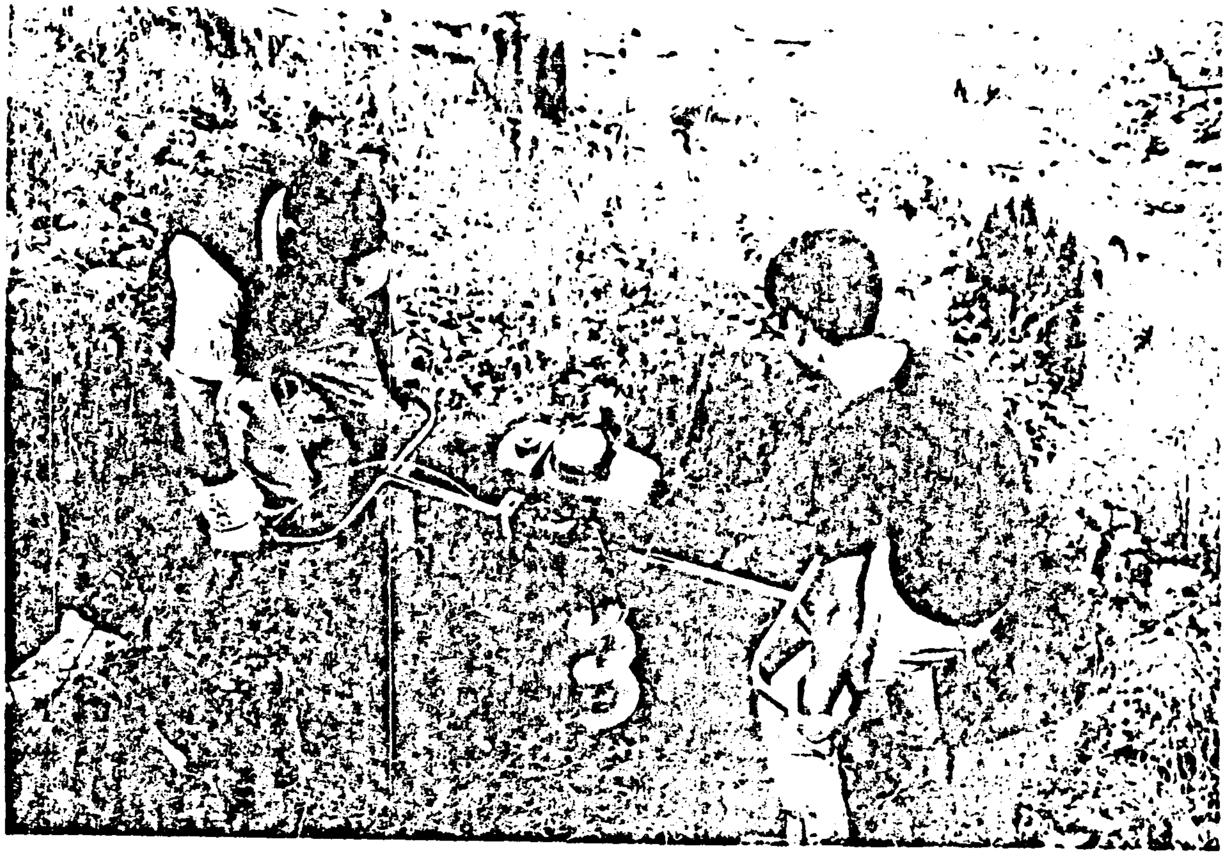

Figure 24. Drilling a hole for a slope indicator tube using a portable, power auger.

cutting, it was necessary to install the casing in such a manner that it would not be damaged during logging operations. Accordingly, a coupling and removable section were attached to the casing about 18 inches below the ground surface. Each of the holes was then carefully surveyed so that they could be relocated without the tops of the casings being visible above ground. During logging, the top sections of the casings were removed, the casing capped, and the top of the hole filled over completely.

Six inclinometer tubes were installed in a random pattern in Watershed No. 1 (clear-cut), five in Watershed No. 2-3 (forested), and six in Watershed No. 10 (forested). In the case of Watershed No. 10, one of the inclinometers was installed in the midst of an area of dead Douglas fir trees. This inclinometer is located only 6 feet away from a large diameter Douglas fir snag as shown in Figure 25. The location or siting pattern of the inclinometer tubes at the Oregon sites is shown in Figures 26 and 27.

Nine inclinometer tubes were installed in a line parallel to the slope but straddling the tree line at the U. S. Naval Radio Station as shown in Figure 28. In addition, an inclinometer installed by the Navy in a deep section of glacial till on a slope immediately above the transmitter station, was also monitored.

A total of eleven inclinometer tubes were installed at the various sites in the Klamath National Forest; seven in the Little South Fork area, three in the Clearview sale site,

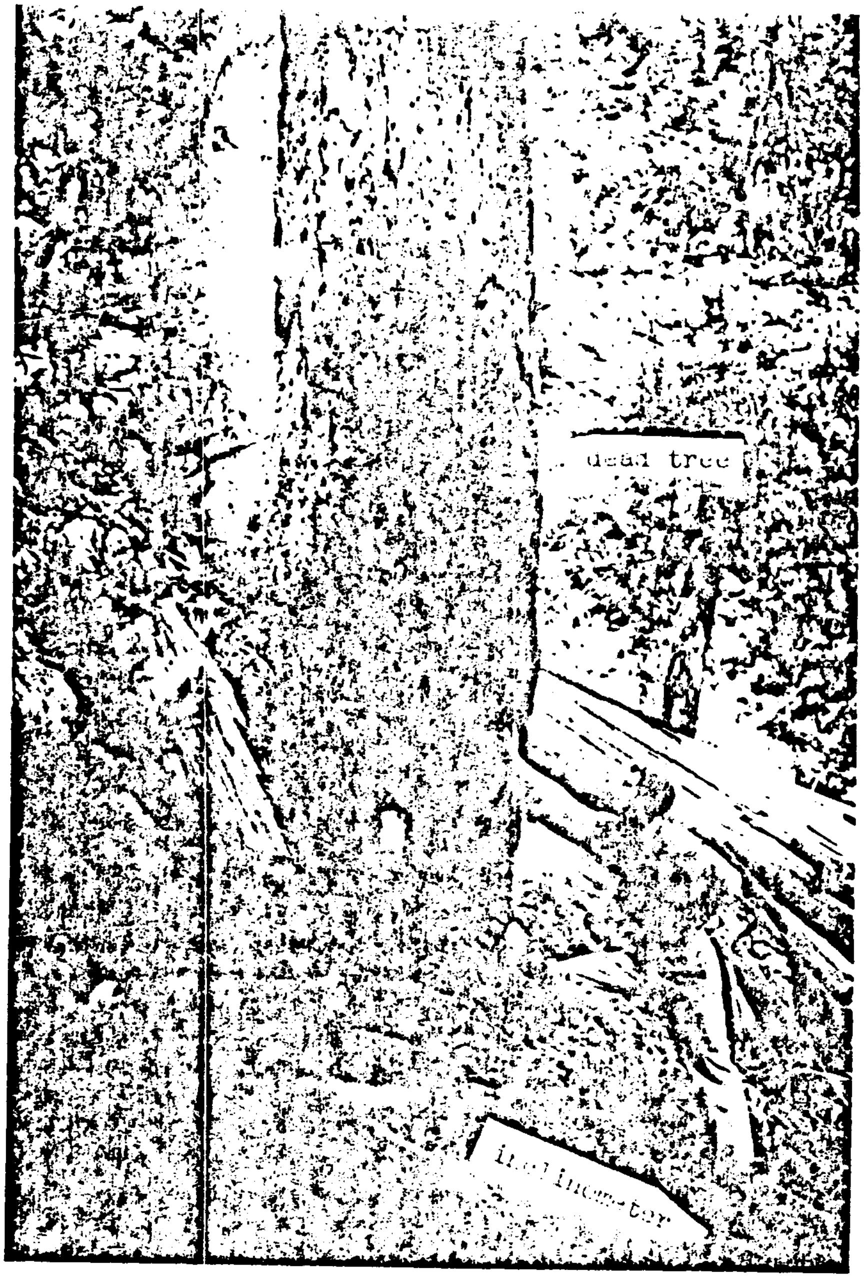

Figure 25. Douglas fir snag (dead tree) located next to inclinometer tube No. 4, Watershed No. 10, H. J. Andrews Experimental Forest.

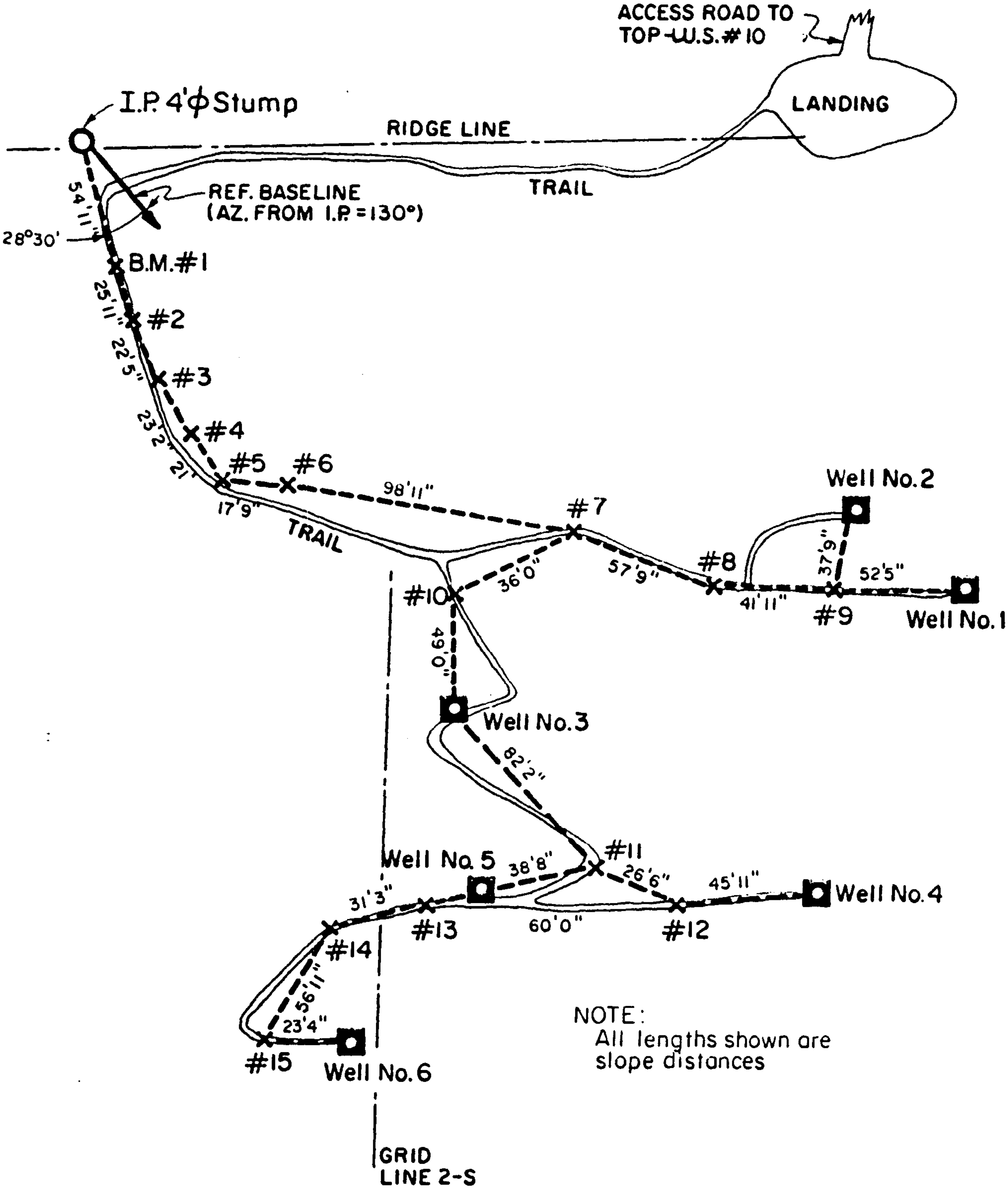

Figure 26. Surveyed location of inclinometer tubes, Watershed No. 10, H. J. Andrews Experimental Forest.

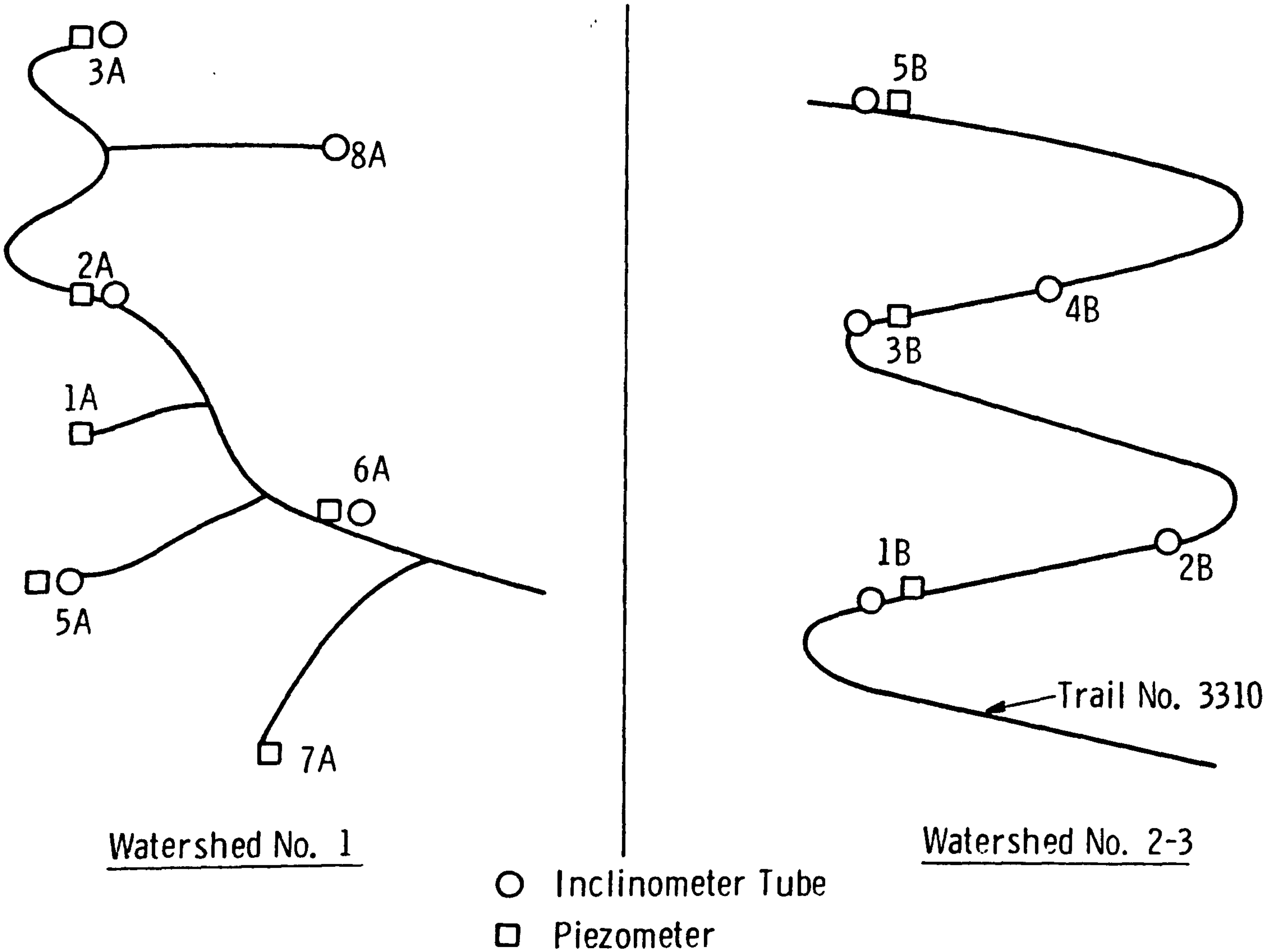

Figure 27. Approximate location or siting pattern of inclinometers in Watersheds No. 1 and No. 2-3, H. J. Andrews Experimental Forest.

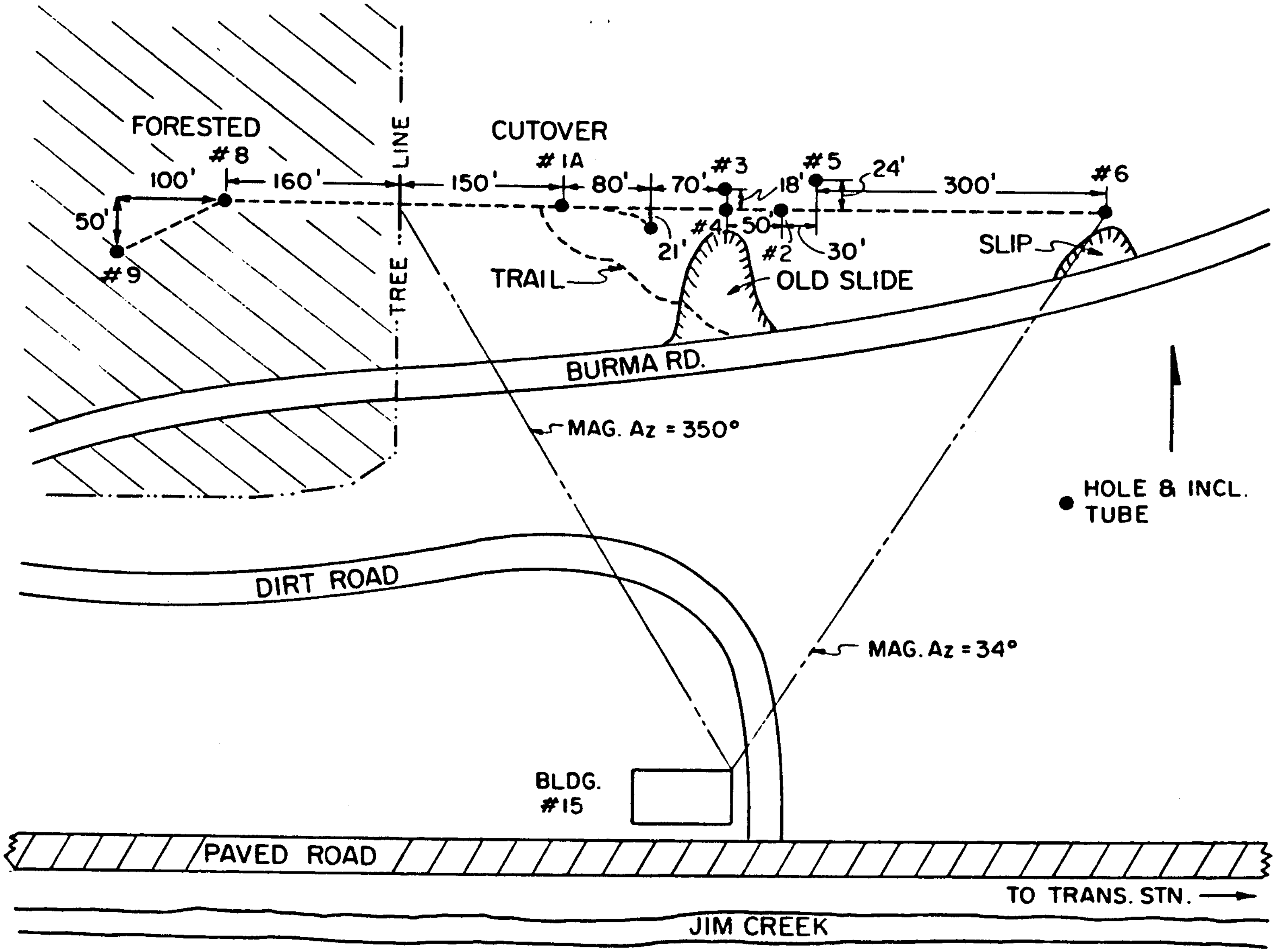

Figure 28. Inclinometer tube locations, U. S. Naval Radio Station, Jim Creek, Washington.

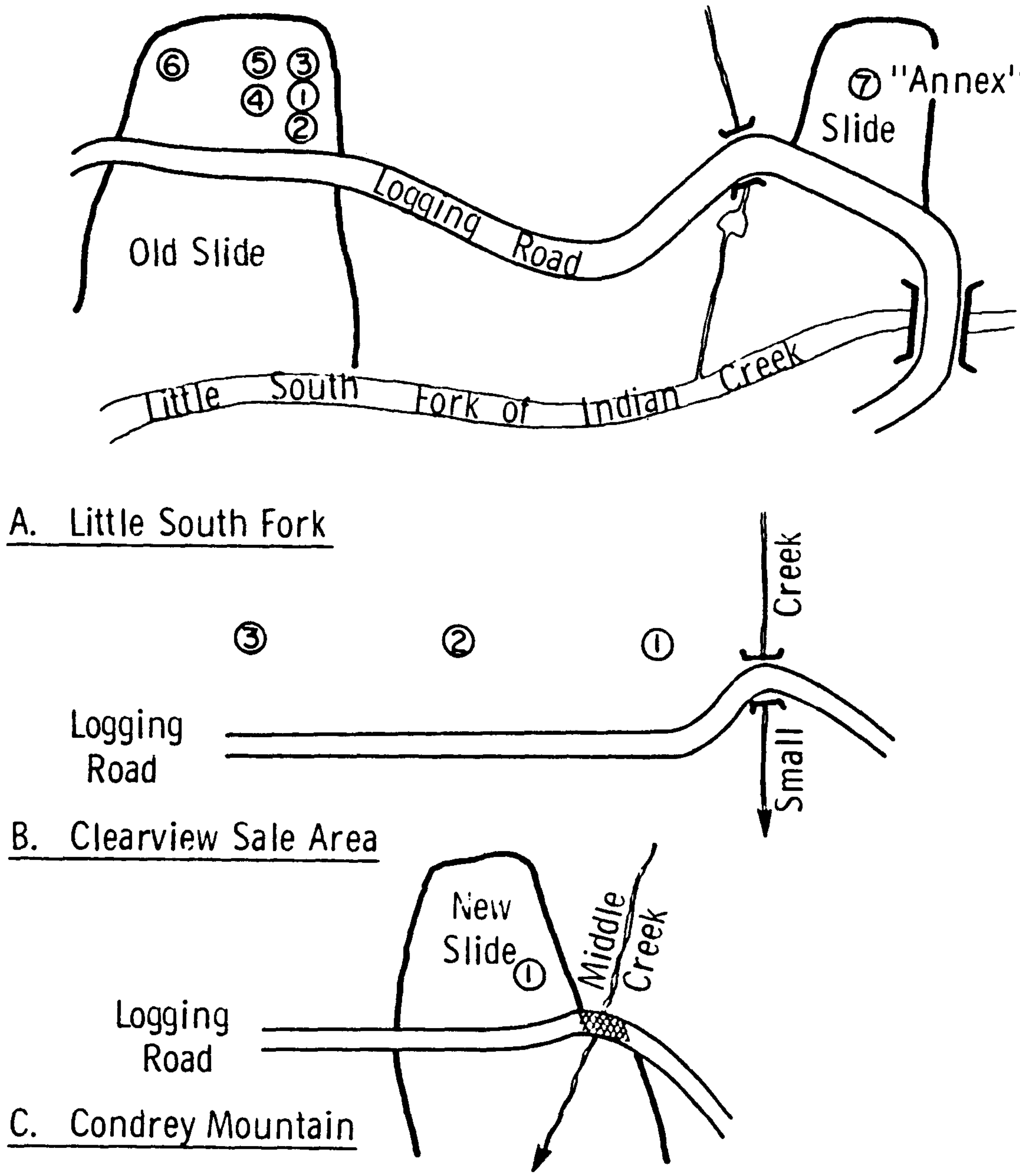

Figure 29. Siting pattern for inclinometer tubes installed at various sites in the Klamath National Forest.

and one in the Condrey Mountain site. The location pattern for the inclinometer tubes at these sites is shown schematically in Figure 29.

B. MEASUREMENT OF SOIL MOISTURE STRESS

There are several alternative methods of measuring soil moisture stress. These include conventional piezometers, maximum recording piezometers, conventional tensiometers, and recording tensiometer-piezometers. The advantage and limitations of each of these methods in regard to the present study has been discussed previously by Gray (1969).

With the notable exception of the cutover portion of the site in Washington, all the sites exhibited soil moisture suctions (negative pore pressures) during most of the year. We decided, therefore to monitor the soil moisture regime with tensiometers. Where ground water tables or piezometric levels develop in the slope, such as the site in Washington, the inclinometer tubes served as piezometers as well. Furthermore, by adjusting the zero point of a tensiometer it is possible to use it as a piezometer over a limited range. One foot of rise in the groundwater table above the porous, measuring tip corresponds to about 3 centibars.

A total of six tensiometers were installed adjacent to the inclinometer holes in Watershed No. 10, H. J. Andrews Experimental Forest. Three tensiometers were installed adjacent the inclinometer holes in the Clearview site, Klamath National Forest. Four-foot long, Bourdon gage type tensiometers were used. These have a sensitivity of only 1 or 2 centibars compared to 1 or 2 millibars for the mercury manometer type, but they are far more rugged. The tensiometers were installed with their measuring tips 5 feet below the surface of the ground and their tops recessed about a foot below the ground surface in a 4-inch diameter cased hole. Figure 30 is a schematic illustration of a typical tensiometer installation.

Tensiometers will cavitate and eventually lose their water at negative pressures or suctions greater than 1 bar. Suctions on this order and higher are common in the top few feet of a forested slope, especially during the summer months (Patric, et al, 1965). For this reason it was necessary to recharge the tensiometers at the end of the summer and also be careful in taking subsequent readings to ensure that low readings in fact meant saturated conditions in the slope and not a spurious effect of cavitation.

Tensiometers were scheduled to be read at least once a month and after major storms. This schedule was not consistently followed because of access problems to the sites. The data from the tensiometers was compared with precipitation records in order to determine the relationship between soil moisture stress and antecedent precipitation in a forested slope. The same procedure was followed after clear-cutting and the soil moisture response compared to the forested condition.

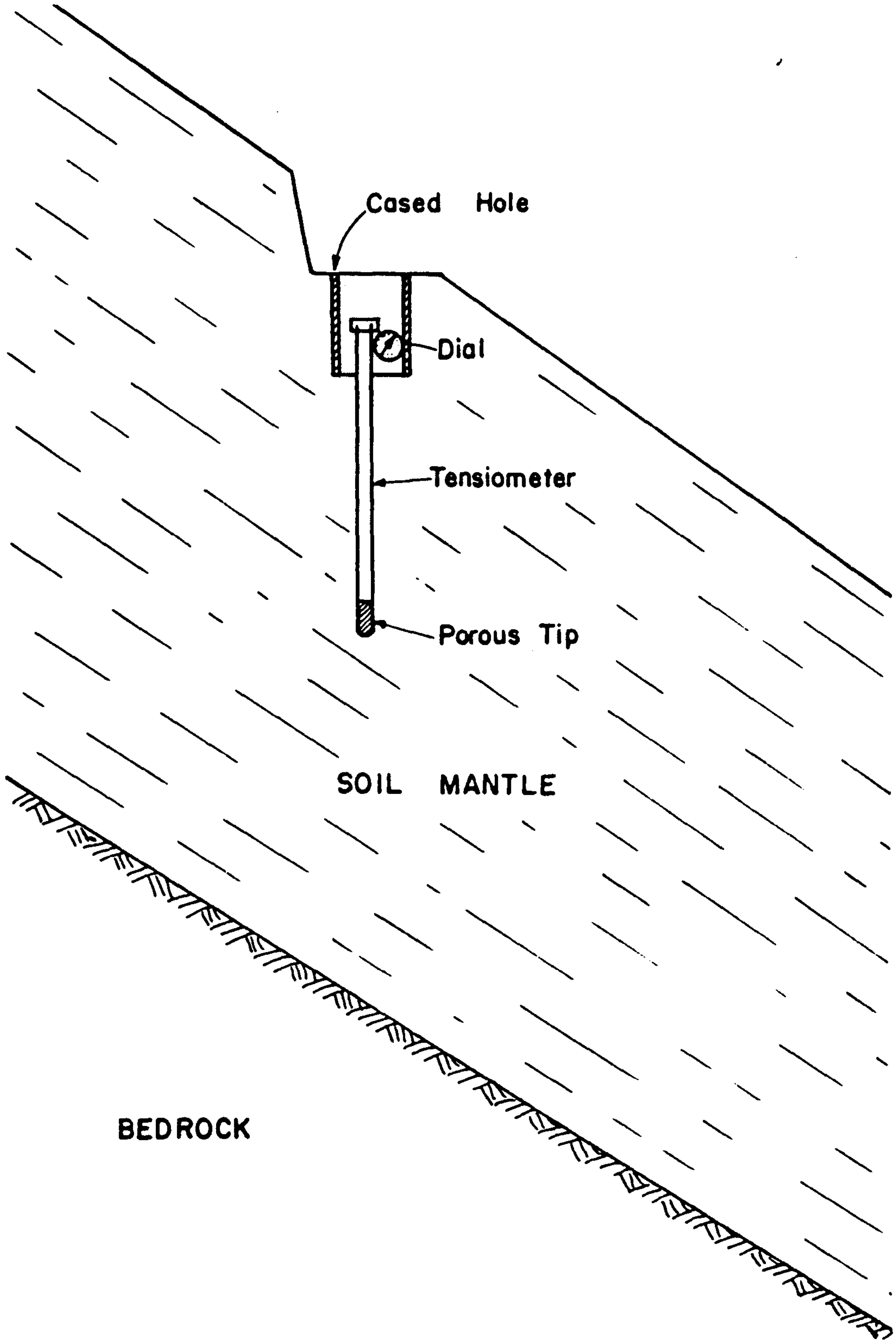

Figure 30. Schematic diagram of a typical tensiometer installation.

V. RESULTS OF FIELD MONITORING

A. CREEP MOVEMENT

1. H. J. Andrews Forest

Creep movement was monitored at sites in Watershed No. 1 and Watershed No. 2-3 for a "side-by-side" comparison of a clear-cut and adjacent forested slope. Creep was also monitored in Watershed No. 10 for a "before-and-after" comparison. Watershed No. 10 was clear-cut in the summer of 1975; therefore, only two years of post cutting data are available from that site at time of writing this report. This short post cutting period also coincided with a record year of drought as shown by precipitation records in Figure 59.

Creep profiles for the inclinometer holes at these sites are presented in Figures 31 through 44. These figures were printed by a calculator-graphics unit* which accepted and processed raw field data; automatically scaled and positioned the vertical and horizontal axes; labeled the axes; and plotted the profiles. The creep profiles provide a record of downslope movement as a function of depth and time. The bottoms of the inclinometer tubes extend into fractured bedrock and are assumed to remain fixed. Downslope movement is measured relative to the bottom of the tubing.

The inclinometers also provide information on the direction of movement in a horizontal plane as well (i.e., in a compass bearing sense). One set of grooves in the inclinometer

---

*Algebraic programmable calculator, Hewlett Packard Model 9820A; and calculator-plotter, Hewlett Packard Model 9862A.

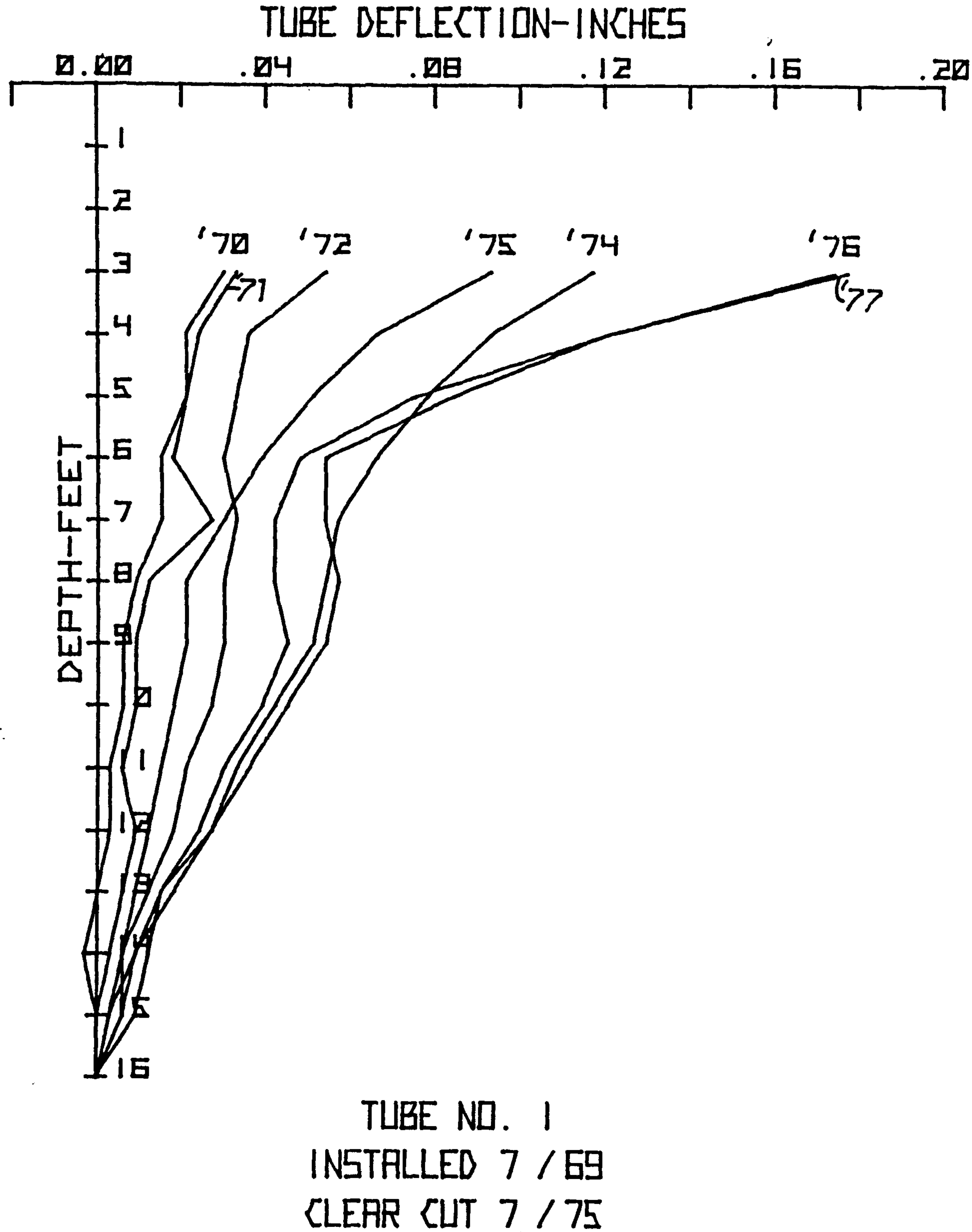

Figure 31. Creep profiles, Watershed No. 10, Tube #1, H. J. Andrews Experimental Forest.

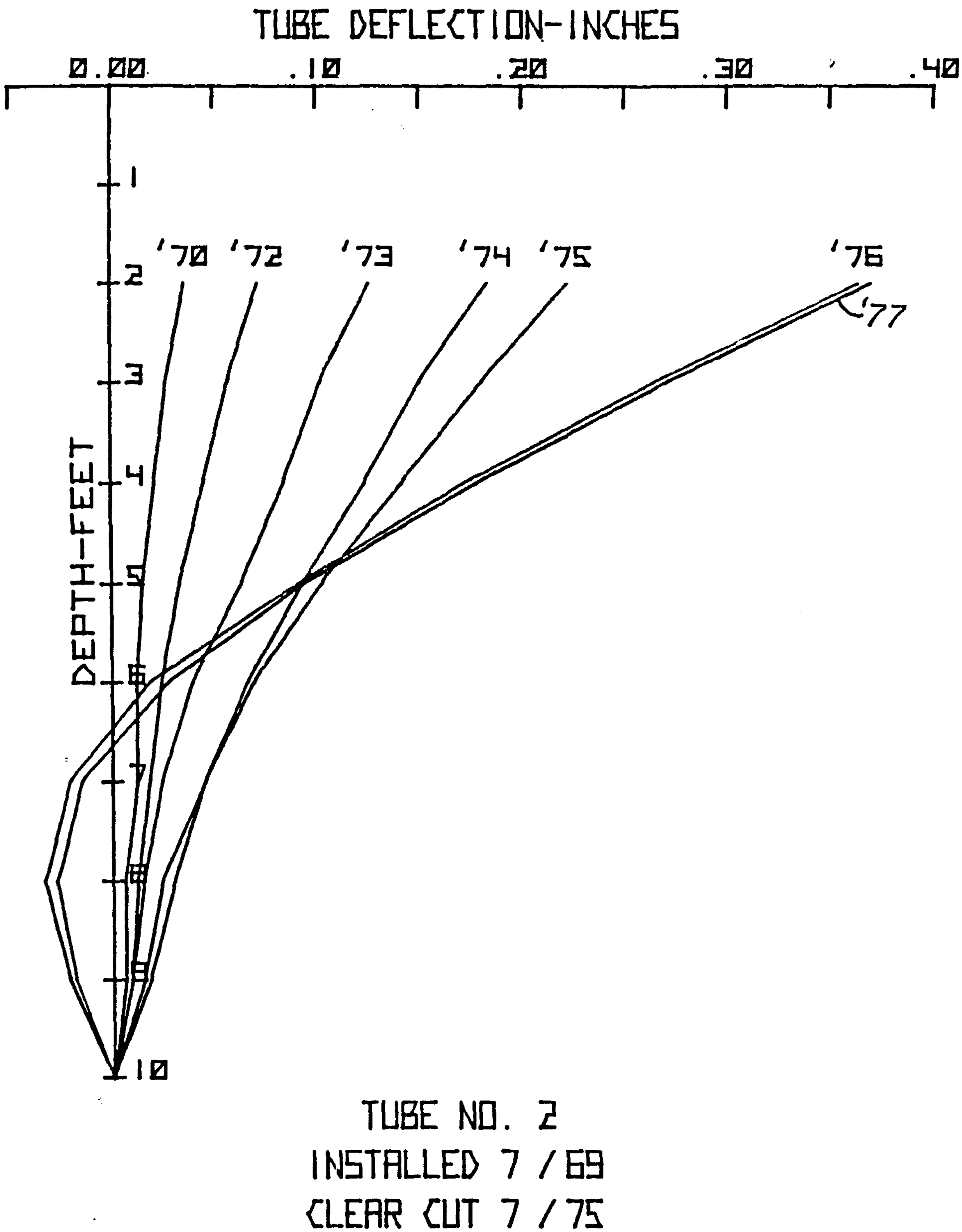

Figure 32. Creep profiles, Watershed No. 10, Tube #2, H. J. Andrews Experimental Forest.

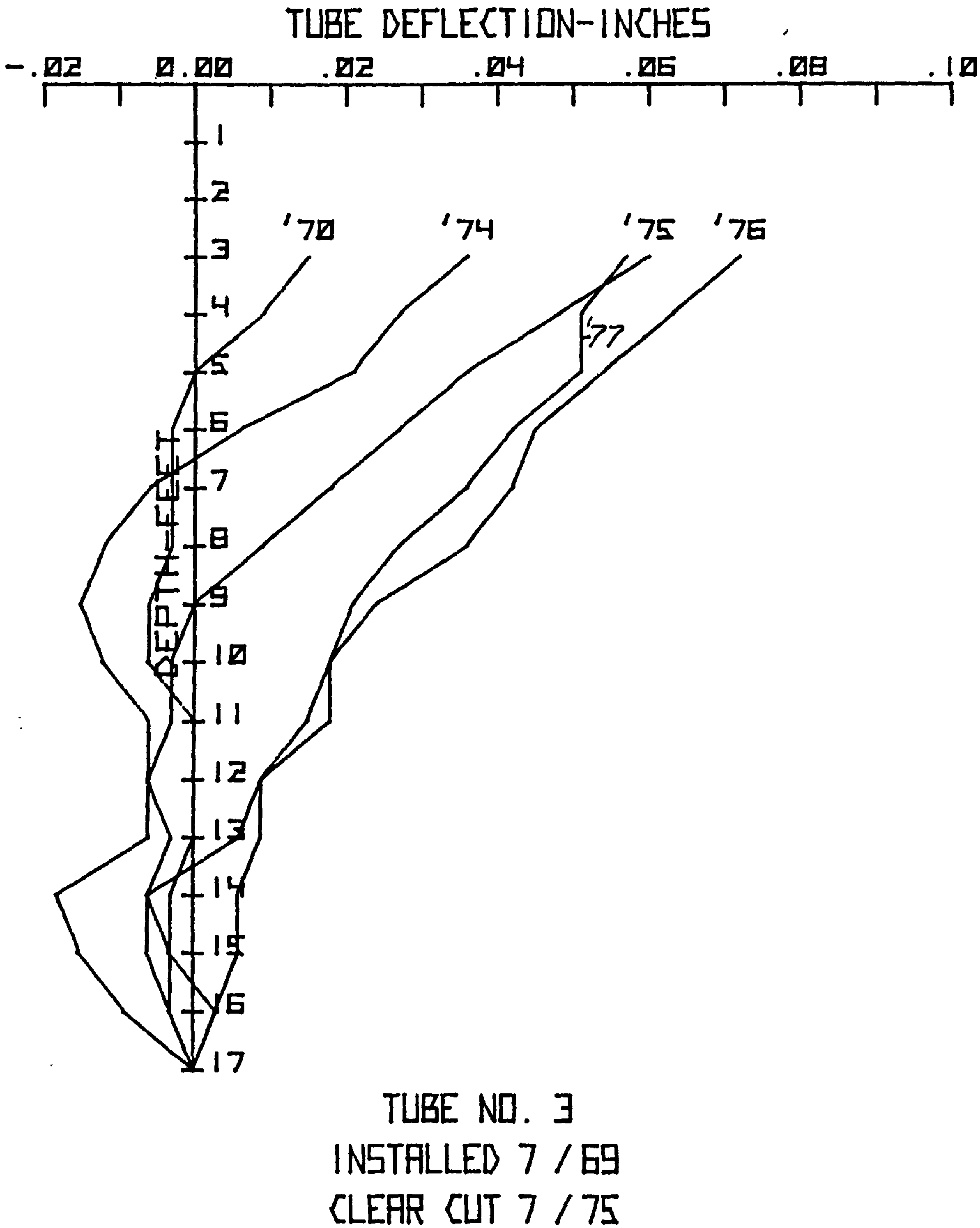

Figure 33. Creep profiles, Watershed No. 10, Tube #3, H. J. Andrews Experimental Forest.

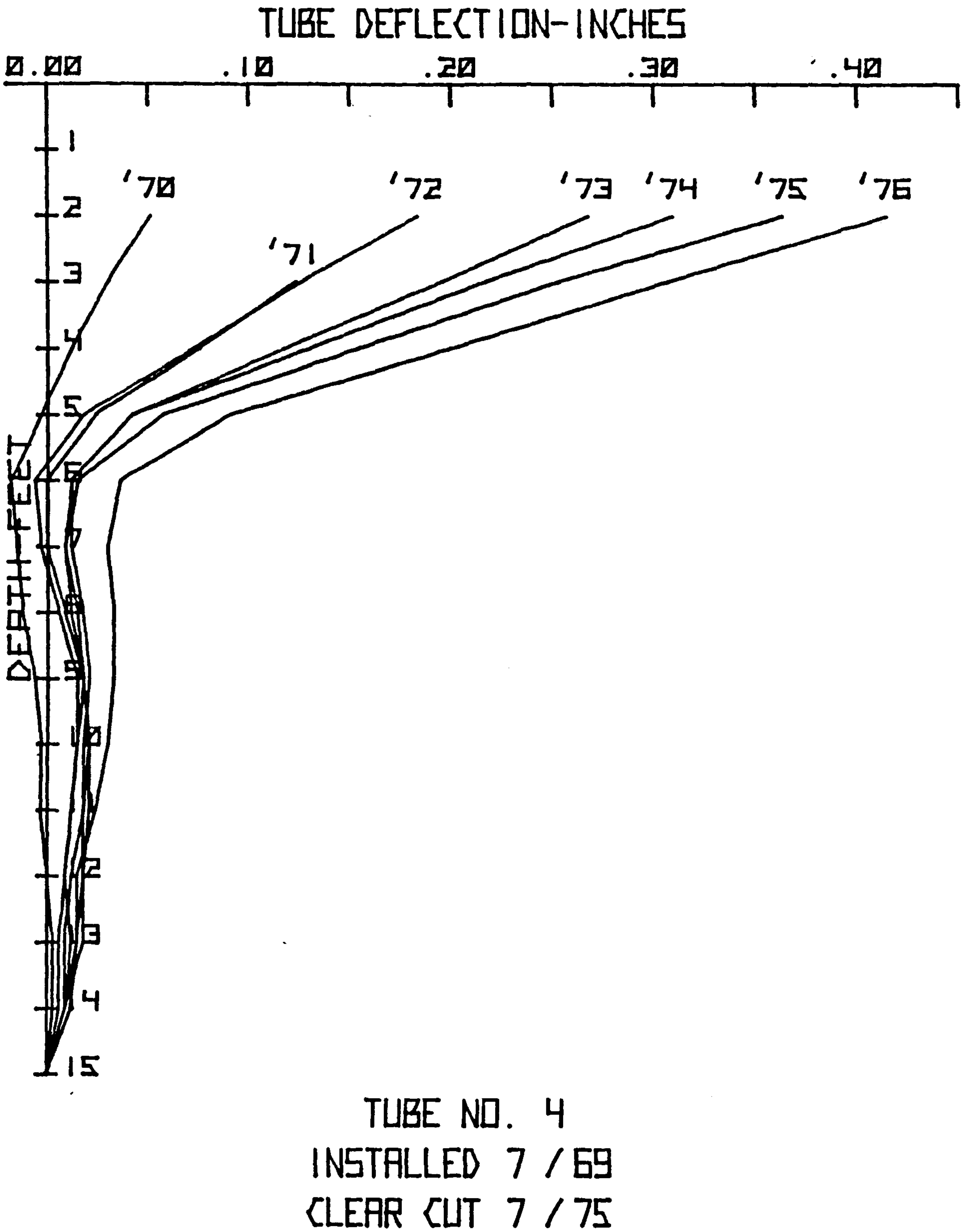

Figure 34. Creep profiles, Watershed No. 10, Tube #4, H. J. Andrews Experimental Forest.

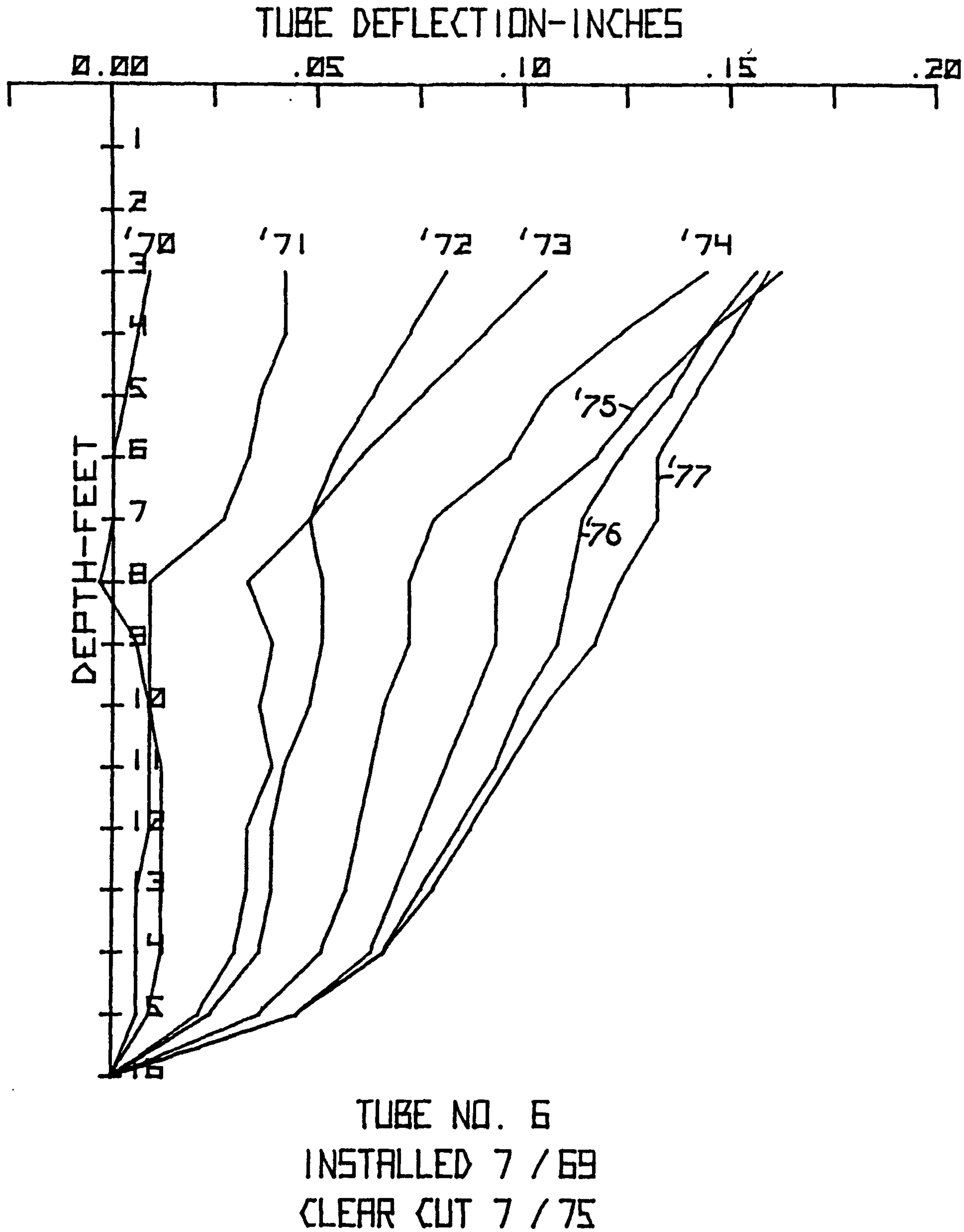

Figure 35. Creep profiles, Watershed No. 10, Tube #6, H. J. Andrews Experimental Forest.

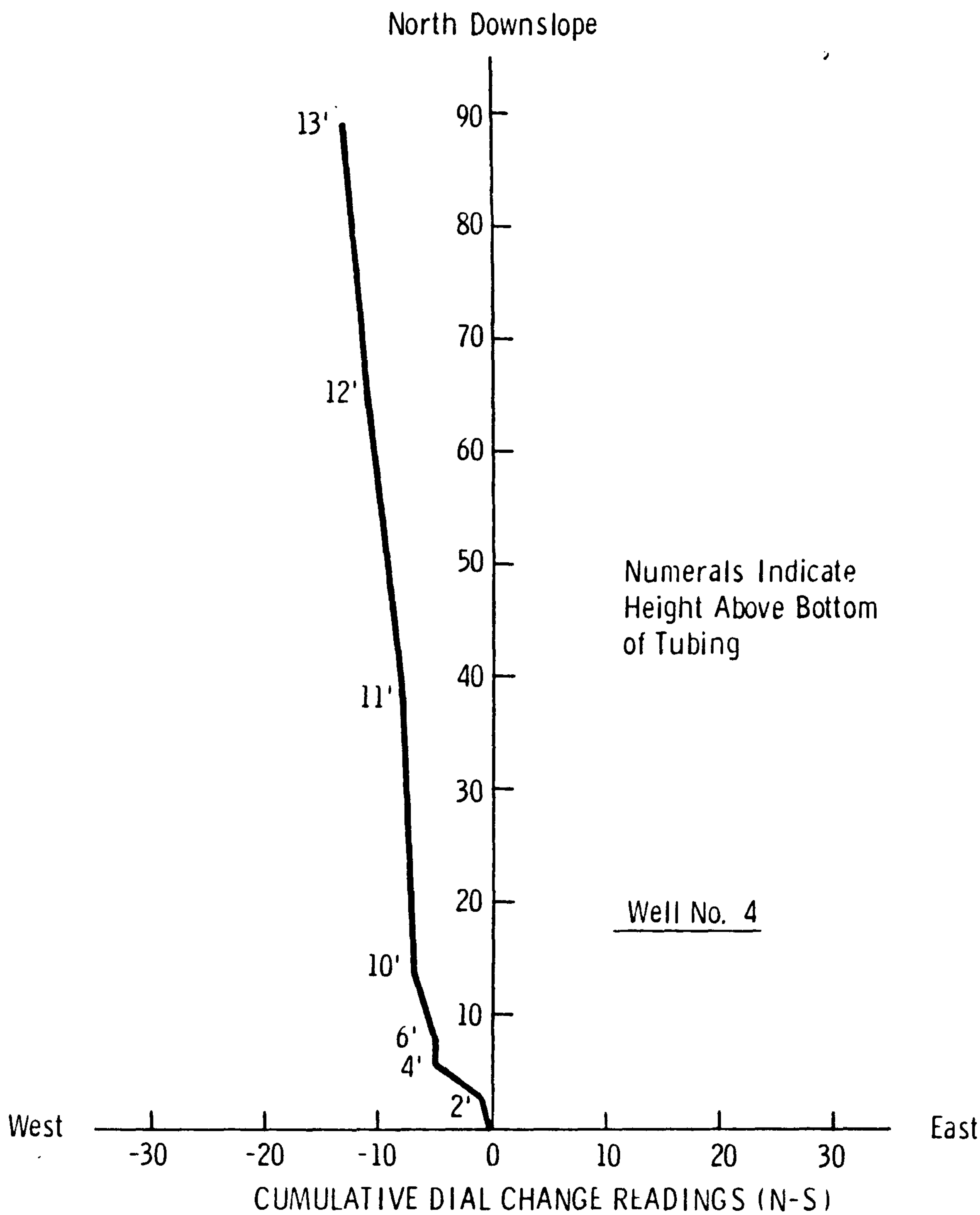

Figure 36. Polar diagram of total creep movement (1973), Watershed No. 10 (forested), H. J. Andrews Experimental Forest.

tubes was oriented as nearly possible in a downdip direction (i.e., perpendicular to the strike of the slope). The resultant movement occurred very close to this direction; hence, only results of creep in this downslope direction (identified arbitrarily as north-south in the data sheets) are included in this report. Some lateral movement along the strike of the slope was recorded in a few holes; Figure 36 gives an idea of the extent of lateral movement in such a case.

Total creep movement was not large in any of the tubes. Maximum movement at the surface (relative to the bottom of the tubes) ranged from 0.1 to 0.4 inches in Watershed 10 after a monitoring period of 7 years. Creep movement measured at the other sites was even less.

The creep profiles indicate what type of downslope movement has occurred at each location over time. Shallow surface movement is clearly reflected, for example, by the profiles shown in Figure 34 for Tube #4, Watershed 10, whereas deep seated movement is indicated by the profiles shown in Figure 38 for Tube #3A, Watershed 1. Other profiles such as those shown in Figure 37 for Tube #2A, Watershed 1, suggest uniform creep gradients or continuous shear deformation over the entire soil profile. Some profiles exhibit a composite type of behavior over time, for example, a change from uniform creep to a more pronounced, shallow movement. This type of behavior was manifest in the profiles shown in Figures 31 and 32 for Tubes Nos. 1 and 2 respectively in Watershed 10, following clear-cutting.

Creep profiles for all years were not always plotted. In some instances they were omitted from the figures for clarity of presentation or simply because no inclinometer readings were taken in a particular hole that year. In a very few instances a profile was omitted because of an obvious error in taking the readings. Occassionally profiles for subsequent years lie uphill of the preceding years. This behavior is shown for example in Figure 42 by Tube #3B, Watershed 2-3, and in Figure 33 by Tube #3, Watershed 10. The most likely explanation for this behavior is that the affected profiles lie within each other's error band, and hence an apparent but spurious uphill movement may be indicated for a particular year. Another source of apparent but steady uphill movement of the profile is rotational movement in the ground. Rotational movement occurring within or near the base of a slide mass will cause an imbedded inclinometer to tilt backwards. If the base of the inclinometer tube does not penetrate beyond the sliding surface, and apparent and steady uphill movement or backward tilting will be reflected in the creep profiles as shown, for example, in Figure 54 by Tube #1, Little South Fork site, Klamath National Forest. This tube was one of several imbedded in a large landslide.

The influence of tree removal or clear-cutting on creep movement can be ascertained by careful study of the creep profiles themselves. This topic is also discussed in a subsequent section of the report in which the creep data have been replotted in order to compare creep rates more readily between forested and cutover slopes. A fairly pronounced increase in creep movement following clear-cutting is shown in Figures 31 and 32 for Tubes #1 and 2, Watershed 10. Other tubes in Watershed 10, did not exhibit such an increase following clear-cutting. This might be explained, however, by the shortness of the post clear-cutting monitoring period (2 years) and its coincidence with a record dry year. The profiles shown in Figure 34 for Tube #4 which was installed in the midst of an area of dead trees (see Figure 25) exhibited higher rates of creep movement than the other tubes in Watershed 10 while still in their forested condition.

A comparison of creep movement between tubes installed in a clear-cut (Watershed 1) and adjacent forested watershed (Watershed 2-3) is difficult from an examination of the profiles alone. The computer graphics unit used to plot the profiles varied the horizontal scale for each tube. This procedure enhances comparison between profiles for a single tube, but also makes comparison between profiles of different tubes more difficult. Careful analysis of the profiles shows, nevertheless, that creep movement at the cutover site (Watershed 1) is generally greater than the forested site (Watershed 2-3). This contrast is more evident when surface creep rates between the two sites are compared as described in the next section of the report (see Figures 70 and 71).

A final comment is also in order regarding re-installation of the removable couplings following timber harvesting operations at a site. Proper installation of the couplings is important in order to make reliable comparisons between pre

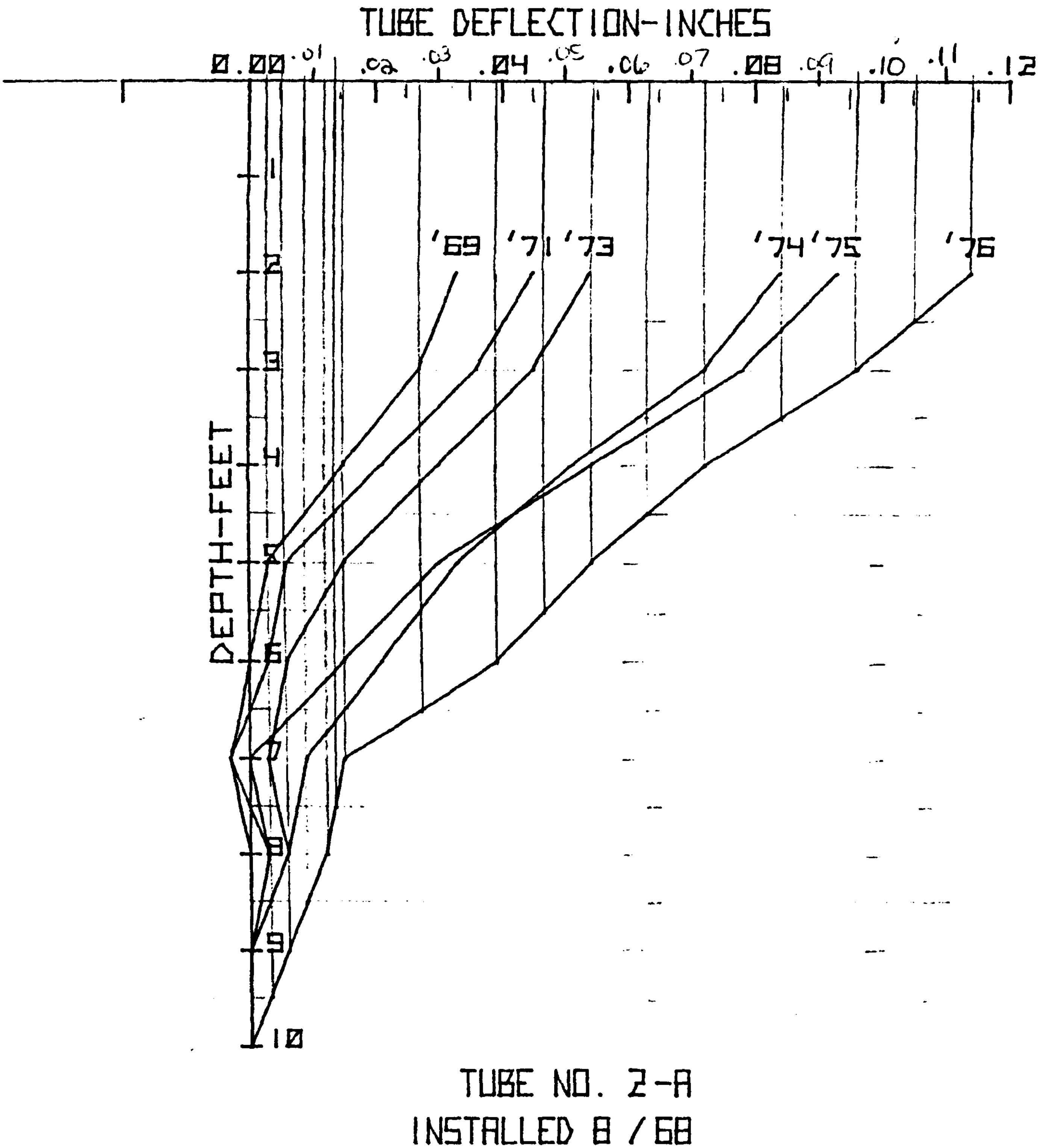

Figure 37. Creep profiles, Watershed No. 1 (clear-cut), Tube #2A, H. J. Andrews Experimental Forest.

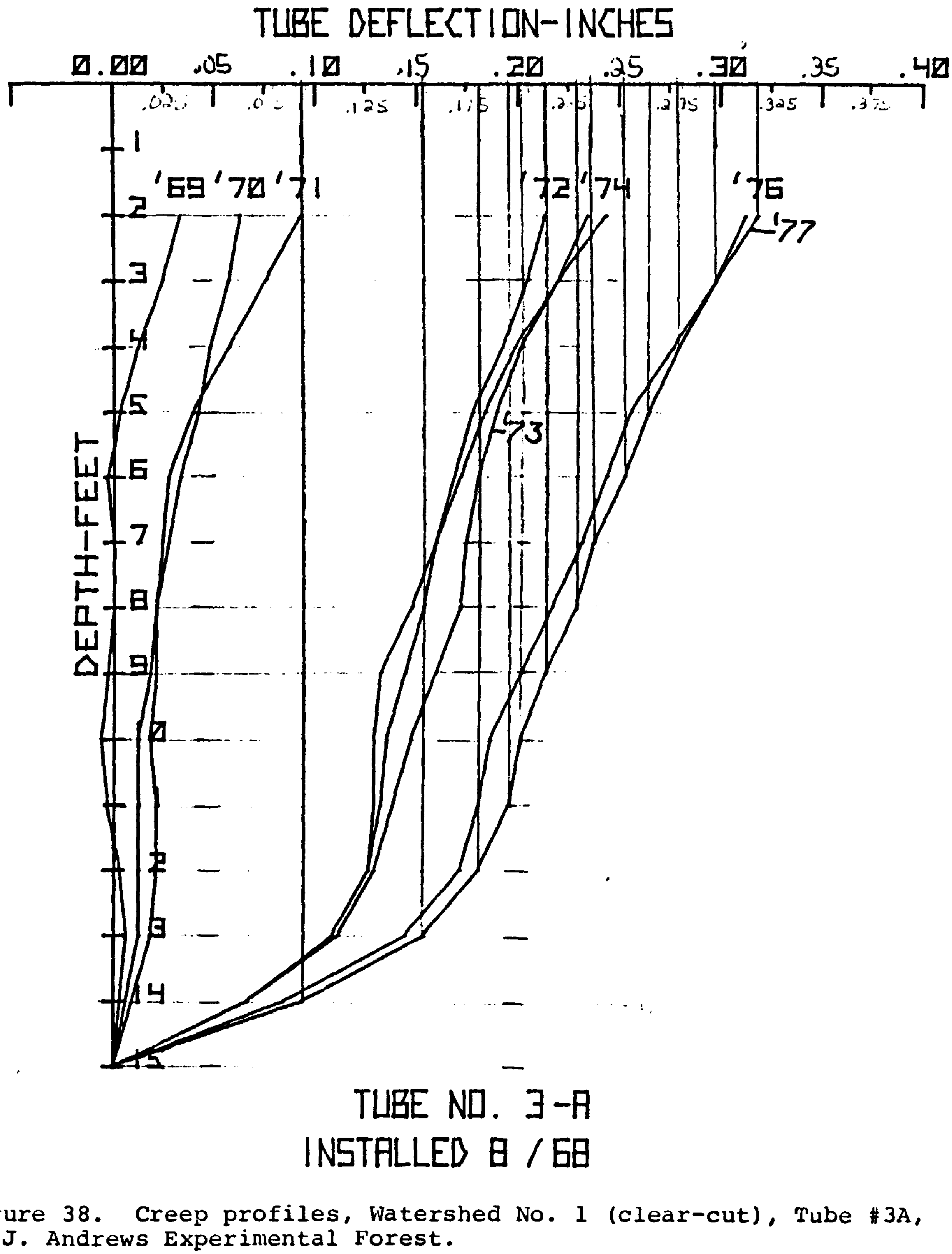

Figure 38. Creep profiles, Watershed No. 1 (clear-cut), Tube #3A, H. J. Andrews Experimental Forest.

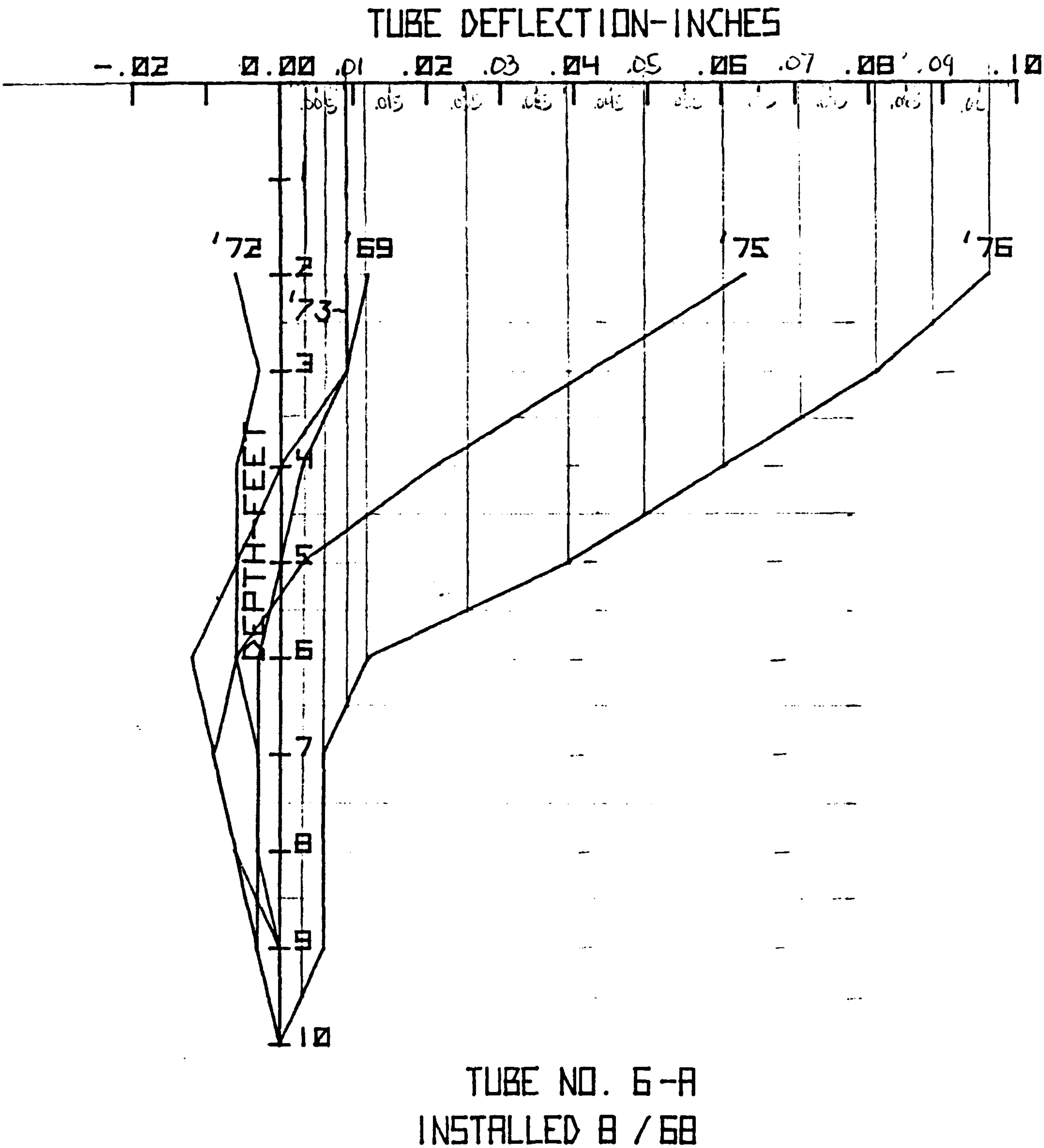

Figure 39. Creep profiles, Watershed No. 1 (clear-cut), Tube #6A, H. J. Andrews Experimental Forest.

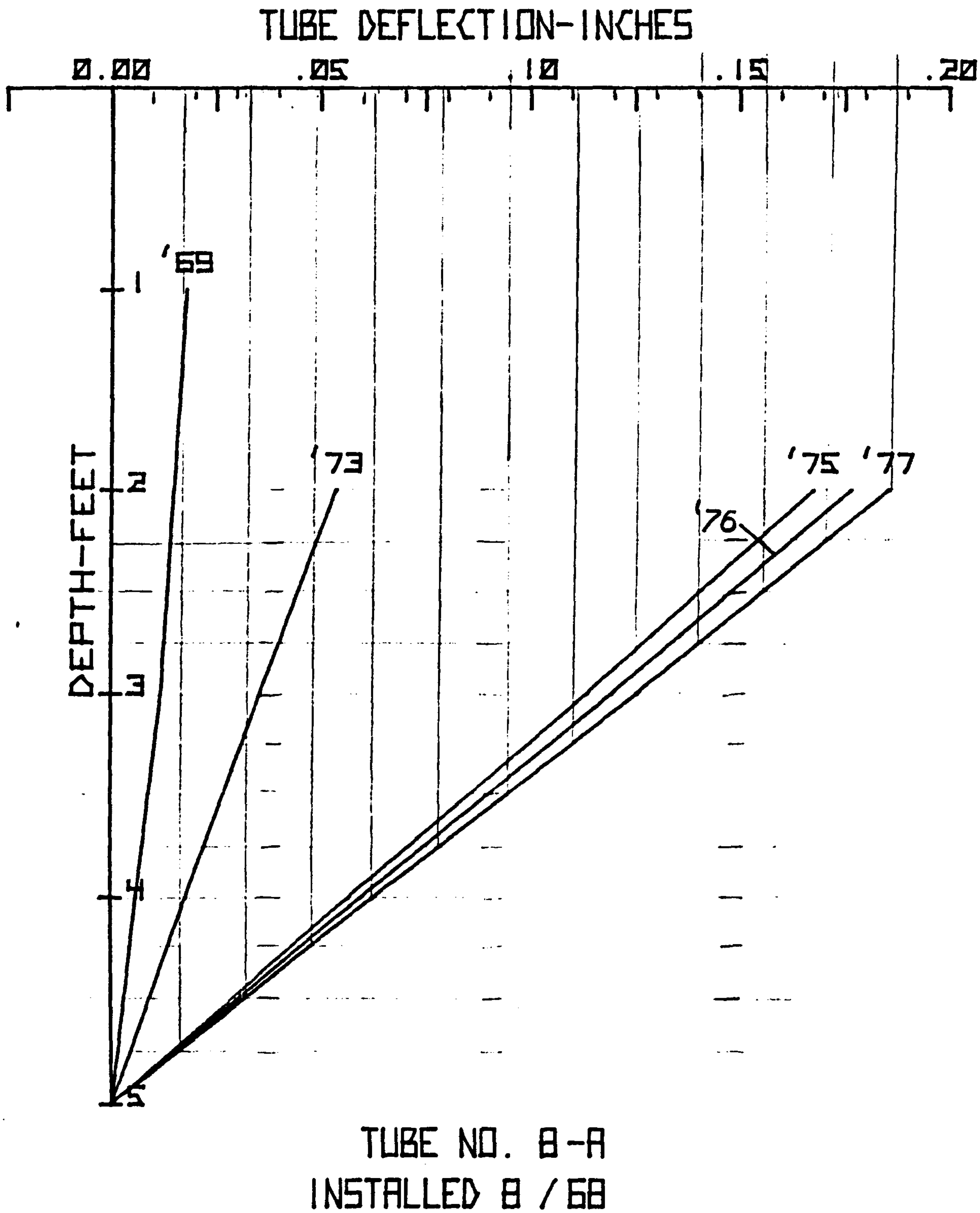

Figure 40. Creep profiles, Watershed No. 1 (clear-cut), Tube #8A, H. J. Andrews Experimental Forest.

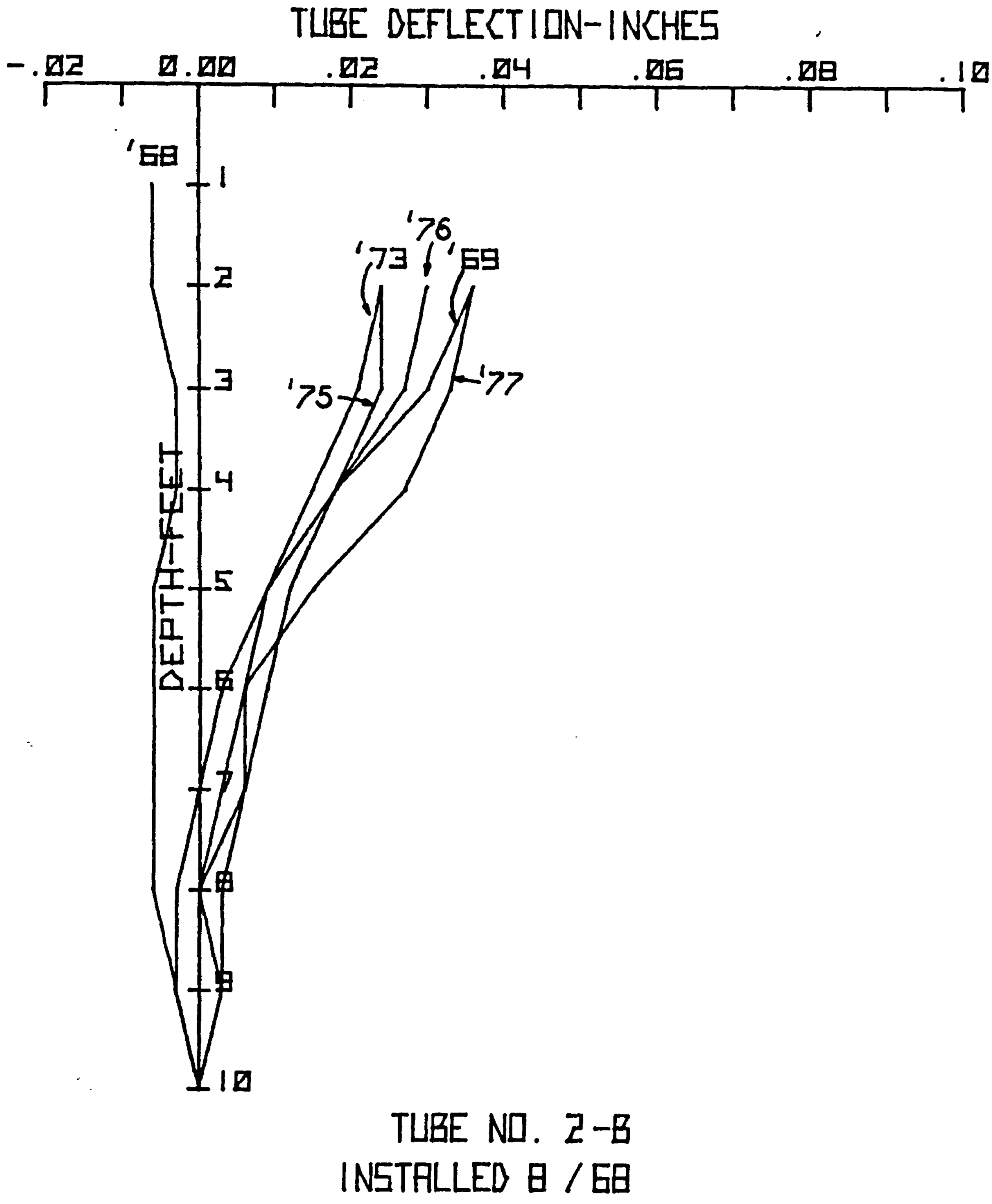

Figure 41. Creep profiles, Watershed No. 2-3 (forested), Tube #2B, H. J. Andrews Experimental Forest.

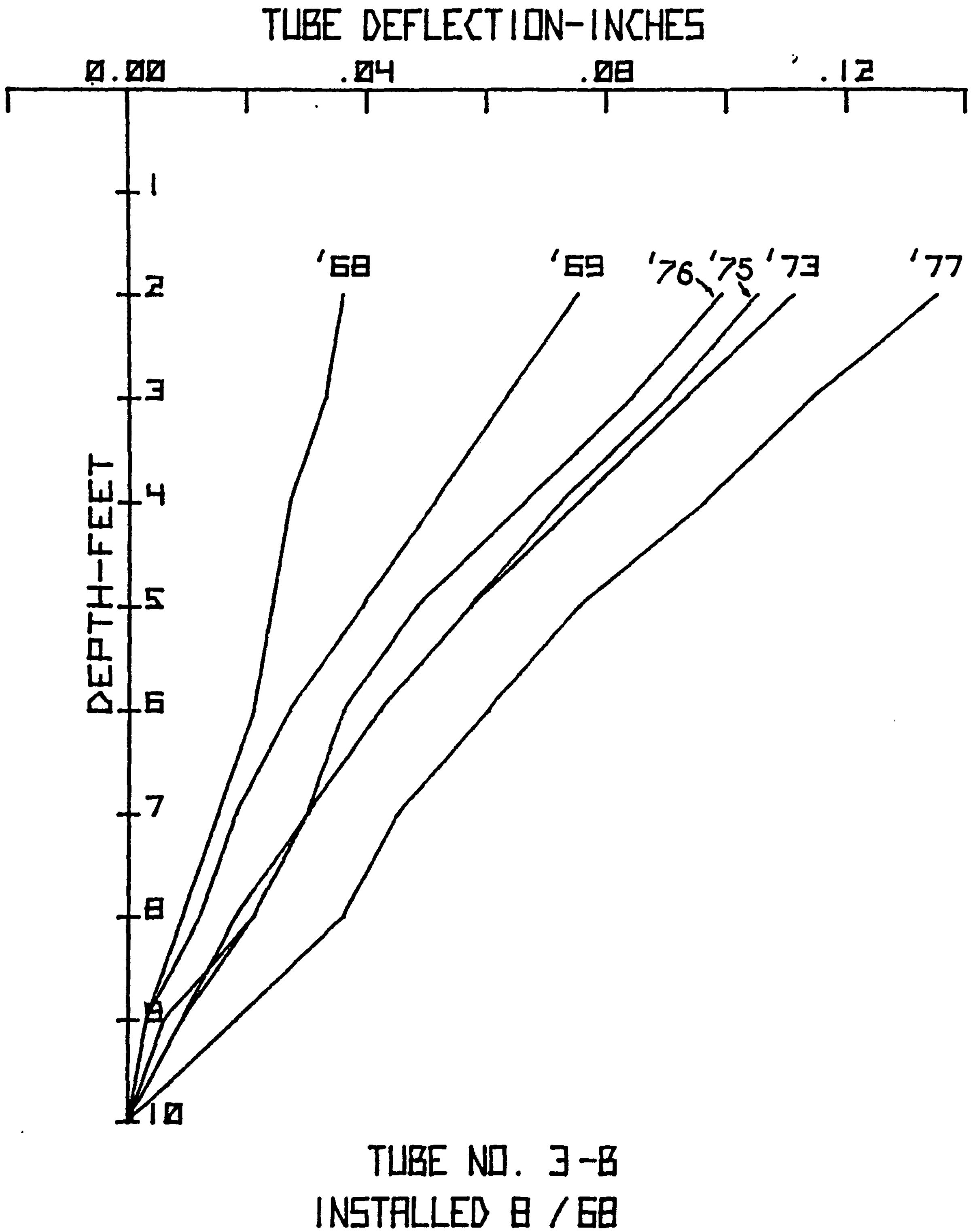

Figure 42. Creep profiles, Watershed No. 2-3 (forested), Tube #3B, H. J. Andrews Experimental Forest.

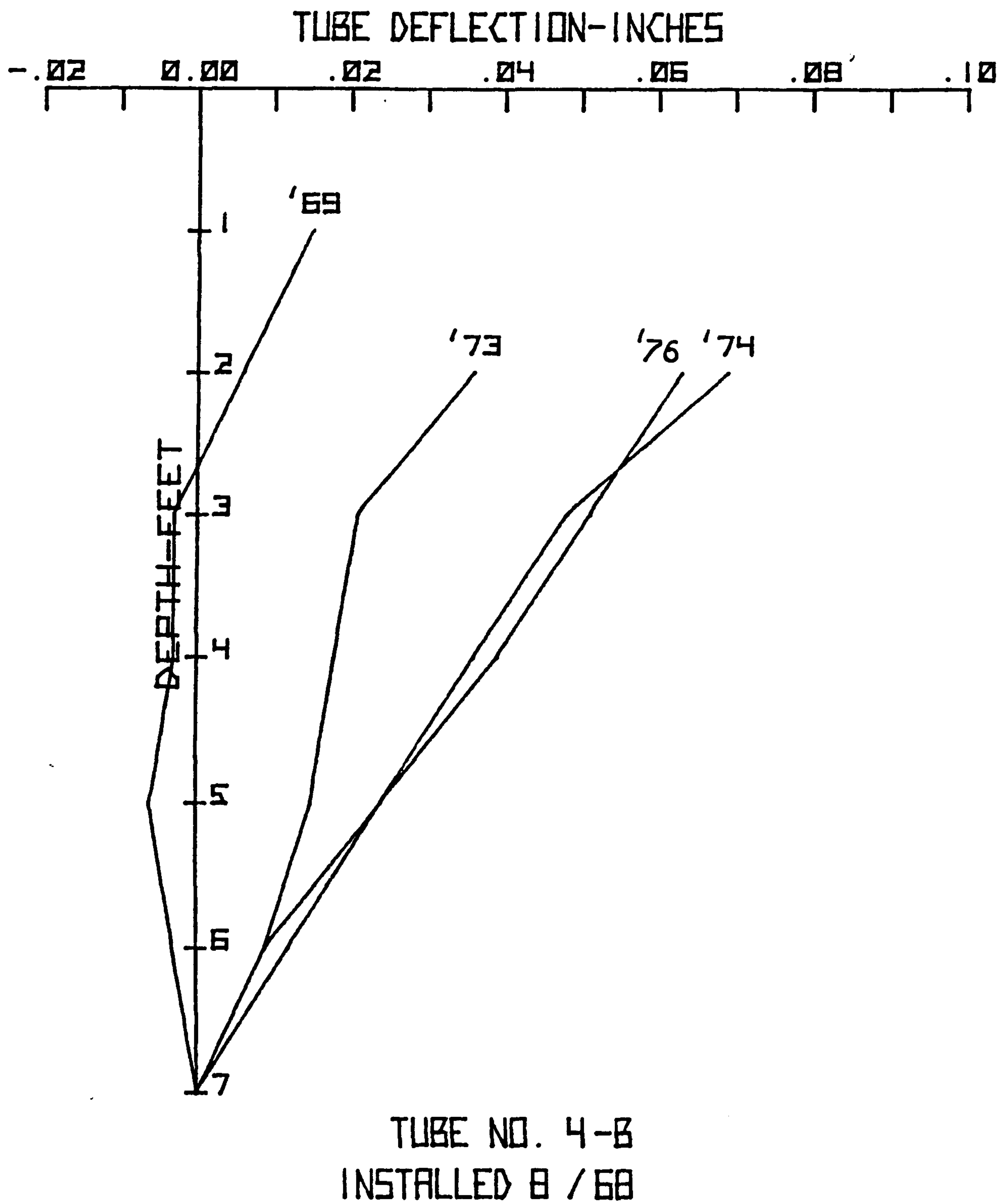

Figure 43. Creep profiles, Watershed No. 2-3 (forested), Tube #4B, H. J. Andrews Experimental Forest.

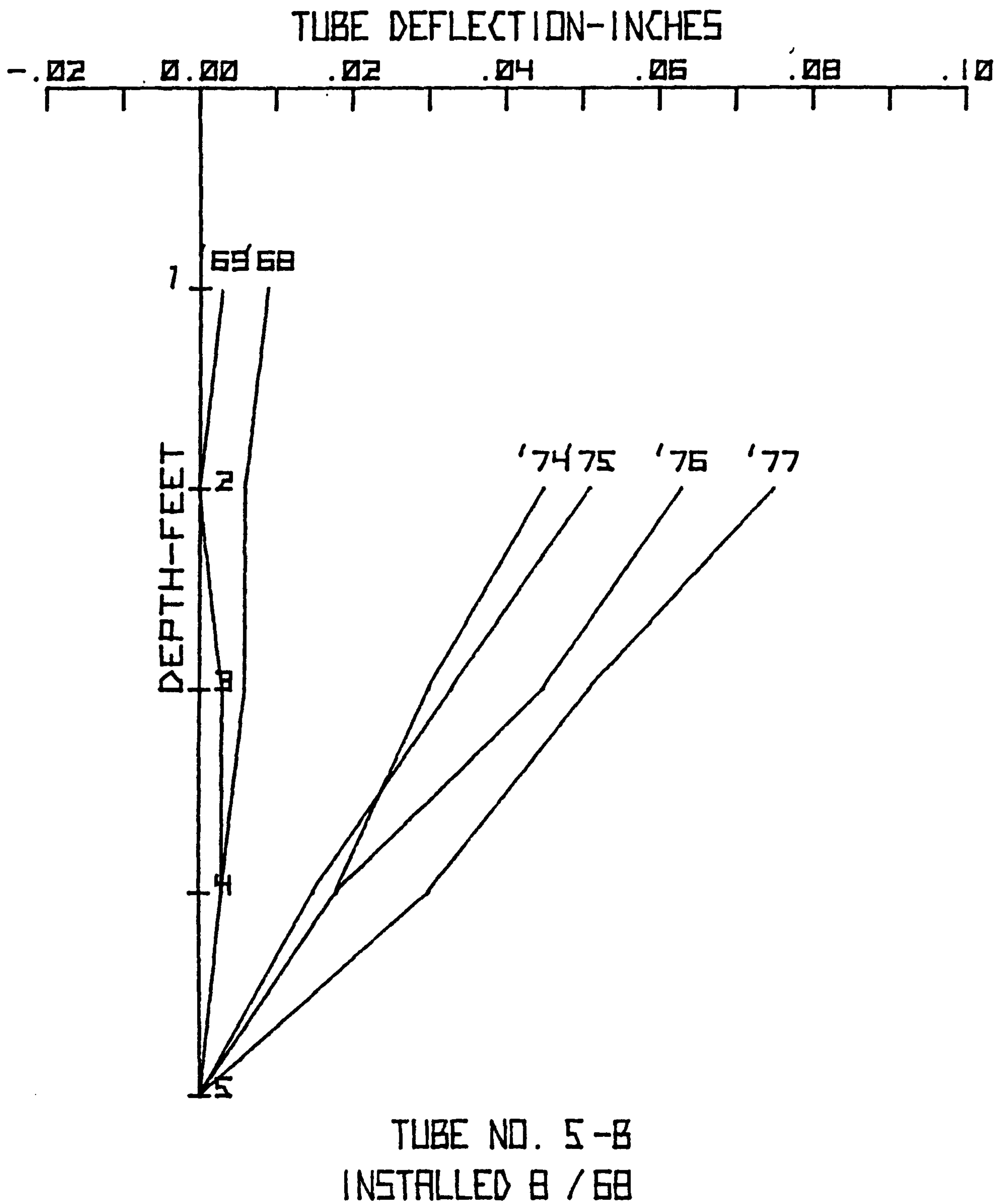

Figure 44. Creep profiles, Watershed No. 2-3 (forested), Tube #5B, H. J. Andrews Experimental Forest.

and post clear-cutting profiles. The couplings must be replaced in exactly their original position and orientation in order to continue using the first or original set of readings in a given hole as a reference. Failure to reposition the coupling exactly in Tube #5, Watershed 10, resulted in spurious profiles being recorded following clear-cutting. Profiles for this tube have been omitted from the report for this reason. If the coupling is not replaced exactly then all subsequent readings must be referenced to the first set of readings after re-installation.

2. U.S. Naval Radio Station

Creep profiles are presented in Figures 45 through 51. Figures 45 through 48 are for tubes installed in a cutover slope whereas Figures 49 and 50 are for tubes in the forested portion of the slope (refer back to Figures 17 and 18 for location of tubes). Creep movement was monitored in these tubes periodically over a 7-year period. Results of creep measurements commissioned earlier by the Navy in the thick section of glacial till above the transmitter station are shown in Figure 51. Additional slope indicator readings were taken at this location during the last seven years to provide a 20-year period of record of creep movement in a cutover slope. Unfortunately, no creep data is available at this slope location in its original forested state.

The total amount of creep measured in the tubes were similar to the Oregon sites. With the exception of the tube above the transmitter building creep movements were not large.

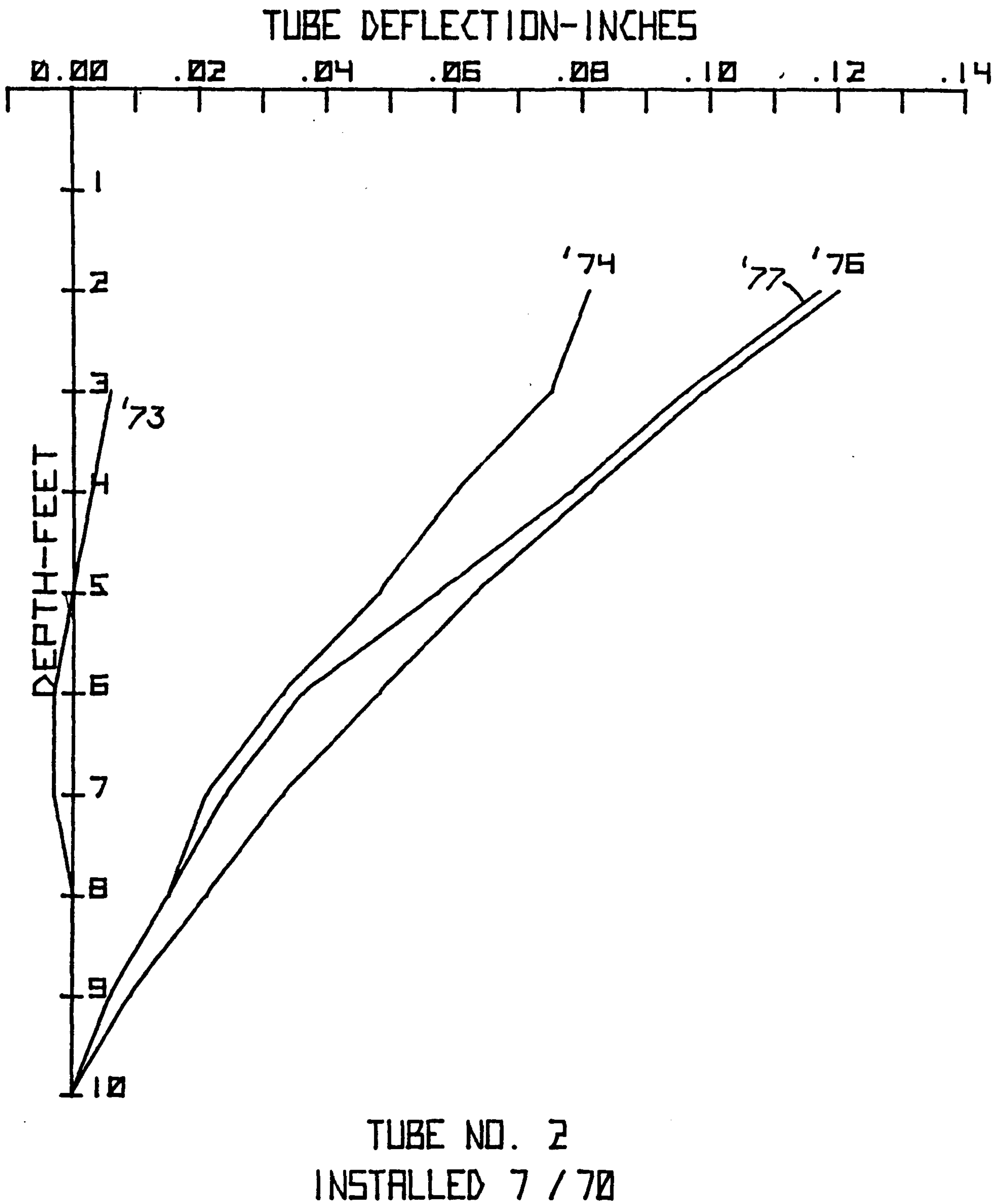

Figure 45. Creep profiles, cutover slope, Tube #2, U.S. Naval Radio Station.

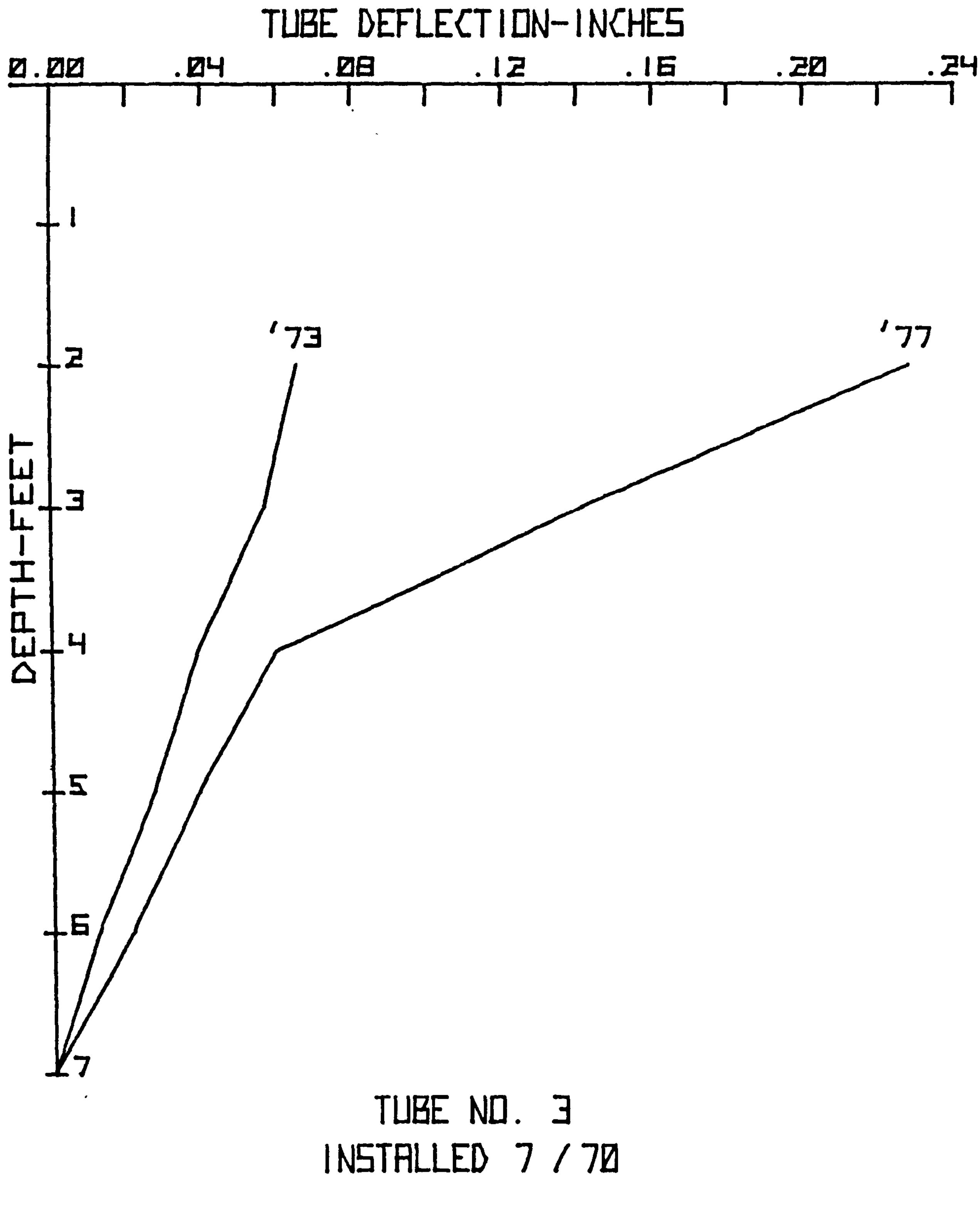

Figure 46. Creep profiles, cutover slope, Tube #3, U.S. Naval Radio Station.

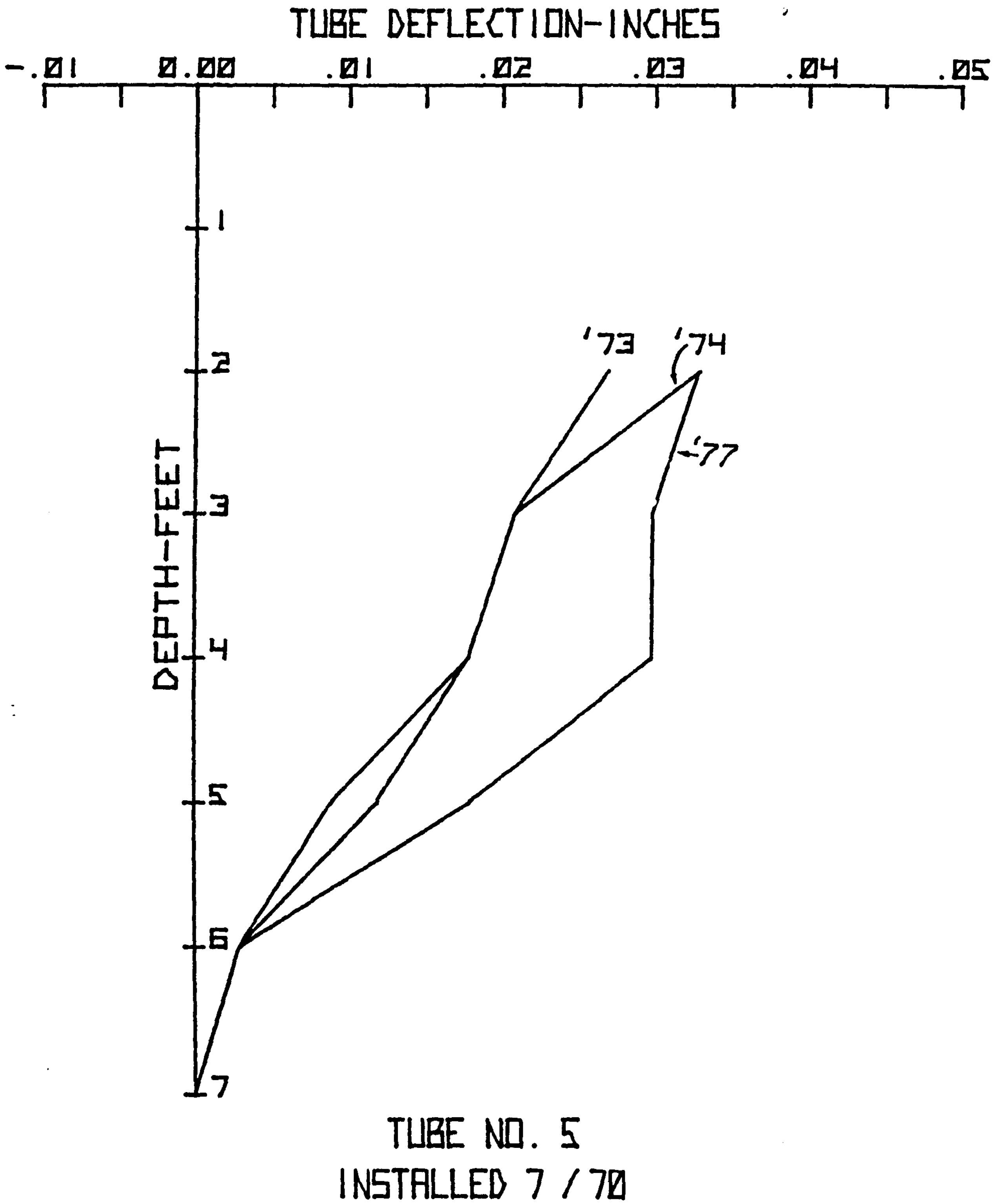

Figure 47. Creep profiles, cutover slope, Tube #5, U.S. Naval Radio Station.

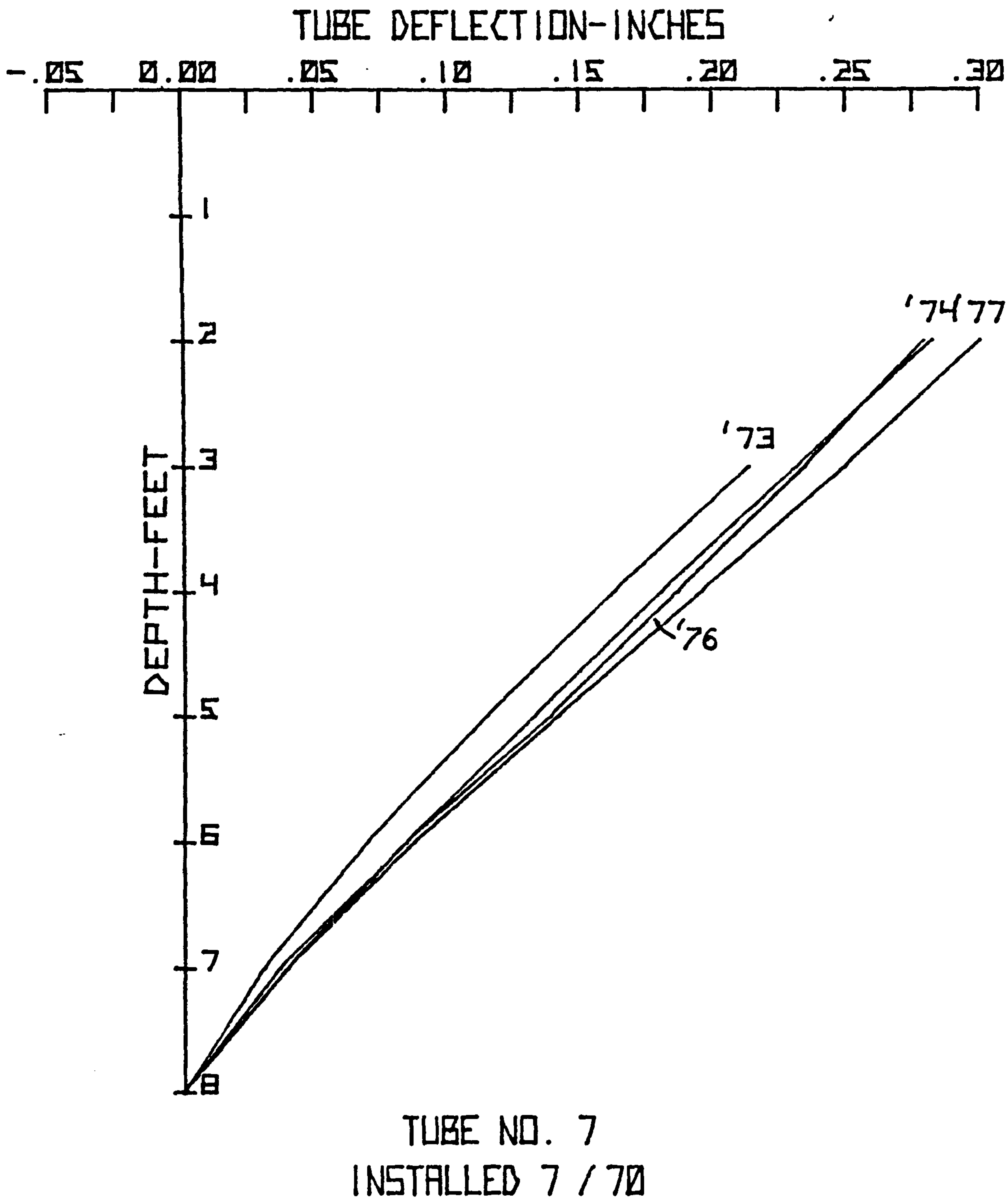

Figure 48. Creep profiles, cutover slope, Tube #7, U.S. Naval Radio Station.

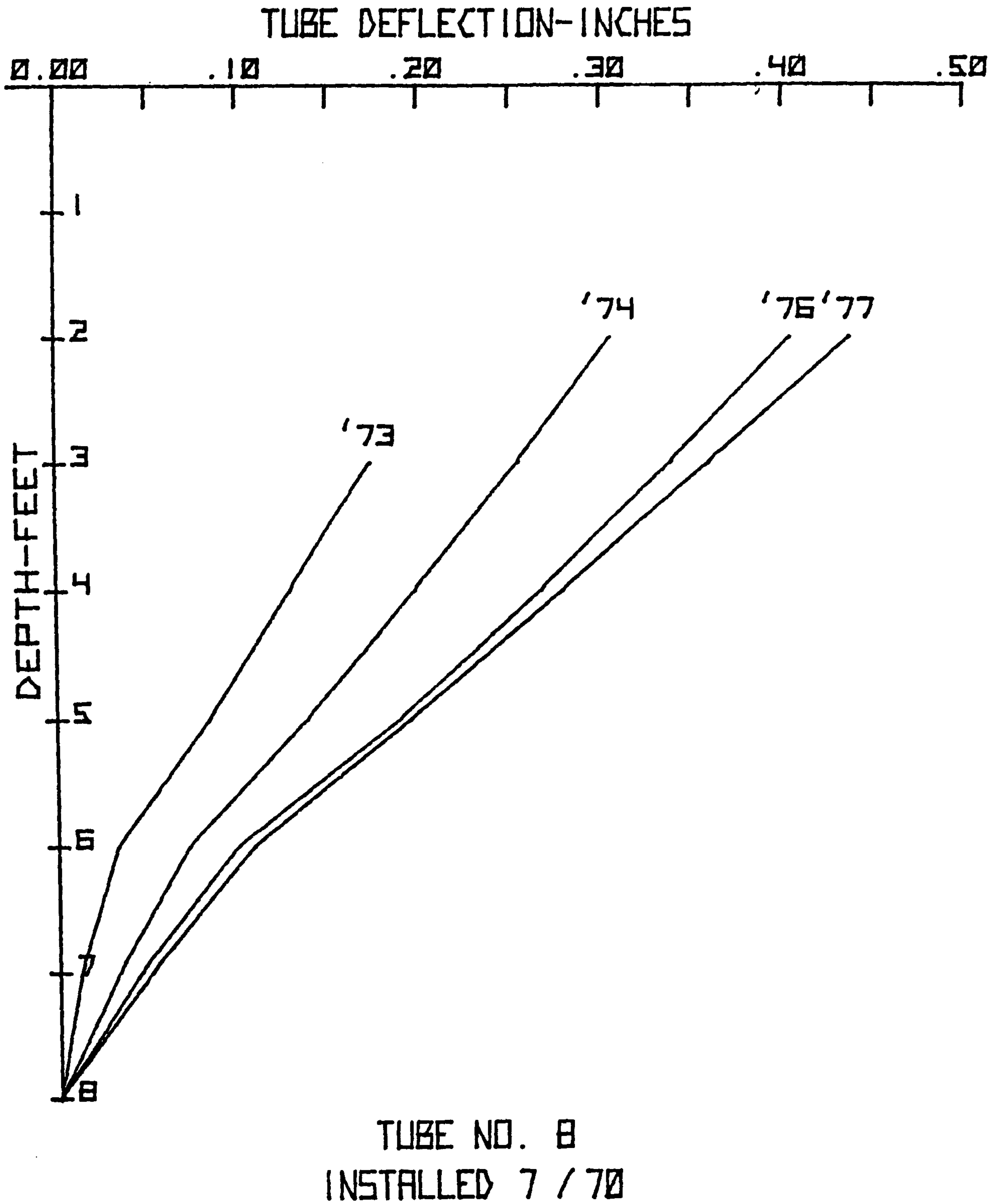

Figure 49. Creep profiles, forested slope, Tube #8, U.S. Naval Radio Station.

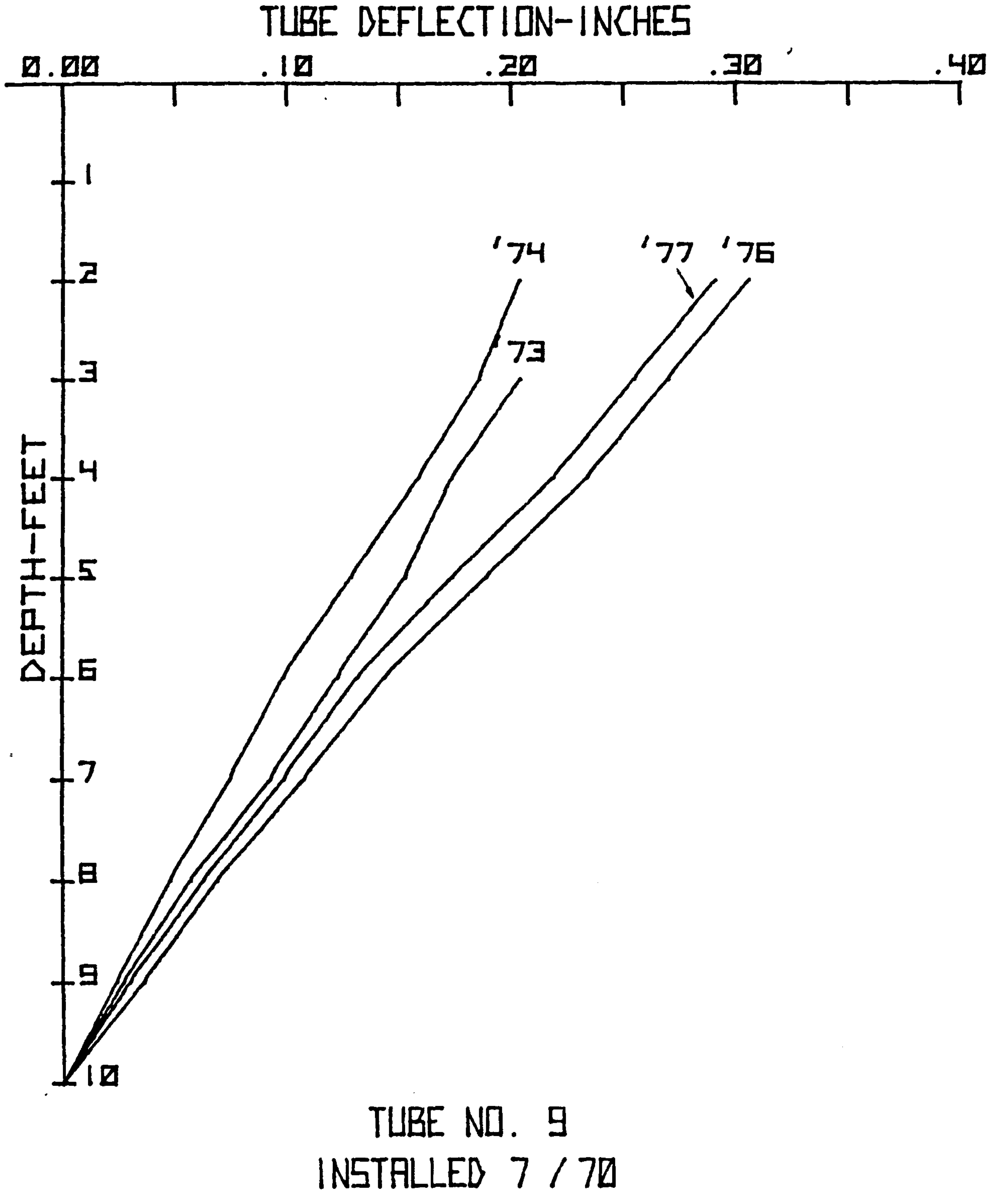

Figure 50. Creep profiles, forested slope, Tube #9, U.S. Naval Radio Station.

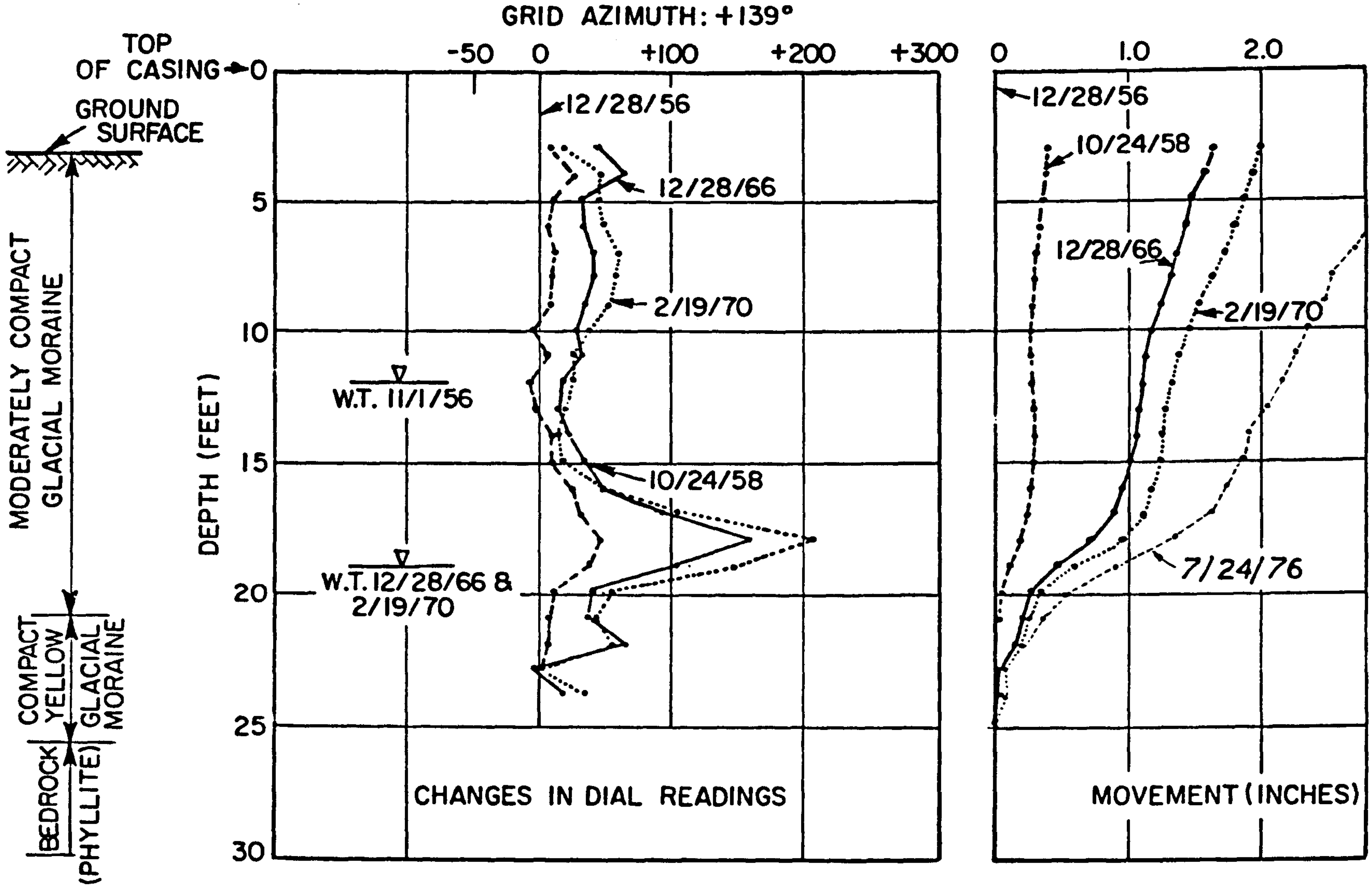

Figure 51. Record of creep movement in the cutover slope above the transmitter building, U.S. Naval Radio Station (from Wilson, 1967 and 1970).

Creep movement in the cutover slope above the transmitter building was an order-of-magnitude higher than creep measured elsewhere at the site. Creep movement appeared to be slightly greater in the two tubes in the forested portion relative to the tubes in the adjacent cutover portion (again excepting the tube above the transmitter station). It is uncertain, however, to what extent this difference merely reflects a difference in tube installation procedure between forested and cutover portions of the slope.

The soils in the forested slope were so dry, loose, and stony that it was impossible to drill a hole through the soil mantle that would not cave in. Consequently, the inclinometer tubes in the forested area were installed in pits which were dug and backfilled by hand. A limitation of this method is that settlement and movement of the backfill around the tubing can lead to artificial or apparent creep movement (Wilson, 1970).

3. Klamath National Forest

Creep profiles from the Clearview and Little South Fork sites are presented in Figures 52 through 58. The Clearview site was clear-cut in the summer of 1974. Of the three tubes installed at this site only Tube #1 was recovered intact. Tube #2 was never relocated as a result of obliterated survey markers and Tube #3 was damaged by logs yarded across its top. The tubes at the Little South Fork site were installed in a large, complex landslide above a logging road.

Some influence of tree removal is indicated by the creep

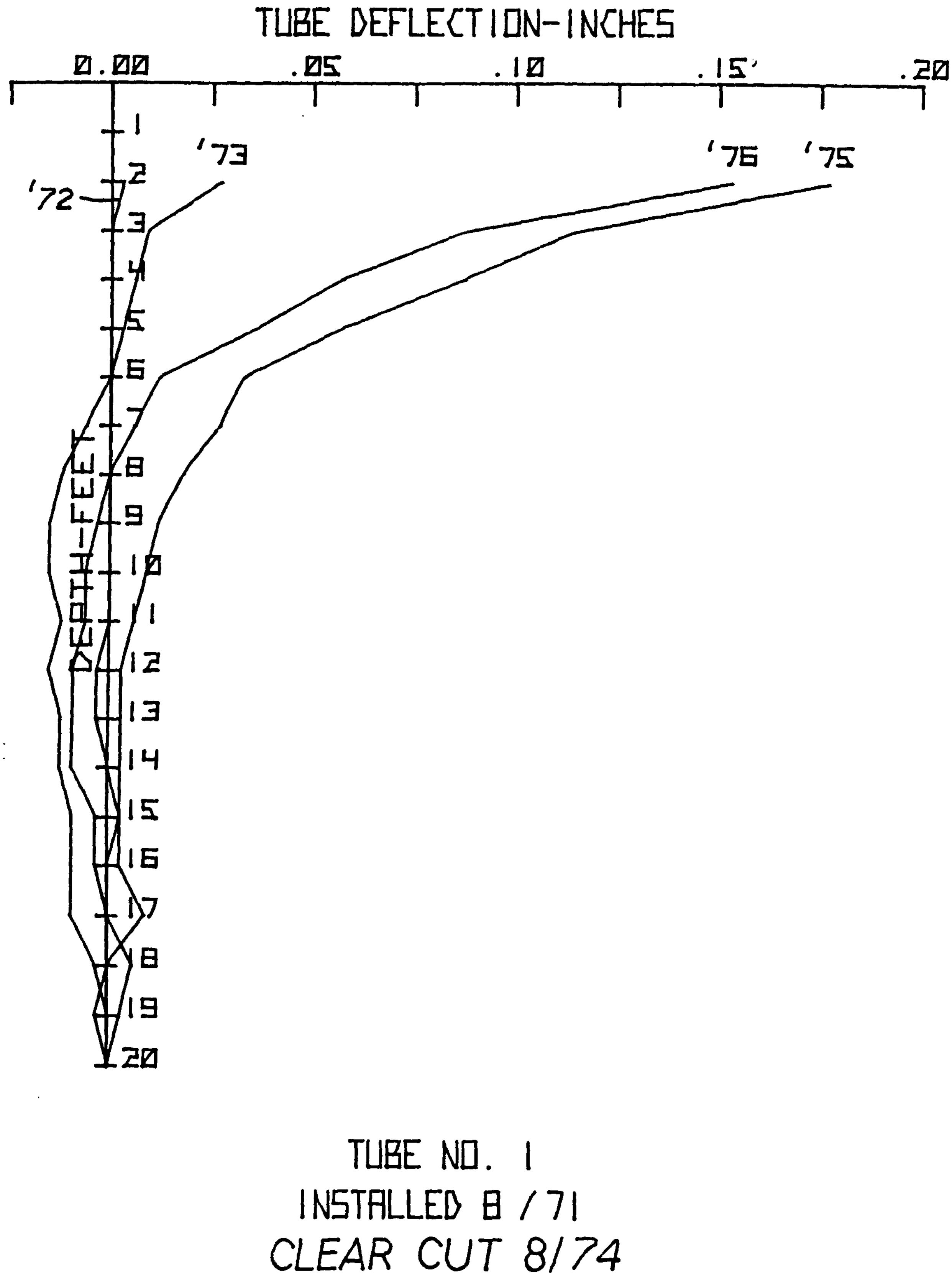

Figure 52. Creep profiles, Clearview site, Tube #1, Klamath National Forest.

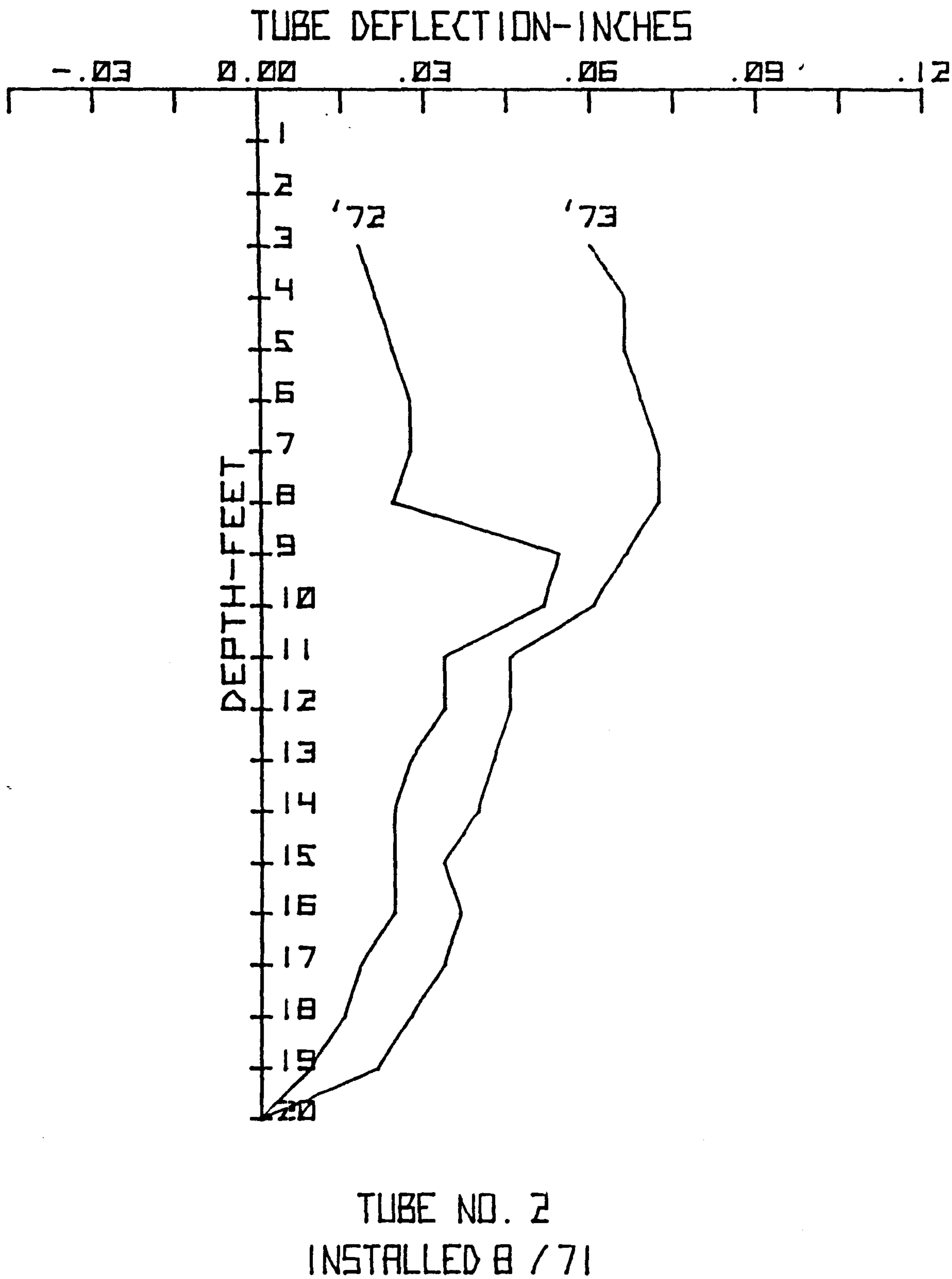

Figure 53. Creep profiles, Clearview site, Tube #2, Klamath National Forest.

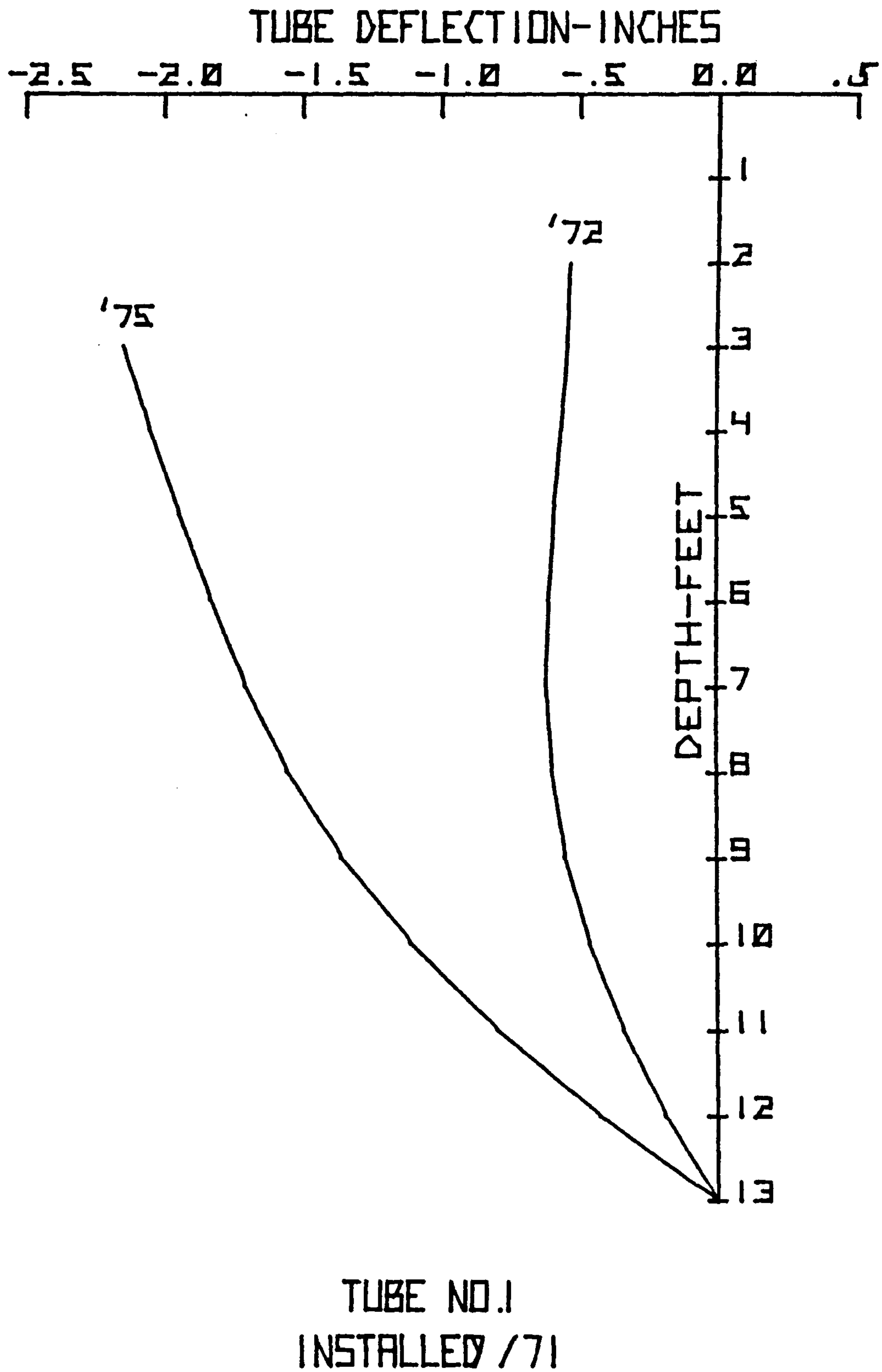

Figure 54. Creep profiles, Little South Fork landslide, Tube #1, Klamath National Forest.

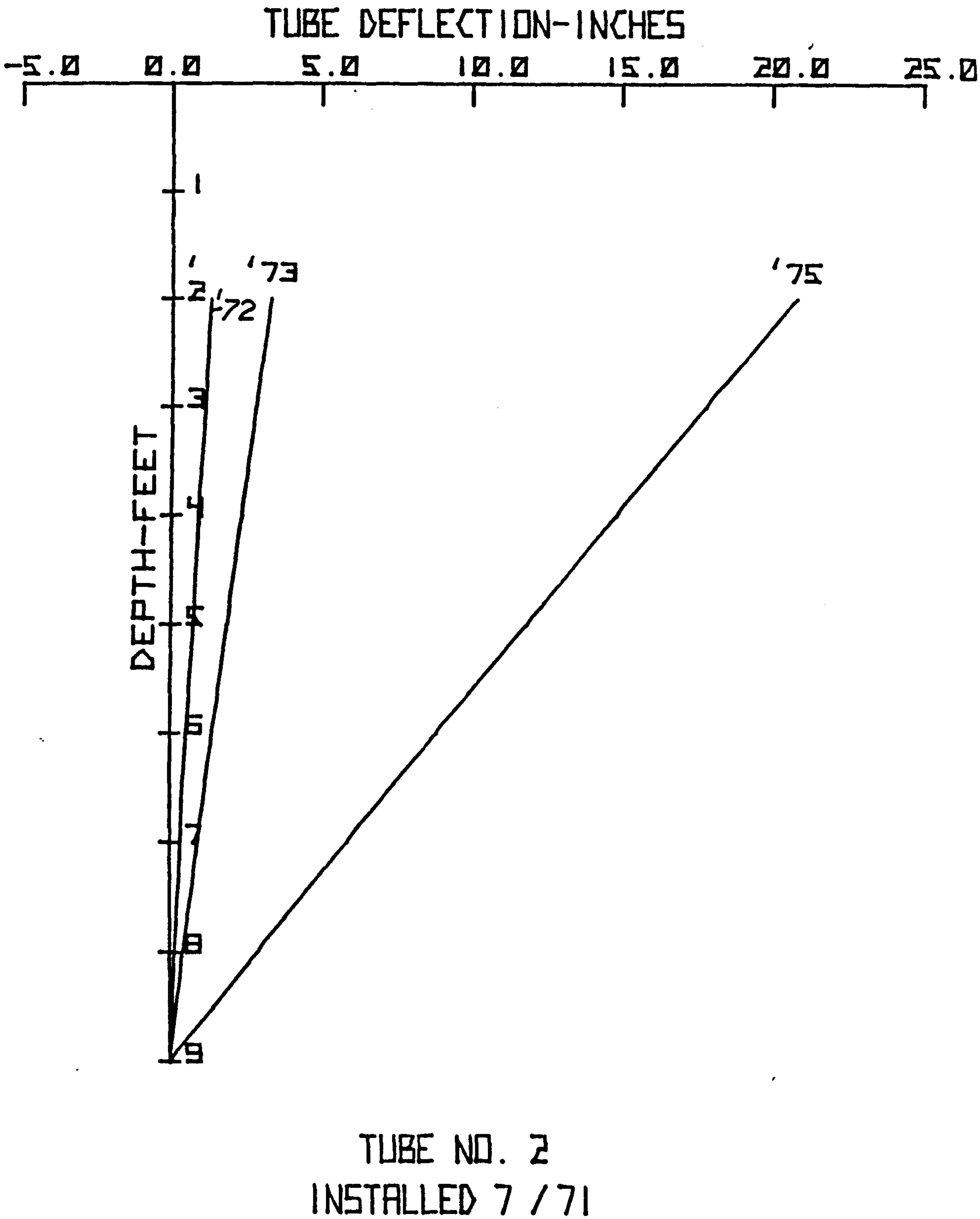

Figure 55. Creep profiles, Little South Fork landslide, Tube #2, Klamath National Forest.

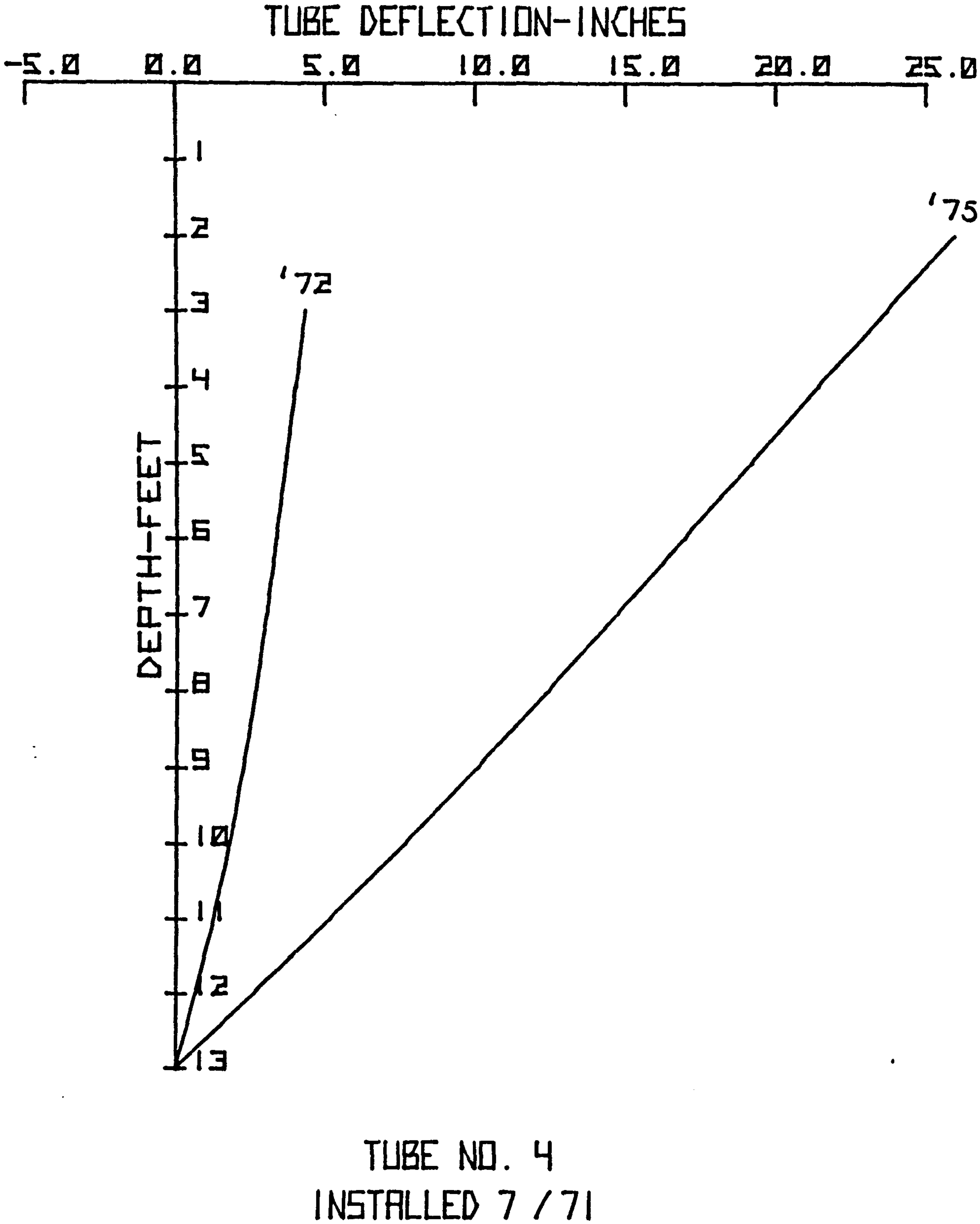

Figure 56. Creep profiles, Little South Fork landslide, Tube #4, Klamath National Forest.

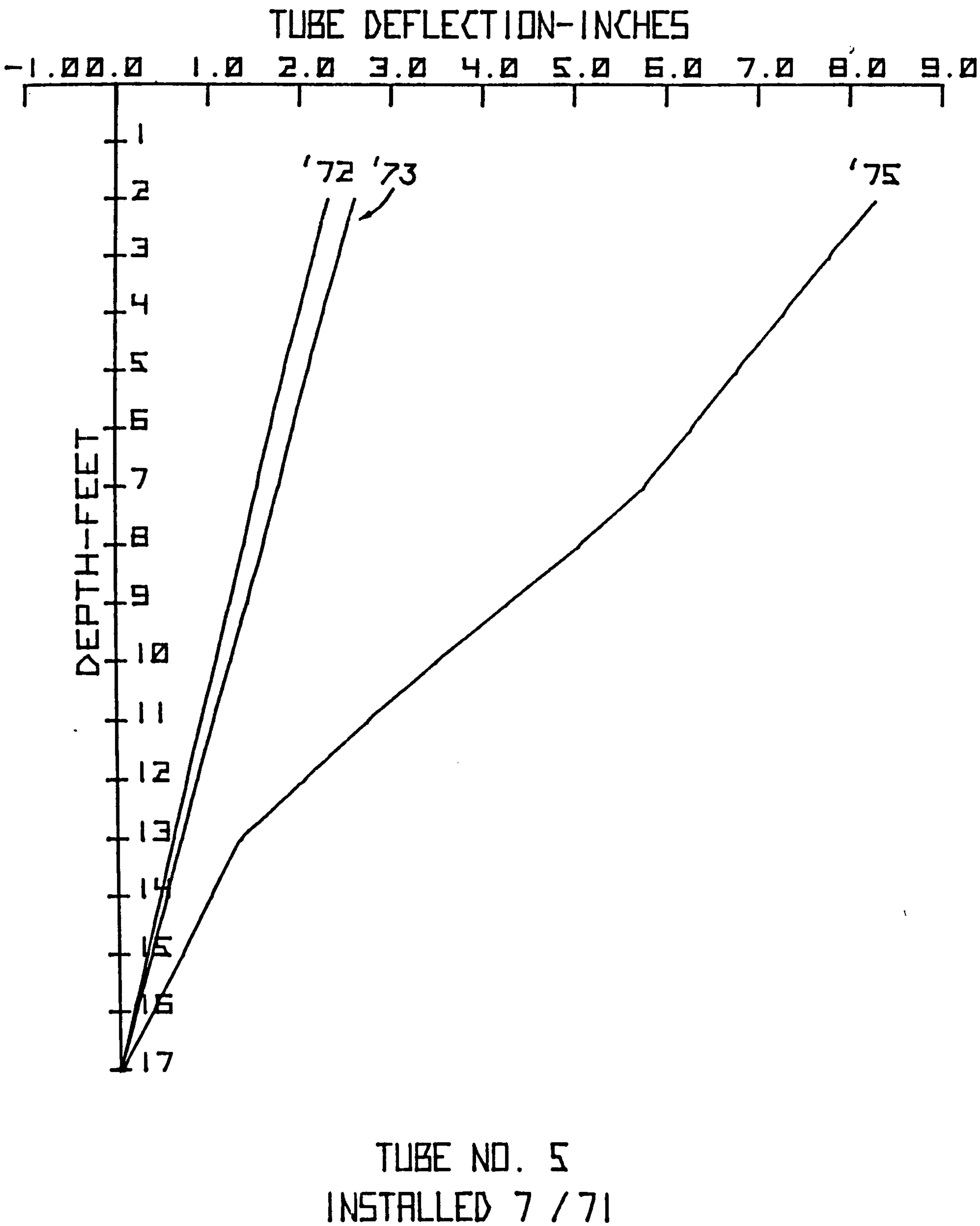

Figure 57. Creep profiles, Little South Fork landslide, Tube #5, Klamath National Forest.

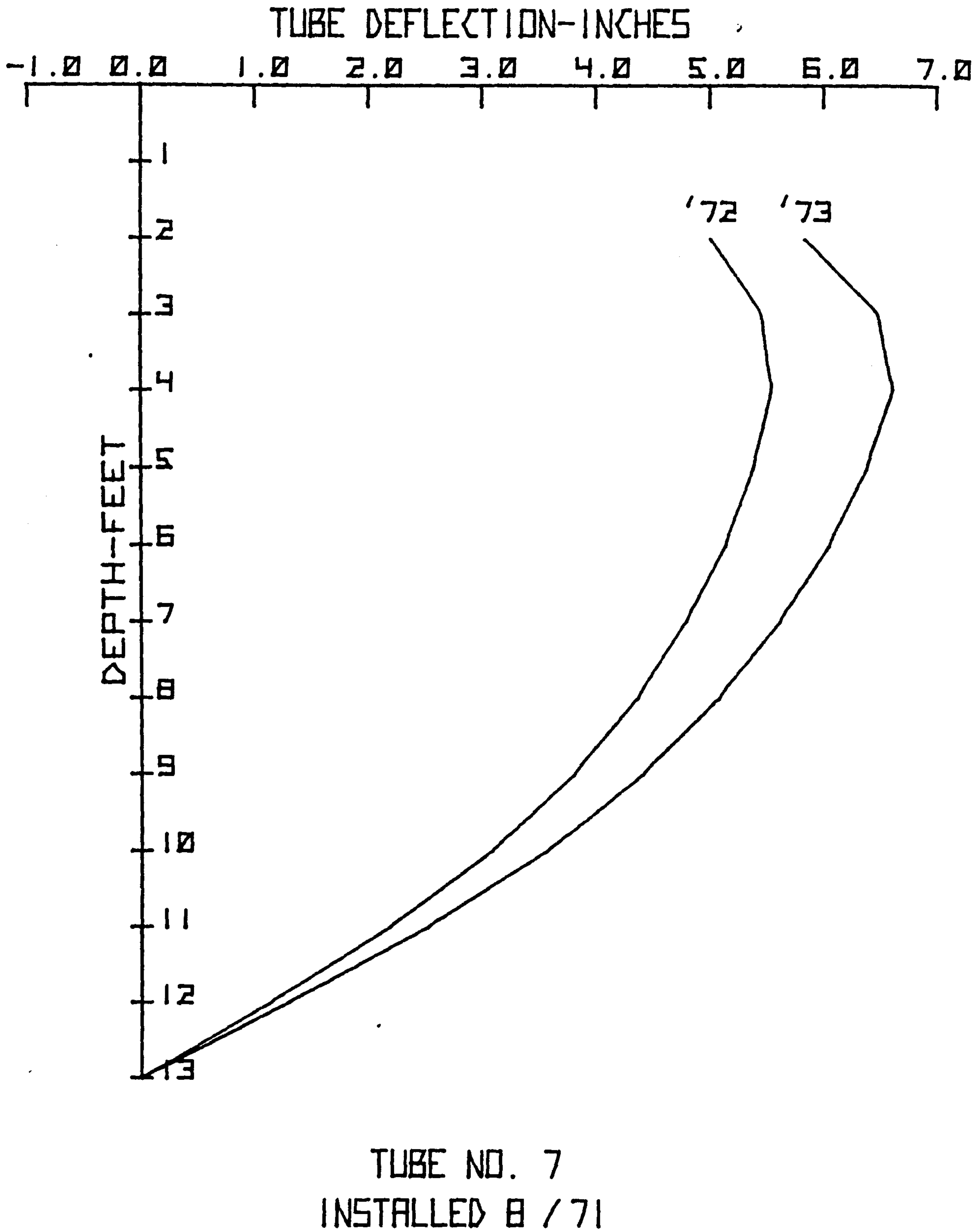

Figure 58. Creep profiles, Little South Fork landslide, Tube #7, Klamath National Forest.

profiles shown in Figure 52 for Tube #1, Clearview site. Shallow creep movement was accentuated following clear-cutting at this location. Additional years of monitoring are required, however, to fully substantiate this trend.

Creep movement measured at the Little South Fork site was substantial - creep rates varied from 2 to 6 inches per year. Most of the tubes were so badly tilted or deformed after 4 years that no further readings were possible after 1975. The creep profiles shown in Figure 54 for Tube #1 indicate that rotational sliding, which can produce a backward tilting of the inclinometer tube, is occurring at this location.

B. PRECIPITATION AND SOIL MOISTURE STRESS

1. H. J. Andrews Forest

Precipitation records for the period 1970-1977 were obtained from the climatic station in the H. J. Andrews Experimental Forest. Monthly rainfall during the study period is plotted in Figure 59. Annual rainfall totals for the water year starting in September are also shown on the plot. Rainfall was high in the winter of 1971 and 1973. A downward trend in total precipitation started in 1974 and culminated with a record low in 1977.

The soil moisture stress history recorded by tensiometers in Watershed No. 10 whilst in a forested condition is presented in Figures 60 and 61. Lapses appear in the soil suction record because of site access difficulties and other problems. The monthly precipitation history is also plotted on these same figures. Soil moisture suction curves appear almost

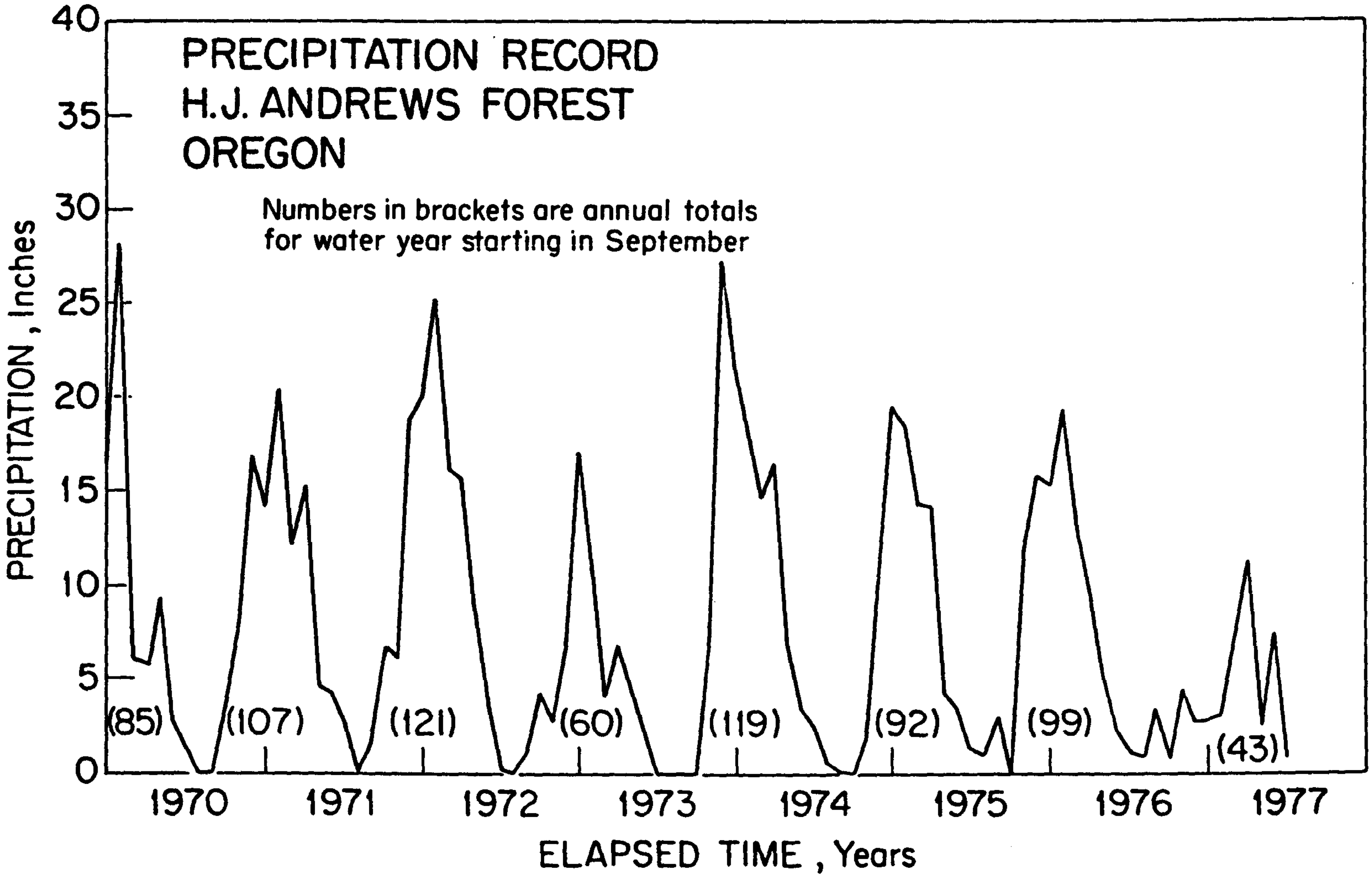

Figure 59. Monthly rainfall totals vs. elapsed time, H. J. Andrews Experimental Forest.

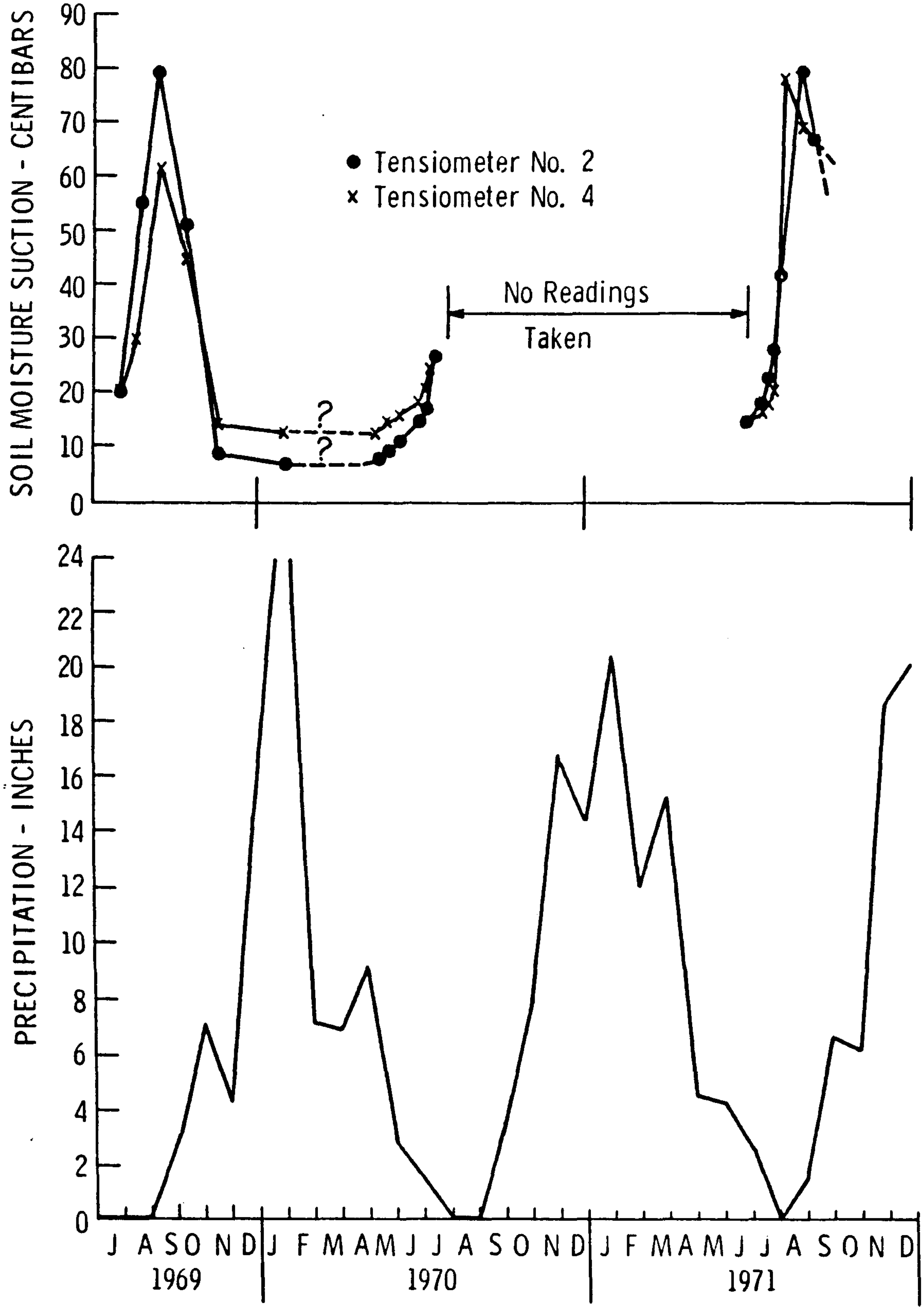

Figure 60. Soil moisture suction and precipitation vs. elapsed time, Watershed No. 10, H. J. Andrews Experimental Forest.

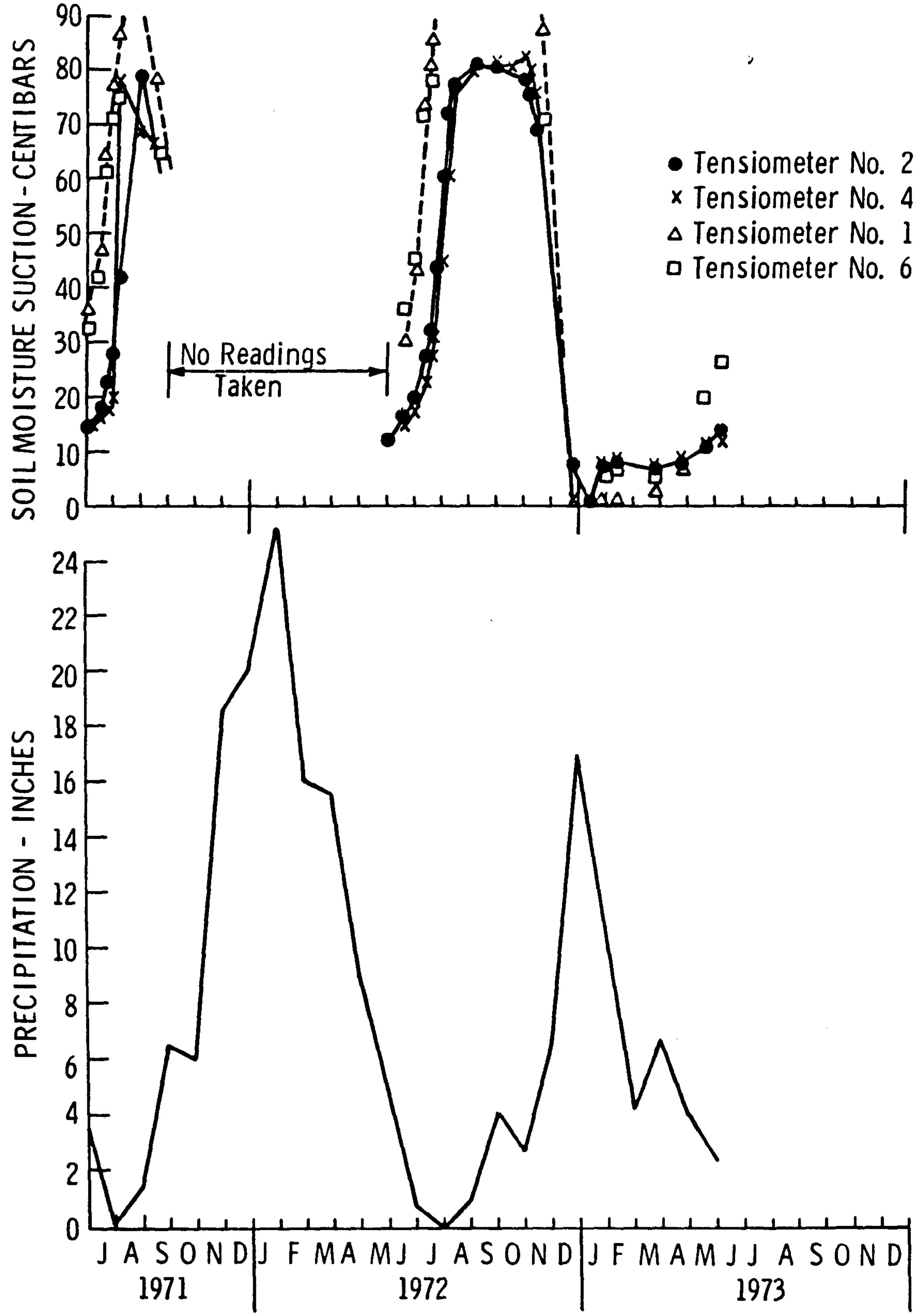

Figure 61. Soil moisture suction and precipitation vs. elasped time, Watershed No. 10, H. J. Andrews Experimental Forest.

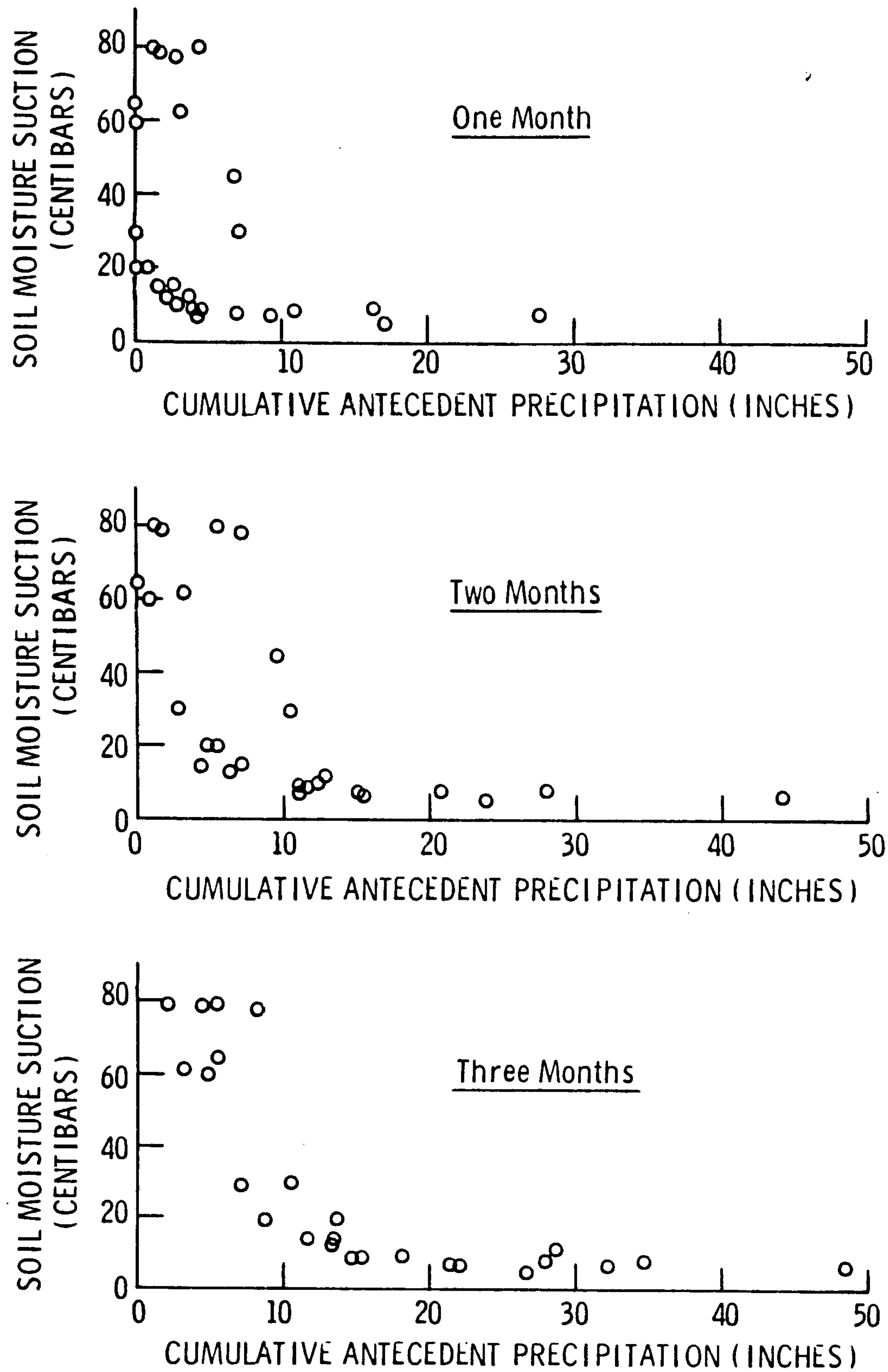

Figure 62. Soil moisture suction vs. antecedent precipitation, tensiometer No. 2, Watershed No. 10, H. J. Andrews Experimental Forest.

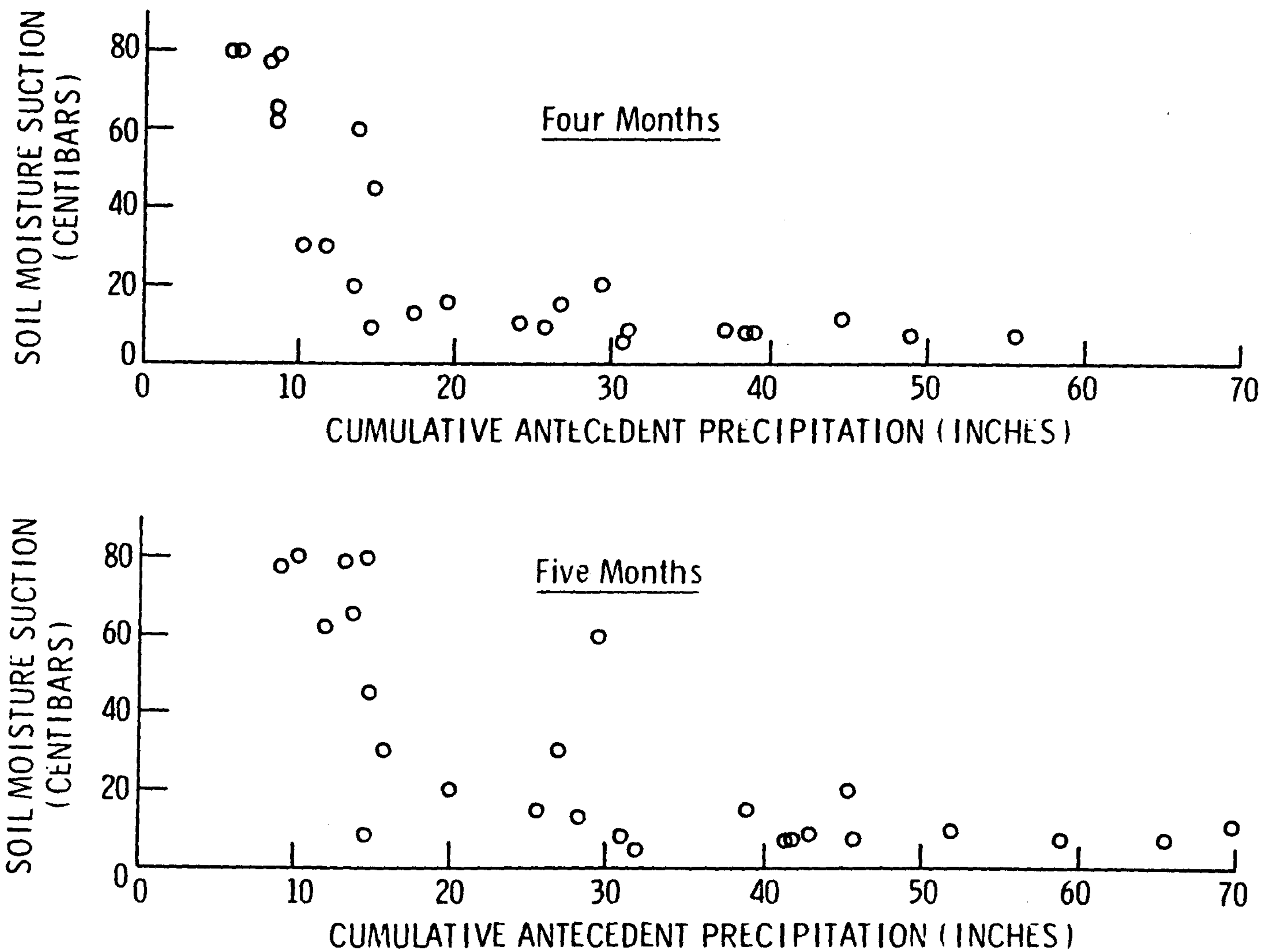

Figure 63. Soil moisture suction vs. antecedent precipitation of different duration, tensiometer No. 2, Watershed No. 10, H. J. Andrews Experimental Forest.

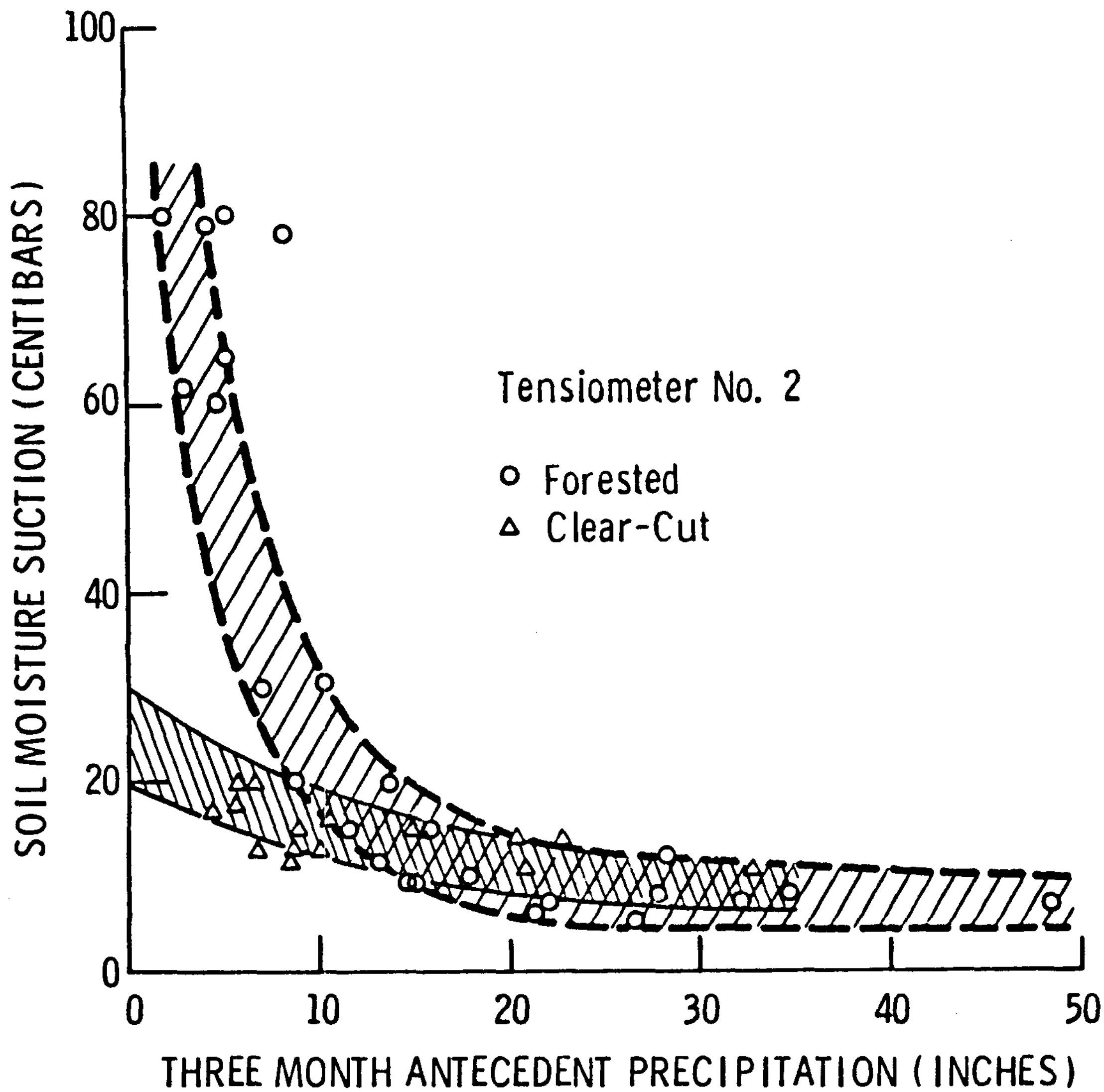

Figure 64. Comparison of soil moisture suction versus three-month antecedent precipitation (forested and cutover), Tensiometer #2, Watershed No. 10, H. J. Andrews Experimental Forest.

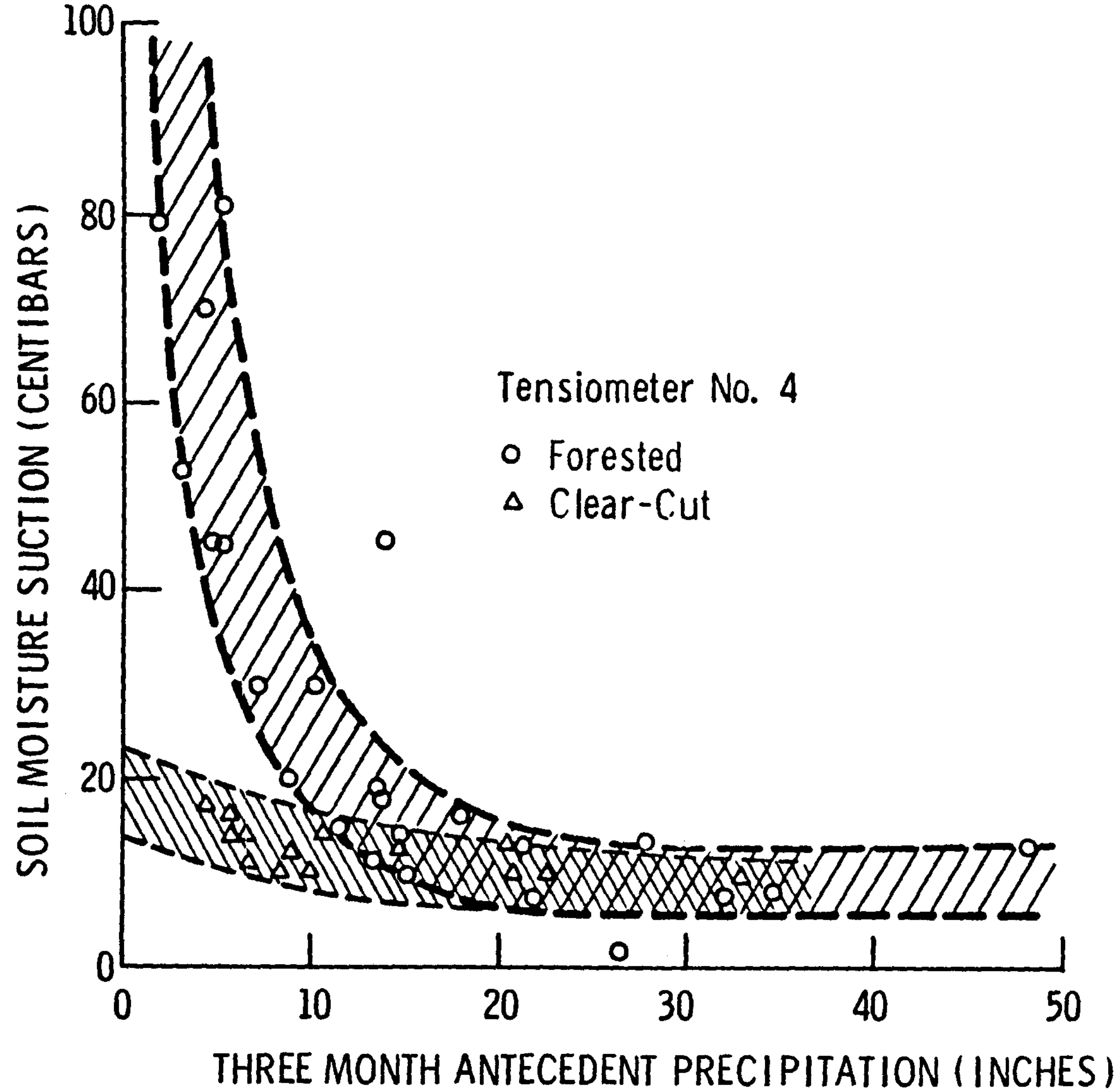

Figure 65. Comparison of soil moisture suction versus three-month antecedent precipitation (forested and cutover), Tensiometer #4, Watershed No. 10, H. J. Andrews Experimental Forest.

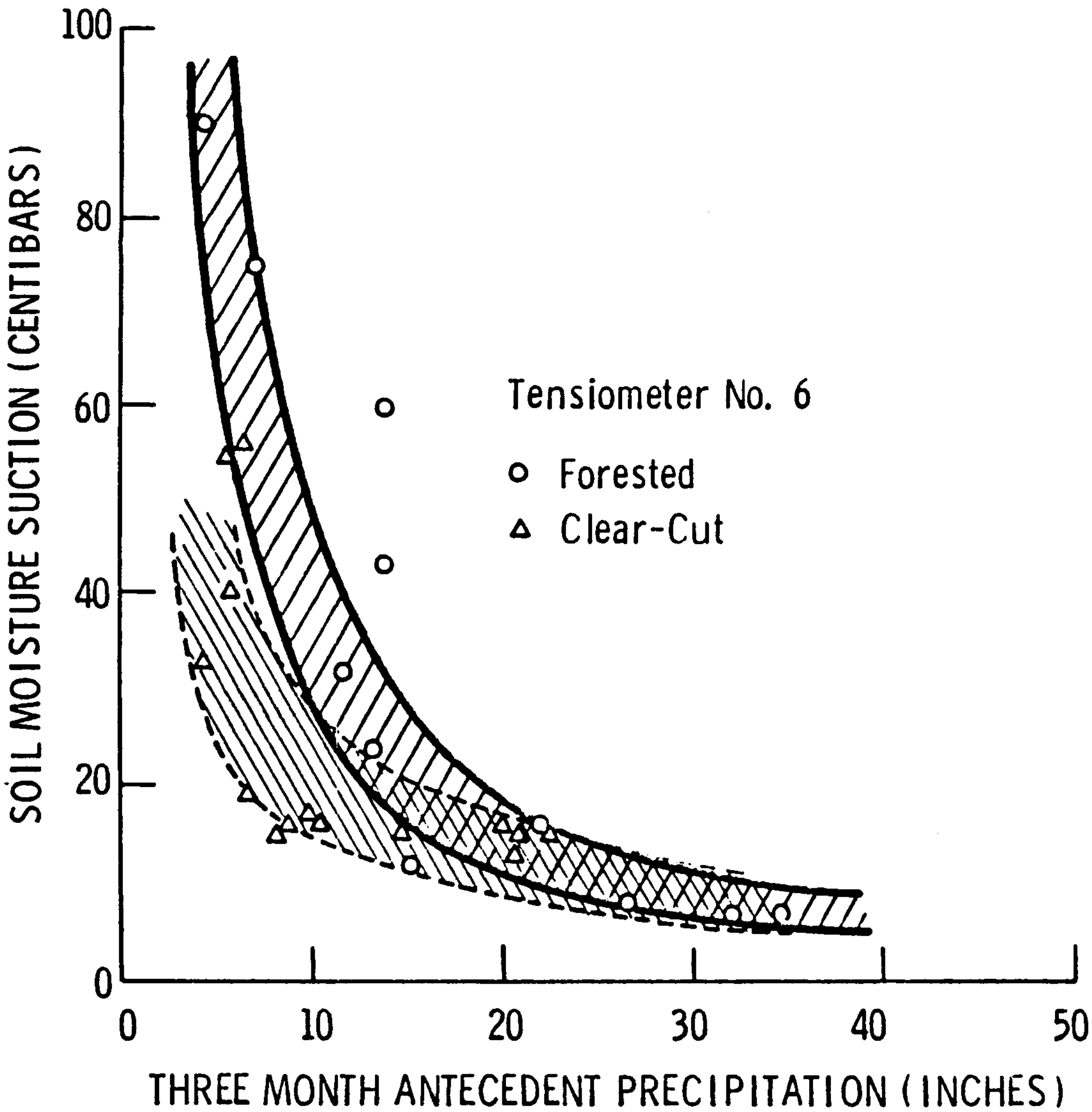

Figure 66. Comparison of soil moisture suction versus three-month antecedent precipitation (forested and cutover), Tensiometer #6, Watershed No. 10, H. J. Andrews Experimental Forest.

as inverse mirror images of the precipitation curves; as precipitation increases soil suction drops off and vice versa.

An attempt was made to look for a relationship between soil suction and antecedent precipitation of different duration using the data from tensiometer No. 2 as shown in Figures 62 and 63. A three-month antecedent precipitation total appeared to give the best relationship although scatter of data was still considerable. Soil suction vs. three-month antecedent precipitation for all the tensiometers is shown plotted in Figures 64 through 66. Suction vs. precipitation for the slope in both a forested and clear-cut condition are shown plotted in these figures.

2. U.S. Naval Radio Station

Monthly precipitation totals at the U.S. Naval Station during the period 1970-1977 are plotted in Figure 67. Annual totals for the same period are also shown. The precipitation pattern at the Station differs from the Oregon site in several respects. The annual totals tend to be lower and there is less variance from year to year. More importantly the precipitation is more evenly distributed throughout the year.

High piezometric levels were noted in the inclinometer tubes installed in the cutover portions of the valley slope at the U.S. Naval Radio Station. Inclinometer holes dug in the forested area, on the other hand, were quite dry. Piezometric levels observed during the summer of 1973 in cutover portion of the slope are shown in Figure 68. A partial record

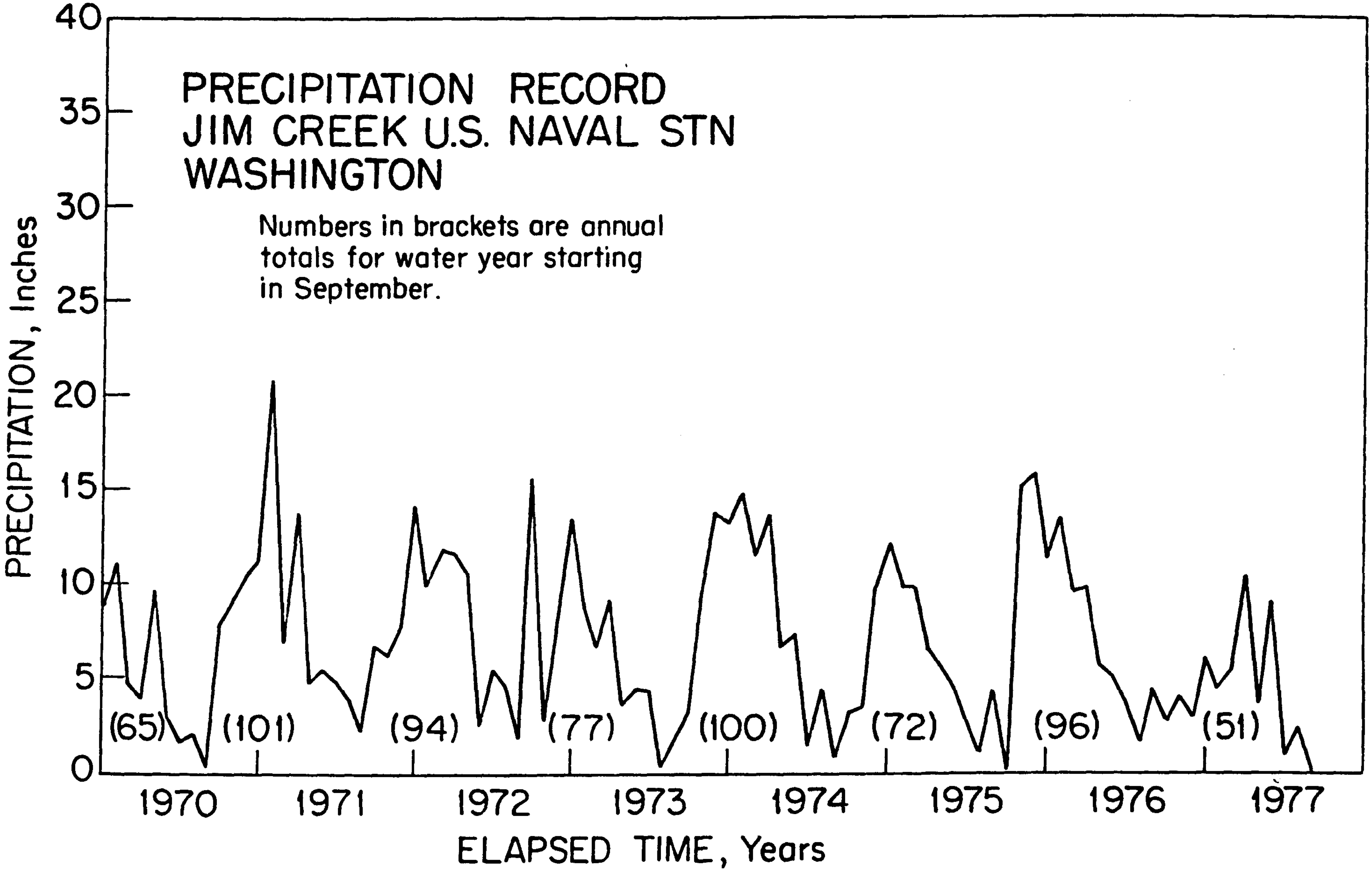

Figure 67. Monthly rainfall totals vs. elapsed time, U.S. Naval Radio Station.

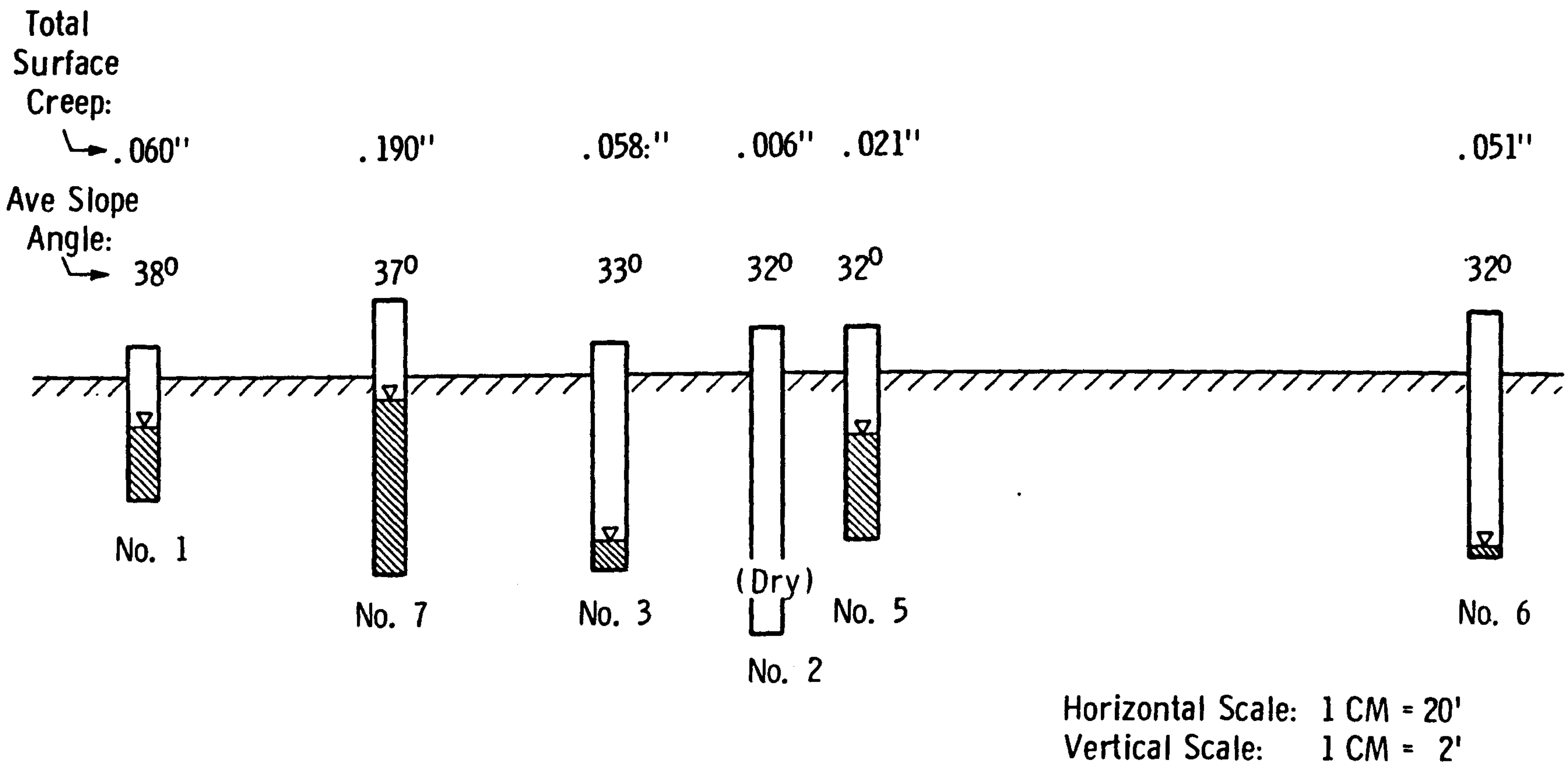

Figure 68. Piezometric levels (July 1973) and surface creep movements measured in inclinometer tubes located on cutover slope, U. S. Naval Radio Station.

of piezometric levels in the deep inclinometer tube installed in the cutover slope above the transmitter station was shown earlier in Figure 51 together with the creep profiles.

3. Klamath National Forest

Precipitation records for the period 1970-1977 were obtained from a climatic station at the U.S. District Ranger Station at Happy Camp, California. Monthly rainfall totals for the area are plotted in Figure 69. The precipitation pattern here is more like the Oregon site with wet winters and dry, hot summers. Annual precipitation totals, however, are considerably lower than either the Oregon or Washington sites. The recent drought in the Far West is clearly reflected in the annual totals for 1975, 1976, and 1977.

Site access problems at the Clearview site precluded obtaining sufficient tensiometer data to establish any meaningful correlation between soil moisture suction and rainfall before and after clear-cutting. A piezometric head of one foot of water was observed in Tube #1, however, the two summers following clear-cutting. This tube was always observed to be dry (i.e., no standing water or piezometric head) the preceding three summers when the slope was forested.

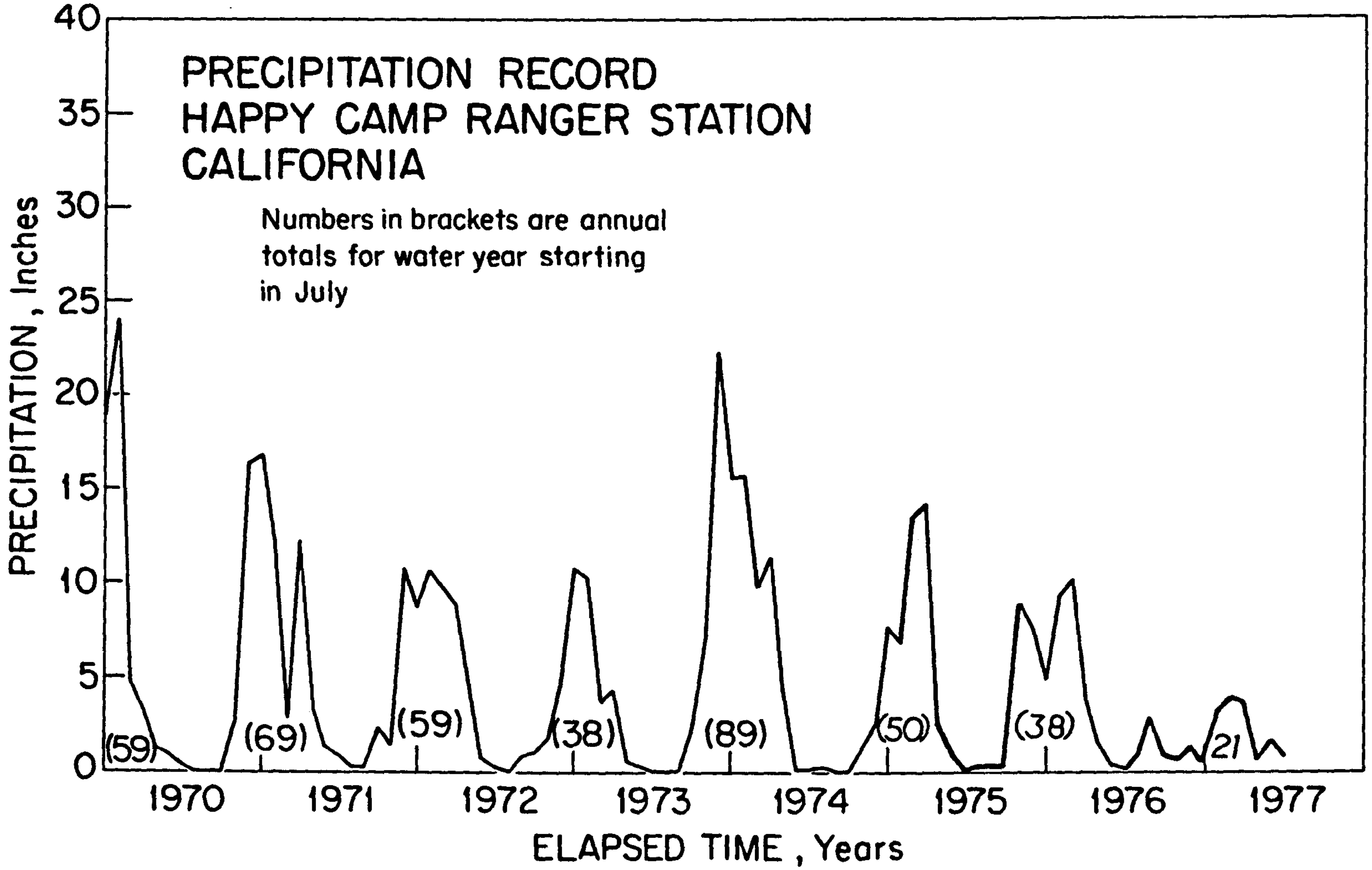

Figure 69. Monthly rainfall totals vs. elapsed time, Happy Camp Ranger District, Klamath National Forest.

VI. ANALYSIS AND DISCUSSION OF RESULTS

A. COMPARISON OF CREEP RATES IN FORESTED VS. CUTOVER SLOPES

Cumulative creep movement measured at the ground surface at each inclinometer installation was plotted versus elapsed time. This procedure made it possible to determine average creep rates and compare creep rates in forested as opposed clear-cut or cutover sites.

Plots of creep movement versus time for the various study sites are shown in Figures 70 through 74. Average creep rates for each of the inclinometers were estimated from these plots and are summarized in Table 2. Site averages were also computed and are listed in Table 2. Creep rates were not computed for sites or site conditions with insufficient monitoring times. This restriction applies to Watershed No. 10, H. J. Andrews Forest, and the Clearview site, Klamath National Forest, following clear-cutting at both sites. Not only was the monitoring period too short to calculate reliable creep rates, but the post cutting period also coincided with very dry years.

Surface creep rates measured in a clear-cut slope (Watershed 1) and adjacent forested slope (Watershed 2-3) can be ascertained from Figures 70 and 71. Average creep rates in the cutover slope (0.50 mm/yr) are twice the creep rates in the forested slope (0.24 mm/yr). Surface creep rates for the site in Watershed No. 10 in a forested condition averaged 0.90 mm/yr. Creep rates for this same site after clear-cutting cannot be computed reliably at this time for reasons already

TABLE 2 - Summary of Average Downslope Creep Rates Measured at Field Research Sites

Site Location	Status	Tube No.	Creep Rate @ Surface mm/yr
Watershed No. 1 H. J. Andrews, Oregon	clearcut	2A 3A 6A 8A slope ave.	.41 .91 .40 .64 0.59
Watershed No. 2-3 H. J. Andrews, Oregon	forested	2B 3B 4B 5B slope ave.	.13 .32 .10 .42 0.24
Watershed No. 10 H. J. Andrews, Oregon	forested (except @ Tube #4)	#1 #2 #4 #6 slope ave. (excl. #4)	.68 1.14 1.38 .88 0.90
U.S. Naval Radio Stn. Washington	cutover slope	#1 #2 #3 #5 #7 slope ave. (excl. #1 & 5)	.08 .57 .95 .08 .61 0.71
U.S. Naval Radio Stn. Washington	forested slope	#8 #9 slope ave.	.91 .57 0.74
U.S. Naval Radio Stn. (above transmitter)	cutover slope	Test pit #2	8.16

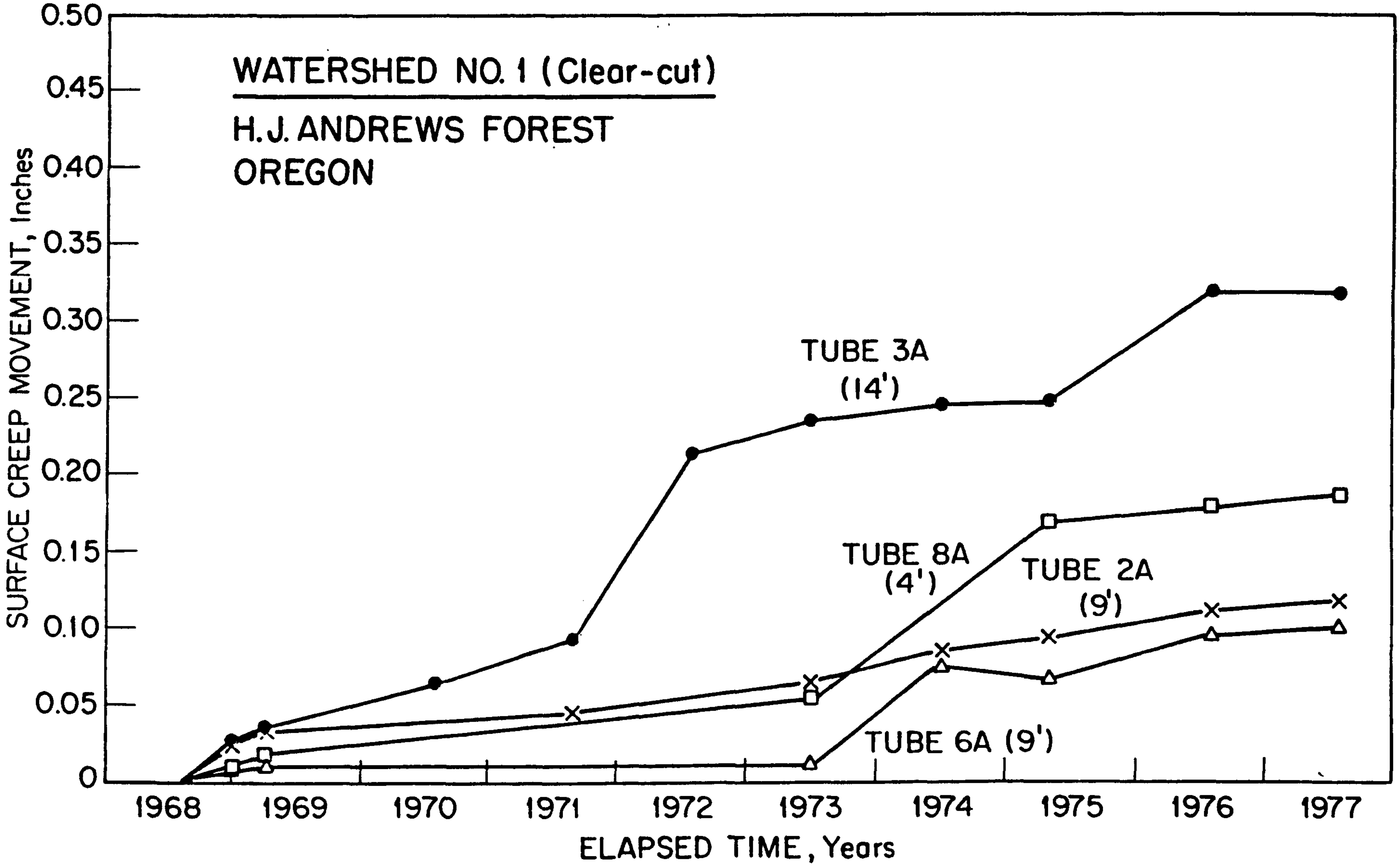

Figure 70. Surface creep movement vs. elapsed time, Watershed No. 1 (clear-cut), H. J. Andrews Experimental Forest.

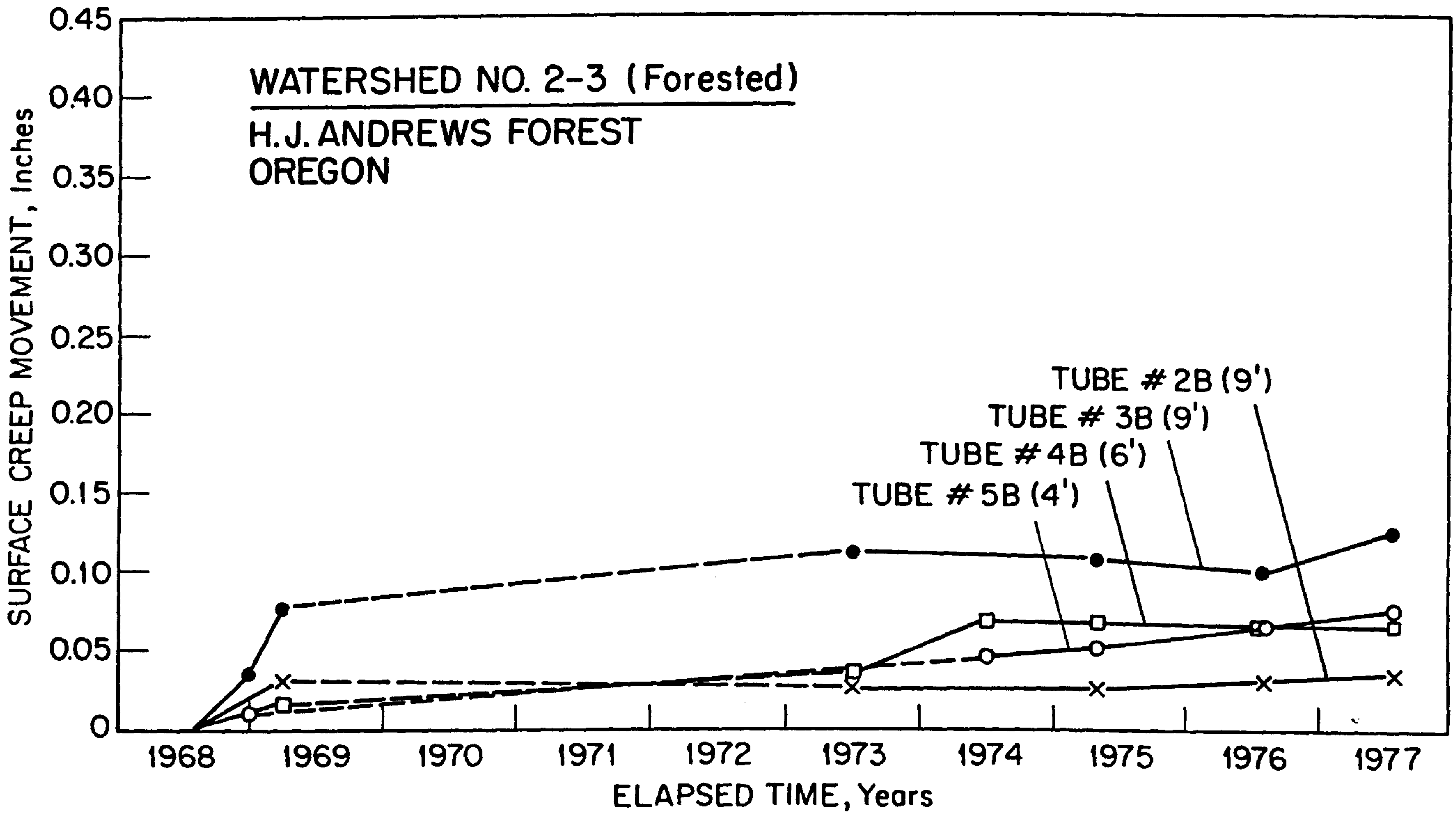

Figure 71. Surface creep movement vs. elapsed time, Watershed No. 2-3 (forested), H. J. Andrews Experimental Forest.

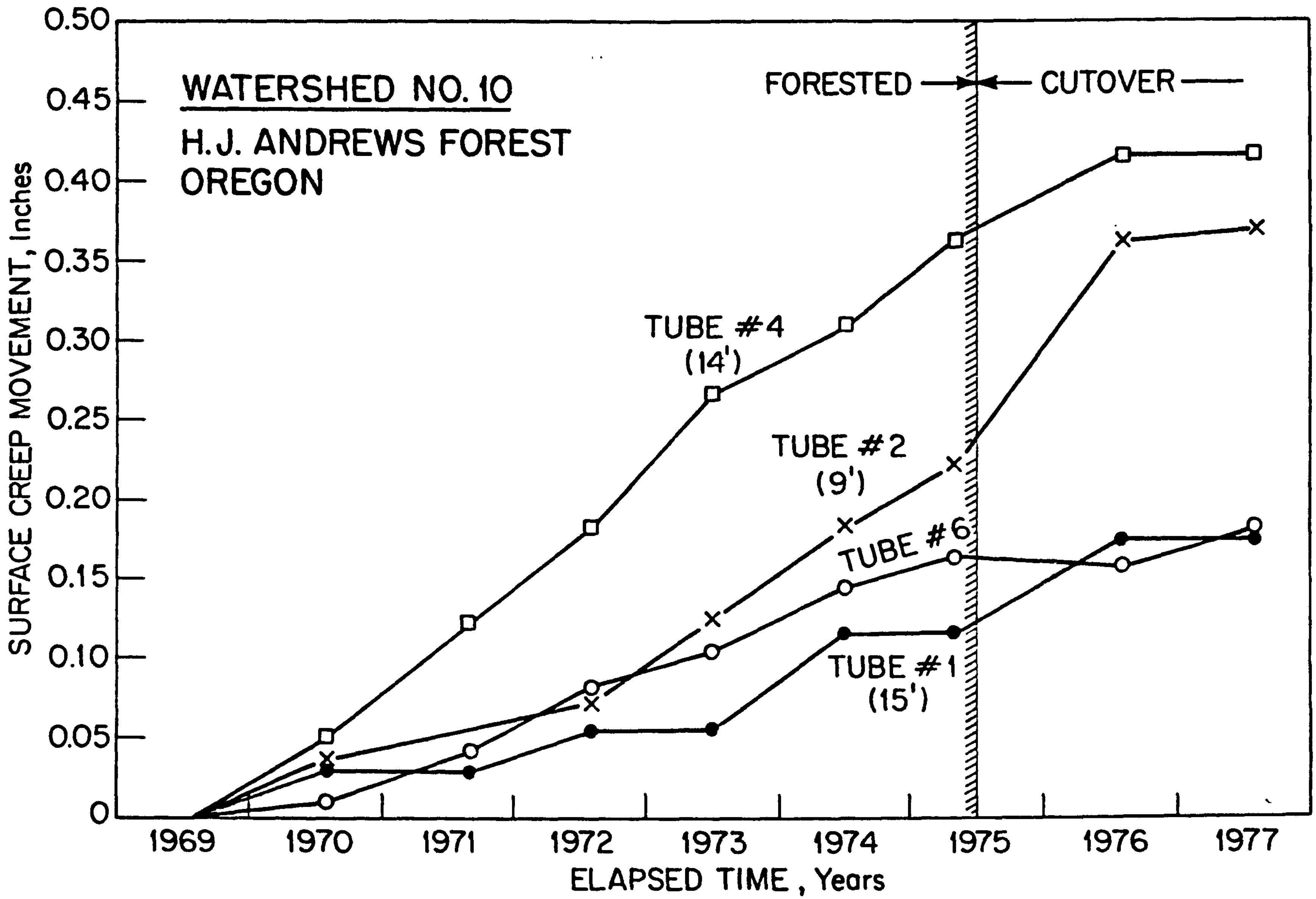

Figure 72. Surface creep movement vs. elapsed time, Watershed No. 10, H. J. Andrews Experimental Forest.

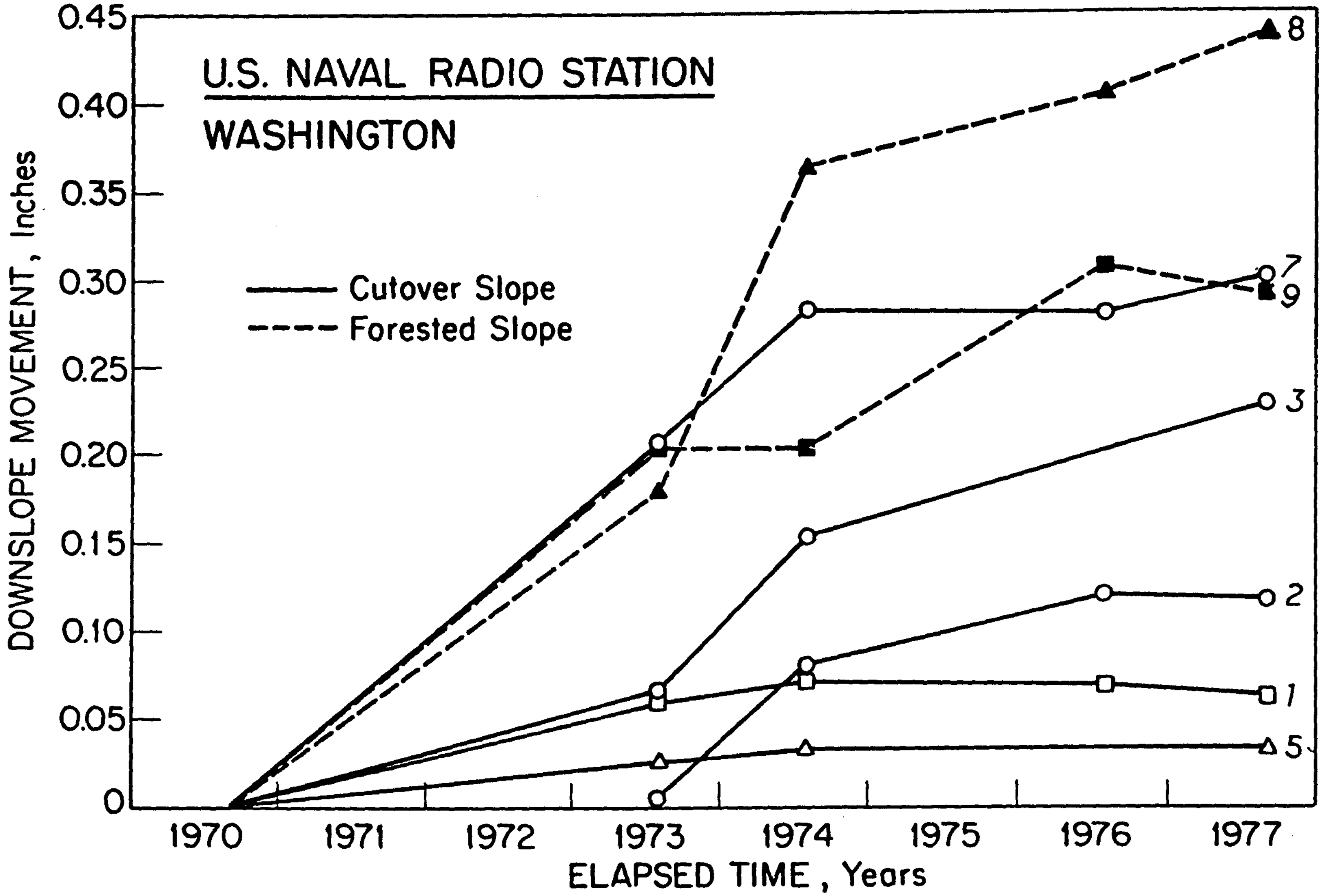

Figure 73. Surface creep movement vs. elapsed time, cutover and forested slope, U.S. Naval Radio Station.

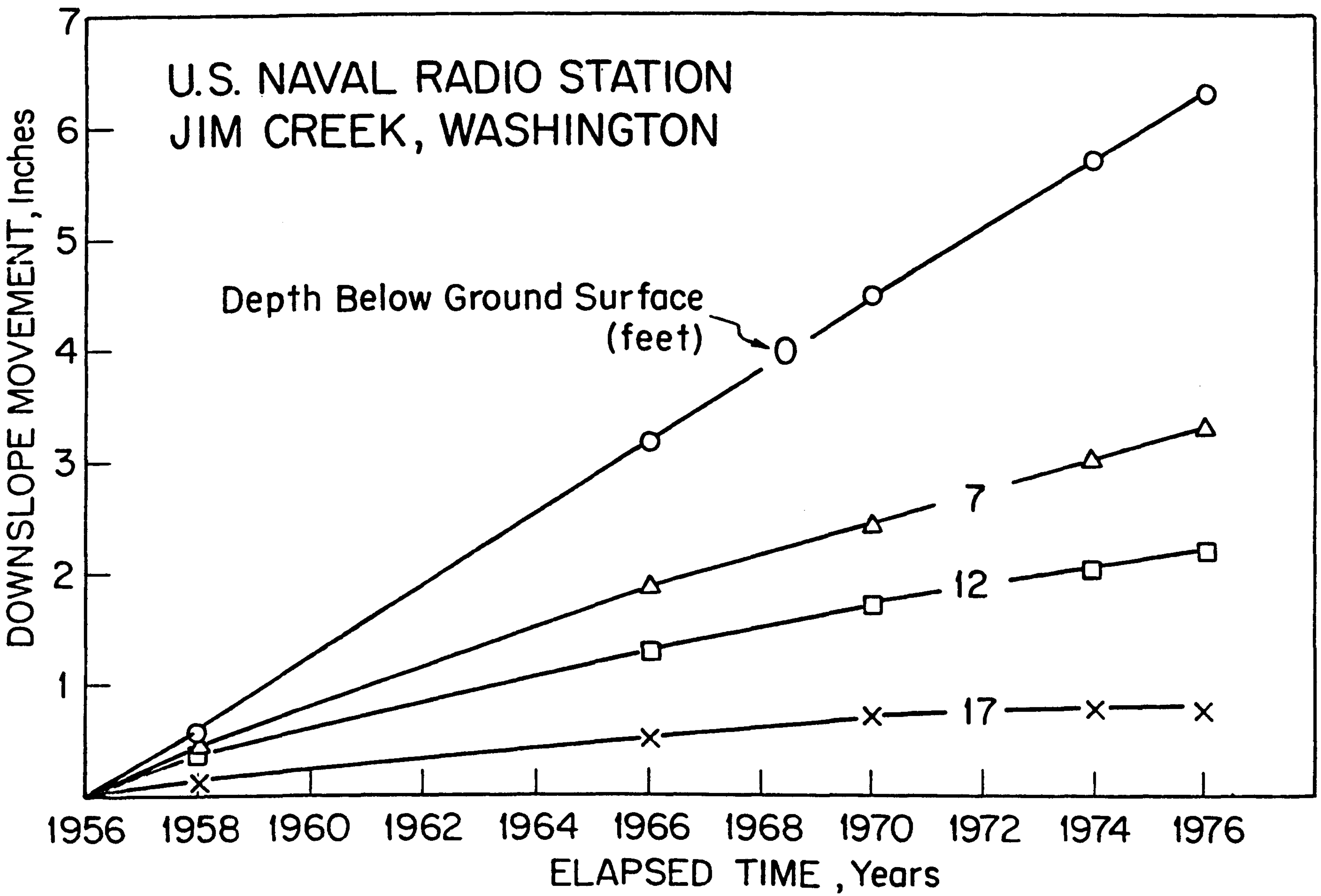

Figure 74. Creep movement at various depths vs. elapsed time, slope above transmitter building, U.S. Naval Radio Station.

noted. It is interesting to observe, however, that the average creep rate measured at Tube #4 (1.38 mm/yr) in an area of dead trees is considerably higher than the average for the rest of the tubes (0.90 mm/yr) at the site while still forested.

Surface creep rates measured in the cutover and forested portions of the slope at the U.S. Naval Radio Station can be determined from the curves in Figure 73. These plots indicate there is little or no difference in creep rates between these two areas. If the two short tubes in the cutover slope are discounted, the annual creep rates are about the same. It is emphasized again, however, that the method of installing the tubes in backfilled pits in the forested slope could have influenced results.

Long term creep rate data for the cutover slope above the transmitter building at the U.S. Naval Radio Station is plotted separately in Figure 74. Creep rates at this location are remarkably constant over time and average about 8 mm/yr. This rate is comparable to measured rates of natural creep tabulated in Table 1 for other slopes in the Pacific Northwest. On the other hand, rates of creep measured at the other sites in the present study, with the exception of the Little Fork landslide, were an order-of-magnitude lower.

B. INFLUENCE OF TREE COVER ON SOIL MOISTURE STRESS

A general observation throughout the entire field study was the noticeably wetter conditions in clear-cut or cutover slopes as opposed to forested slopes. This was apparent at all three field sites as discussed previously. This observation was always made, however, in the summer. During this time of year the absence of significant precipitation coupled with the presence of transpiring slope vegetation can indeed result in a moisture deficit in the ground and the development of higher soil moisture suction in forested as opposed to cutover sites. Results of the present field study corroborate the findings of other investigators in this regard, e.g., Bethlahmy (1962), Patric *et al* (1968), and Hallin (1967).

A more critical question with regard to slope stability is what happens to soil moisture stress in forested as compared to cutover slopes in the winter when intense and frequent storms tend to saturate the ground and when transpiration is reduced. This is the time that is critical for slope stability because of the loss of tension in the pore water and the development of piezometric heads which can greatly reduce shear resistance and stability. No "side-by-side" comparisons of soil moisture stress are available from the present study to answer this question. There are however the results of soil moisture measurements in Watershed No. 10, H. J. Andrews Forest, which were obtained while the slopes were in both a forested and clear-cut condition.

Precipitation patterns will also affect soil moisture stress response. In order to use the results of the tensiometer measurements in Watershed 10 for comparison it is necessary to take into account climatic differences between the two monitoring periods. This was done by plotting soil moisture suction or tension versus antecedent precipitation for the slope in both a forested and cutover condition. These plots are shown in Figures 64 through 66 using a 3-month antecedent precipitation for both the forested and cutover condition. Ideally the precipitation patterns should still be reasonably similar to maximize reliability of the comparison. Unfortunately this was not the case in the present study because the post cutting monitoring period coincided with a very dry year (i.e., 1976-1977).

As expected the soil suction at low antecedent precipitation levels was considerably lower in the cutover condition. On the other hand, at high levels of antecedent precipitation there appeared to be little difference. In other words, after intense and prolonged rainfall the hydrologic response of both forested and cutover slopes was the same. Even so there are still important benefits vis à vis slope stability from the drier condition which prevails in the forested slope at least part of the year. Interception and transpiration by a forest canopy could either partially mitigate or delay onset of waterlogged conditions in a slope. All other things being equal, a forested slope might not reach a critical moisture stress level as quickly. Also drier conditions at least part of the year may retard the rate of weathering in the soil profile and hence slow down the decrease in shear resistance and instability over time.

C. CONSEQUENCES OF TREE REMOVAL ON SLOPE STABILITY

As discussed previously woody vegetation can affect the stability of natural slopes via surcharge from the weight of trees, by mechanical reinforcement from the roots, by depleting soil moisture through transpiration, and by slope buttressing. The effect of surcharge and increasing piezometric level on the stability of slopes at the field research sites has been reported by Gray (1973). Slope stability calculations showed that safety factors exceeded unity as long as high piezometric levels did not develop in the slopes. An exception was noted at the U.S. Naval Radio Station where fairly high piezometric levels could be tolerated before unstable conditions would develop. The effect of surcharge from the weight of trees was minor and in certain circumstances actually enhanced stability.

A safety factor greater than unity means the slope is safe against rapid, catastrophic sliding but this does not preclude slow creep movement. The closer the factor of safety to unity the more rapid the creep movement. Creep movement tends to destabilize slopes and make them more vulnerable to catastrophic sliding for reasons explained previously in the report. The linkage between creep and other mass-erosion processes is schematically illustrated in Figure 75. The influence of forest vegetation on soil creep is thus an important consideration in the overall stability of natural slopes.

The results of the tensiometer measurements suggest that a forest cover will have little effect on the soil moisture stress in a slope once precipitation of sufficient duration

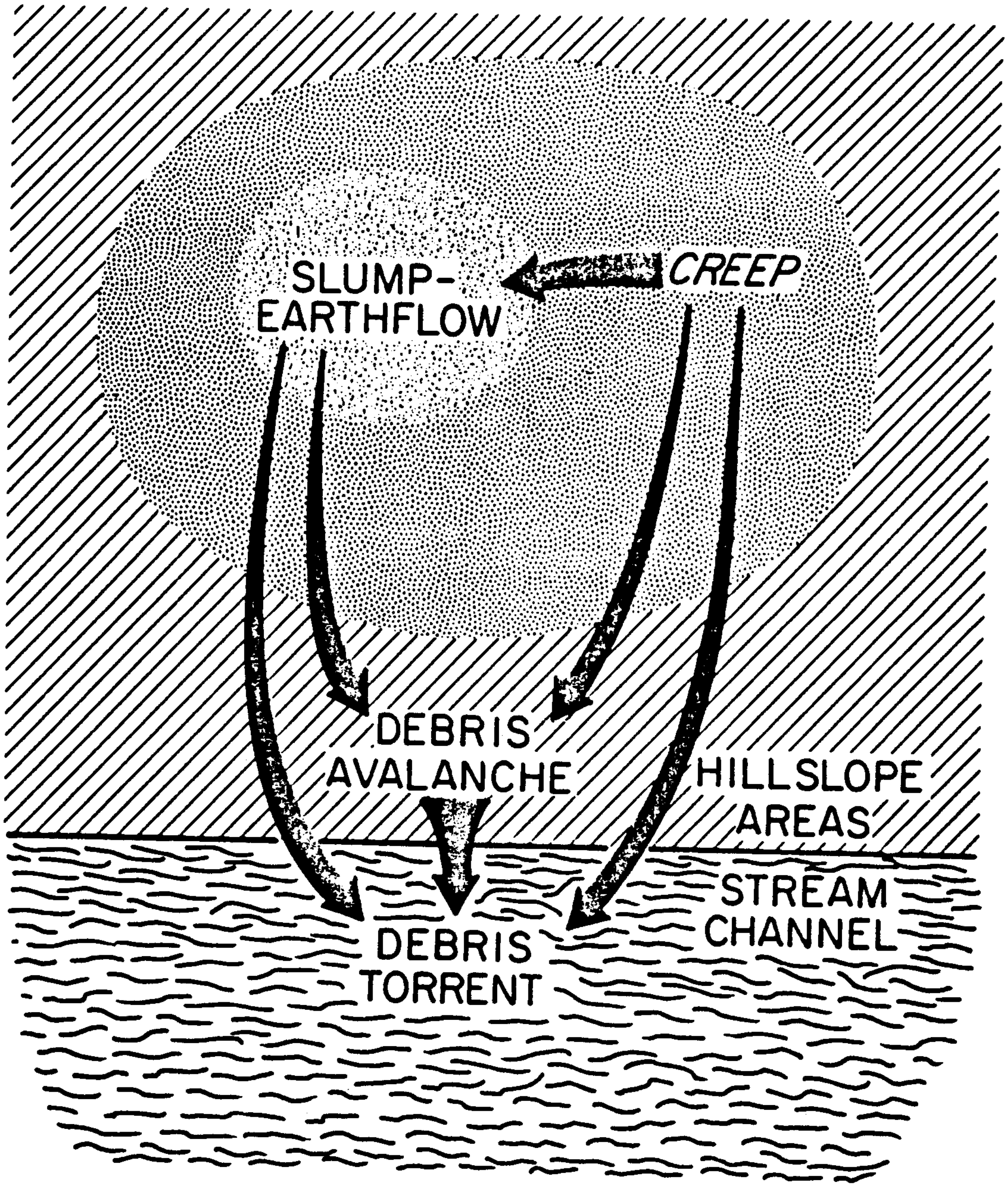

Figure 75. Schematic illustration showing linkages between soil creep and other mass-erosion processes (after Swanston and Swanson, 1976).

and intensity falls on the slope and eliminates soil moisture suction. Loss of soil moisture tension and development of piezometric levels in a slope frequently lead to catastrophic slope failure. Is there any value then in a forest cover which does not appear to influence the wet end of the soil moisture stress spectrum as shown by the results in Figures 64 through 66? The results of this and earlier studies do confirm, however, that tree removal decreases pore water suction or tension on the dry side of the spectrum, i.e., during the summer months. If this reduction is sufficient to decrease mobilized shear resistance below the yield stress value, creep movement will result. Some creep movement does in fact occur during the summer when soil water tension normally prevails in a slope although at many sites most of the movement tends to occur during the winter (Swanston and Swanson, 1976). Thus, if removal of tree cover results in greatly decreased soil moisture suctions, creep movement may extend over a longer period of the year in a cutover slope than it would in the same slope in a forested condition.

The influence of loss of root reinforcement per se and its contribution to observed creep movement were not investigated in the field study. The contribution of root tensile strength to soil shear strength was discussed in detail in the review of past work earlier in the report. There appears little doubt that roots can and do increase shear resistance. The work of Burroughs and Thomas (1977) also provides information on the decrease in root strength and reinforcement with time after felling. From this work plus the earlier studies by Swanston (1970) it is clear that sufficient time must elapse before loss of root strength will manifest itself in accelerated creep rates and other forms of mass-wasting or erosion. Both Watershed No. 10, H. J. Andrews Forest, and the Clearview site, Klamath National Forest, thus have not been observed over a sufficiently long enough period of time following cutting to detect effects of significant root deterioration. It is very important, therefore, that monitoring continue for at least another 3 years at these sites. A second reason for this continued monitoring is to observe the creep response of these sites during a wetter climatic season. The post cutting monitoring period at the two sites has so far coincided with record dry years. The creep record from Tube #4 which was installed originally in an area of dead trees in the midst of a forested slope (Watershed No. 10, H. J. Andrews Forest) provides some clue or indication of the effects of root deterioration. Creep rates have been consistently higher at this location over a 7-year monitoring period relative to rates measured in neighboring tubes installed in forested portions of the slope.

VII. CONCLUSIONS

1. An emerging concensus in the technical literature shows that trees enhance the stability of steep slopes by mechanical reinforcement from the root system and by soil moisture depletion by transpiration. Trees may also improve stability by a buttressing or soil arching action particularly in sandy slopes but this mechanism requires further investigation.
2. Creep is a primary and important link in the natural transport of soil downslope. Excessive creep tends to destabilize slopes and accelerate or trigger other mass-erosion processes. These in turn contribute to increased rates of sedimentation to streams and rivers.
3. Vegetation can affect creep rates in the same way it affects the resistance of slopes to catastrophic failure or sliding. Removal or cutting of trees on steep slopes can lead to higher creep rates. Evidence from the present study includes:
    a. Consistently higher creep rates measured at an inclinometer installed in the midst of an area of dead trees relative to creep movement measured in inclinometer tubes installed in forested portions of the same slope (Watershed No. 10, H. J. Andrews Forest).
    b. Creep rates in a cutover slope (Watershed No. 1) which averaged twice those in an adjacent forested slope (Watershed No. 2-3, H. J. Andrews Forest).

c. Pronounced increases in creep movement in Tubes #1 and 2, Watershed No. 10, H. J. Andrews Forest, following clear-cutting. Other tubes in this watershed, however, did not exhibit such behavior.

4. The results of comparative creep studies at the U.S. Naval Radio Station do not support the conclusion that tree removal increases creep rates. Both forested and adjacent cutover slope exhibited approximately the same creep rates. The creep response of the former may be influenced however by the installation procedure which differed significantly.

5. With one or two exceptions surface creep rates measured at the field research sites averaged 1 mm/yr or less. This rate is an order-of-magnitude less than the rates reported by Swanston and Swanson (1976) for natural rates of creep of forested slopes in the Pacific Northwest. The exceptions were the cutover slope above the transmitter building at the U.S. Naval Station which averaged about 8 mm/yr and the Little South Fork landslide which averaged about 100 mm/yr.

6. Monitoring times were too short in order to compute reliable creep rates in Watershed 10, H. J. Andrews Forest and the Clearview site, Klamath National Forest, following clear-cutting. Insufficient time elapsed for significant root deterioration to occur during this period and furthermore the post cutting period coincided with record dry years. It is very important, therefore, to continue monitoring these two sites for at least another 3 years.

7. The results of tensiometer measurements indicate that a forest cover affects the dry side of the soil moisture suction vs. precipitation relationship but not the wet side. A tree cover thus may not prevent loss of soil moisture tension following prolonged and intense precipitation in the winter. On the other hand, it does tend to maintain high suctions in the summer and thus limit the duration and extent of creep by maintaining a higher mobilized shear resistance relative to the yield shear stress over a longer period of time.

VIII. ACKNOWLEDGMENTS

The research described herein was supported by Grants Nos. ENG 74-02427 and GK-24747 from the National Science Foundation. The Pacific Northwest Forest and Range Experiment Station, U.S. Forest Service, kindly made available the study areas in the H. J. Andrews Experimental Forest. Logistical aid and manpower assistance were furnished by U.S. Forest Service personnel in the Klamath National Forest. The permission of the U.S. Navy to instrument a site at the Naval Radio Station at Jim Creek likewise is acknowledged.

Several persons in the U.S. Forest Service have been particularly helpful and instrumental in making the field studies possible. They include Ross Mersereau, Field Research Supervisor, and Dick Fredriksen, Soil Scientist, both with the Pacific Northwest Forest and Range Experiment Station; and Bill Hicks, Engineering Geologist, presently with the Rogue River National Forest.

Peter Bosscher assisted with the analysis of field data, plotting of creep profiles, and preparation of this report. Roger Gray and Peter Brenner provided photographic assistance. Last but not least the assistance of the many students, both graduate and undergraduate, who assisted with the early field work is greatly acknowledged. Installation of the inclinometers on steep slopes often without benefit of existing trails was a demanding task. Persons assisting in this capacity over a four-year period include Peter Brenner, In-Kuin Kim, Ted Webster, Steve Flodin, Jerry Carignani, Maurice Cooper, and Dana Bayuk.

IX. REFERENCES

Bailey, R. G. and Rice, R. M. (1969), "Soil Slippage: An Indicator of Slope Instability on Chapparal Watersheds of Southern California," The Professional Geographer, Vol. XXI, No. 3, pp. 172-177.

Bailey, R. G. (1971), "Landslide Hazards Related to Land Use Planning in the Teton National Forest, Northwest Wyoming," U.S. Forest Service publication, Intermountain Region, Ogden, Utah, 131 pp.

Bethlahmy, N. (1962), "First Year Effects of Timber Removal on Soil Moisture," Int. Assn. Sci. Hydrol. Bull., Vol. 7, No. 2, pp. 34-38.

Brown, C. B. and Sheu, M. S. (1975), "Effects of Deforestation on Slopes," Journal of the Geotechnical Engineering Division, ASCE, Vol. 101, pp. 147-165.

Burroughs, E. P. and Thomas, R. R. (1976), "Root Strength of Doulgas-fir as a Factor in Slope Stability," USDA, Forest Service, review draft INT 1600-12 (9/66), 30 pp.

Crandell, D. R. and Waldron, H. H. (1952), "Geology of Part of the U.S. Naval Radio Station," Arlington, Washington, U.S. Geological Survey, Dept. of the Interior, 25 pp. (May).

Curtis, J. D. (1964), "Roots of a Ponderosa Pine," USDA Forest Service, Research Paper INT-9, 10 pp.

Dodge, et al (1976), "An Investigation of Soil Characteristics and Erosion Rates on California Forest Lands," State of California Resources Agency, Department of Forestry, 105 pp.

Dyrness, C. T. (1967), "Mass-soil Movements in the H. J. Andrews Experimental Forest," U.S. Forest Service Res. Paper PNW-42, 12 pp., illus.

Flaccus, E. (1959), "Landslides and Their Revegetation in the White Mountains of New Hampshire," Duke University, Ph.D. Thesis, Botany.

Fredriksen, R. L. (1965), "Christmas Storm Damage on the H. J. Andrews Experimental Forest," U.S. Forest Service Res. Note PNW-1.

Fredriksen, R. L. (1970), "Erosion and Sedimentation Following Road Construction and Timber Harvest on Unstable Soils in Three Small Western Oregon Watersheds," USDA Forest Service Research Paper, PNW-104, 15 pp.

Gonsior, M. J. and Gardner, R. B. (1971), "Investigation of Slope Failures in the Idaho Batholith," USDA Forest Service Research Paper INT-97, 34 pp., illus.

Gray, D. H. (1973), "Effects of Forest Clear-Cutting on the Stability of Natural Slopes: Results of Field Studies," Interim Report to the National Science Foundation, Grant No. GK-24747, Dept. of Civil Engineering, University of Michigan, Ann Arbor, 119 pp.

Gray, D. H. (1974), "Reinforcement and Stabilization of Soil by Vegetation," Journal of the Geotechnical Engineering Division, ASCE, Vol. 100, No. GT6, pp. 695-699.

Gray, D. H. (1976), "Stabilization of Sandy Slopes by Soil Arching Effects Derived from Woody Vegetation," Grant No. ENG 7522766, National Science Foundation, Washington, D.C.

Gray, D. H. and Brenner, R. P. (1970), "The Hydrology and Stability of Cutover Slopes," Proceedings, Symposium on Interdisciplinary Aspects of Watershed Management, Bozeman, Montana, (publ. by ASCE), pp. 295-326.

Haefeli, R. (1965), "Creep and Progressive Failure in Snow, Soil, Rock, and Ice," Proceedings, 6th International Conference on Soil Mechanics and Foundation Engineering, Vol. 3, pp. 134-138.

Hicks, W. G. and Collins, T. K. (1970), "Use of Engineering Geology to Reduce the Impact of Road Construction and Clear-cut Logging on the Forest Environment," paper presented at the Annual Meeting of the Assoc. of Engrg. Geologists, Washington, D.C., October.

Kojan, E. (1969), "Mechanics and Rates of Natural Soil Creep," Proceedings, 1st Session of the International Association of Engineering Geologists, Prague, pp. 122-154.

Moore, J. T. and Dunlap, S. S. (1970), "Erosion Damage in the Klamath National Forest and Adjacent Private Forest Land," report of investigation, copy on file at U.S. Forest Service HQ, Yreka, California, 31 pp.

Patric, J. H., Douglass, J. E., and Hewlett, J. D. (1965), "Soil Water Absorption by Mountain and Piedmont Forests," Soil Sci. Soc. of America Proc., Vol. 29, pp. 303-308.

Paeth, R. C. (1970), "Genetic and Stability Relationships of Four Western Cascade Soils," Ph.D. Thesis, Oregon State University, 126 pp.

Rice, R. M. and Krammes, J. S. (1970), "Mass-wasting Processes in Watershed Management," Proceedings, Symposium on Interdisciplinary Aspects of Watershed Management, Bozeman, Montana, (publ. by ASCE), pp. 231-260.

Rice, R. M., Corbett, E. S., and Bailey, R. G. (1969), "Soil Slips Related to Vegetation, Topography, and Soil in Southern California," Water Resources Research, Vol. 5, No. 3, pp. 647-59.

Rothacher, J., Dyrness, C. T., and Fredriksen, R. L. (1967), "Hydrologic and Related Characteristics of Three Small Watersheds in the Oregon Cascades," Spec. Publ. U.S. Forest Service, Pac. Northwest Range and Exp. Station, Corvallis, Oregon, 54 pp.

Rothacher, J. (1970), "Increases in Water Yield Following Clear-cut Logging in the Pacific Northwest," Water Resources Research, Vol. 6, No. 2, pp. 653-657.

Schumm, S. A. (1967), "Ratio of Surficial Rock Creep on Hillslopes in Western Colorado," Science, Vol. 155, (Feb. 3, 1967), pp. 160-161.

Senate Subcommittee on Public Lands, (1971), "Clear-Cutting Practices on National Timberlands," record of Hearings before Subcommittee on Public Lands, U.S. Senate Committee on Interior and Insular Affairs, Parts I-III, Washington, D.C., April 5 and 6, 1971.

Shannon, W. L. and Wilson, S. D. (1956), "Jim Creek-Wheeler Mountain Slide Problem," Interim Rept. to District Public Works Office, 13th Naval District, Seattle, Washington, 4 pp.

Storey, H. C. and Irvin, C. G. (1970), "Vegetation Management to Increase Water Yield," Proceedings, Symposium on Interdisciplinary Aspects of Watershed Management, Bozeman, Montana, (publ. by ASCE), pp. 271-293.

Swanson, F. J. and James, M. E. (1975), "Geology and Geomorphology of the H. J. Andrews Experimental Forest, Western Cascades, Oregon," USDA Forest Service Research Paper PNW-188, 14 pp.

Swanson, F. J. and Dyrness, C. T. (1975), "Impact of Clearcutting and Road Construction on Soil Erosion by Landslides in the Western Cascade Range, Oregon," Geology, Vol. 3, pp. 393-396.

Swanston, D. N. (1967), "Soil Water Piezometry in a Southeast Alaska Landslide Area," U.S. Forest Service Research Note PNW-68, 17 pp., illus.

Swanston, D. N. (1969), "Mass Wasting in Coastal Alaska," USDA Forest Service Research Paper PNW-83, 15 pp.

Swanston, D. N. (1970), "Mechanics of Debris Avalanching in Shallow Till Soils of Southeast Alaska," USDA Forest Service Research Paper, PNW-103, 17 pp.

Swanston, D. N. (1974), "Slope Stability Problems Associated with Timber Harvesting in Mountainous Regions of the Western United States," USDA Forest Service General Technical Report, PNW-21, 14 pp.

Swanston, D. N. and Walkotten, W. J. (1970), "The Effectiveness of Rooting as a Factor of Shear Strength in Karta Soil," Progress Report, Study No. FS-PNW-1604:26, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Swanston, D. N. and Swanson, F. J. (1976), "Timber Harvesting, Mass Erosion, and Steepland Forest Geomorphology in the Pacific Northwest," in Geomorphology and Engineering, pp. 199-221, D. R. Coates, ed., Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa.

USDA Forest Service, (1971), Erosional Effects of Timber Harvest, in "Clear-Cutting Practices on National Timberlands," -- Part 3, record of hearings, U.S. Senate Subcommittee on Public Lands, Washington, D.C., pp. 1202-1223.

Waldron, H. W. (1954), "Landslide Possibilities at the U.S. Naval Radio Station, Arlington, Washington," U.S. Geol. Survey and Public Works Office, 13th Naval District, U.S. Navy, 26 pp. (May, 1954).

Wilson, S. D. (1962), "The Use of Slope Measuring Devices to Determine Movements in Earth Masses," Field Testing for Soils, Amer. Soc. for Testing Materials, STP 322, pp. 187-197.

Wilson, S. D. (1967), "Analysis and Report on Soil Movement--Naval Radio Station, Jim Creek, Oso, Washington," Report to Naval Facilities Engineering Command, Seattle, Washington.

Wilson, S. D. (1970), "Observational Data on Ground Movements Related to Slope Instability," Journ. of Soil Mechanics and Foundation Engineering, ASCE, Vol. 96, No. SM5, pp. 1521-44.

Wu, T. H. (1976), "Investigation of Landslides on Prince of Wales Island, Alaska," Geotechnical Engineering Report No. 5, Dept. of Civil Engineering, Ohio State University, Columbus, 94 pp.