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Rates of Slope Degradation as Determined from Botanical Evidence White Mountains California

By VALMORE C. LAMARCHE, JR.

EROSION AND SEDIMENTATION IN A SEMIARID ENVIRONMENT

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RATES OF SLOPE DEGRADATION AS DETERMINED FROM BOTANICAL EVIDENCE WHITE MOUNTAINS, CALIFORNIA

By Valmore C. LaMarche, Jr.

ABSTRACT

Methods of calculating long-term rates of slope degradation have been developed by studying exposed roots in relation to age of ancient bristlecone pines in dolomite areas in the semiarid White Mountains of east-central California. The Precambrian Reed Dolomite, a closely jointed but homogeneous and relatively resistant bedrock unit, underlies parts of a fluvially eroded terrane of high local relief where drainage channels and interchannel ridges are major topographic features.

A subalpine bristlecone-pine forest covers dolomite areas between altitudes of 9,500–11,500 feet. A few living trees are known to be more than 4,000 years old, but the average age of trees studied is about 1,000 years. Age determinations were made by counting annual growth rings. Uncertainties in assigned ages are due to incomplete growth records caused by weathering and decay of early formed wood and to the absence of certain growth increments in some samples.

Exposed tree roots are direct evidence of degradation. Developing roots of bristlecone pines are concentrated in the uppermost foot of soil and are uncovered and progressively exposed with time. Root exposure is due partly to the general lowering of the ground surface in the vicinity of a tree, but deep exposure of roots on the downslope side is also caused by the damming of surficial rock debris by the tree itself. The depth of root exposure, measured from the axis of an exposed root, must be corrected for local topographic changes related to the presence of the tree in order to estimate the minimum slope degradation.

Local degradational rates are estimated from tree or root age and depth of root exposure. Grouping of data from 76 bristlecone pines at scattered points within a 20-square-mile area suggests that degradational rates vary from place to place and reflect differences in the intensity of degradational processes that are closely related to existing topography. These rates range from less than 0.5 foot per 1,000 years on the gentle lower slopes of high ridges to perhaps 4 feet per 1,000 years along the adjacent steep banks of channels incised into alluvial fill. Degradational rates in crestal areas are high and apparently increase with ground-surface slope, whereas those of the main valley side slopes are lower and are not closely related to slope angle.

The best estimates of long-term rates of slope degradation are those based on study of samples containing a relatively large number of specimens from small topographically homogeneous areas. A comparative study of 72 dated trees in two selected areas showed that a rocky knoll has been degraded at about 1.2 feet per 1,000 years during the past 2,700 years, whereas the average degradational rate on a long valley side slope has been only about 0.8 foot per 1,000 years in the same period. These rates of degradation are similar to denudational rates that have been estimated for comparable areas in other regions.

Slope degradation indicated by widespread exposure of root systems of bristlecone pines involves production and removal of large volumes of rock debris. Frost action is a prime factor in the breakdown of bedrock, in the development of miniature patterned-ground features, and in soil creep. Accumulations of surficial material behind logs and standing trees are evidence of rapid downslope movement of weathered material. Cloudburst floods transport coarse sediment in the stream channels and produce mudflows that reach the alluvial fans flanking the range.

Transport rates of products of rock weathering on slopes and in stream channels are concluded to be great enough to account for the estimated degradational rates. The Reed Dolomite terrane seems to have been adjusted to the study production and removal of rock debris under conditions of the past 3,000 years, and local degradational rates do not appear to have changed measureably in this period.

INTRODUCTION

Elevated areas of the earth's surface are gradually being lowered as rock debris is removed by degradational agents. Despite their importance in comparing past with present rates of soil erosion, natural rates of slope degradation during the past several thousand years are little known (Leopold, 1956; Ruhe and Daniels, 1965). Direct observations of slope degradation and channel erosion are inadequate or lacking, however, so that sediment sources within a drainage basin must usually be inferred from indirect evidence (Anderson, 1957; Glymph, 1954).

This report describes the development and application of methods for obtaining long-term rates of slope degradation in areas where the exposed roots of old trees bear record of the prior levels of a progressively lowered land surface. The root systems of young trees of many species are concentrated at shallow depths. In time the roots will be uncovered and progressively exposed if the soil that overlies and encloses them is removed by erosional agents. The depth of root exposure and the age of the tree can be used to estimate the local degradation rate. Although based on study of bristlecone pines (*Pinus aristata* Engelm.) in the White Mountains of California, the approach used in this report is valid wherever the landscape changes significantly within the lifetime of individual trees. Where combined with other geomorphic evidence, knowledge of local degradation rates can be applied to the study of landscape evolution and to problems of sediment production and transport.

No general agreement exists as to the usage of terms that refer to certain kinds of quantitative geomorphic changes. "Denudation" is widely used to describe the wearing down of a landscape. A denudation rate is often calculated from measurements of the sediment and dissolved load of streams (Corbel, 1959; Judson and Ritter, 1964). The rate expresses only the time required for the removal of a hypothetical layer of certain thickness uniformly ditributed over the entire drainage area upstream from the point of observation. Degradation and local aggradation on slopes, in stream channels, and on floodplains within the area may all contribute to the net result.

Degradation means "The gradual lowering of the surface of the land by erosive processes * * *" (Rice, 1940). In this report degradation refers to the actual decrease in altitude of the land surface, relative to a previous altitude, due to the production and removal of rock debris by weathering, mass-wasting, and erosion. The term "slope degradation," when applied to areas between permanent drainage lines and adjacent divides, is virtually synonymous with the term "hillslope erosion" as used by Schumm (1964), but its use does not necessarily imply that flowing water is a dominant transporting agent.

The investigation of root exposure in relation to slope degradation in the White Mountains was limited to about 20 square miles underlain by the Reed Dolomite (Nelson, 1962) because the bristlecone pines are virtually restricted to areas underlain by this formation. The study area lies at an altitude of about 10,000 feet and has an average relief of about 500 feet; however, within the area, Blanco Mountain reaches an altitude of 11,278 feet. The area is drained by streams flowing into Deep Spring Valley, a small desert basin 10 miles to the east. The Blanco Mountain 15-minute quadrangle map of the U.S. Geological Survey shows the area, which is in the Ancient Bristlecone Pine Forest of the White Mountain District, Inyo National Forest. The area is accessible by road from Big Pine, Calif.

The investigation was begun in the summer of 1962 with a reconnaissance study of about 100 trees. The work included the determination of ages of root wood and stem wood by tree-ring dating techniques. Study results showed that exposed roots are a common feature of older trees and that root exposure is the result of lowering of the ground surface and of differential downslope soil movement. The methods developed in the initial study were then applied to intensive study of 83 trees in 3 selected areas for comparision of rates and processes of degradation on contrasting types of slopes. These areas were mapped by planetable methods in 1963.

Rates of degradation were computed from the measurements of root exposure and the age determinations from tree-ring dating. The significance of various degradational processes has been inferred from indirect evidence, such as bedrock characteristics, dimensions and detailed features of the drainage network, dimensions and surface forms of slopes, textural and mineralogical features of the surficial mantle, microtopographic effects of vegetation, and climatic data.

ACKNOWLEDGMENTS

The work described in this report was the basis for a doctoral thesis submitted to Harvard University in 1964. Alan V. Jopling contributed his time and knowledge to many discussions. Elso S. Barghoorn and Martin H. Zimmerman were of great assistance in resolving some of the botanical questions which arose during this study. The Laboratory of Tree-Ring Research of the University of Arizona made available a partial chronology of the bristlecone pines in the study area. Special acknowledgment is given to C. W. Ferguson for his help and cooperation.

PHYSICAL SETTING

The study area consists of a fluvially eroded landscape where drainage channels and interchannel ridges are major topographic features. With its high local relief, sparsely vegetated slopes, and ephemeral stream channels, the area is similar to many other mountainous areas in semiarid regions. Mass-wasting processes and forms are ubiquitous but are restricted in scope to individual hillside slopes. Despite the rare occurrence of runoff, the area is being denuded through the removal of rock debris by water concentrated in stream channels.

GENERAL GEOLOGY

The White Mountains form the northern apex of a wedge-shaped complex of fault-block ranges and closed basins that lies east of Owens Valley in east-central California (fig. 233). The range, triangular in outline, is a tilted fault block 50 miles long and 20 miles wide that has been elevated relative to the adjacent basins since late Tertiary time (Knopf, 1918). Flanked by coalescing alluvial fans, the straight steep western

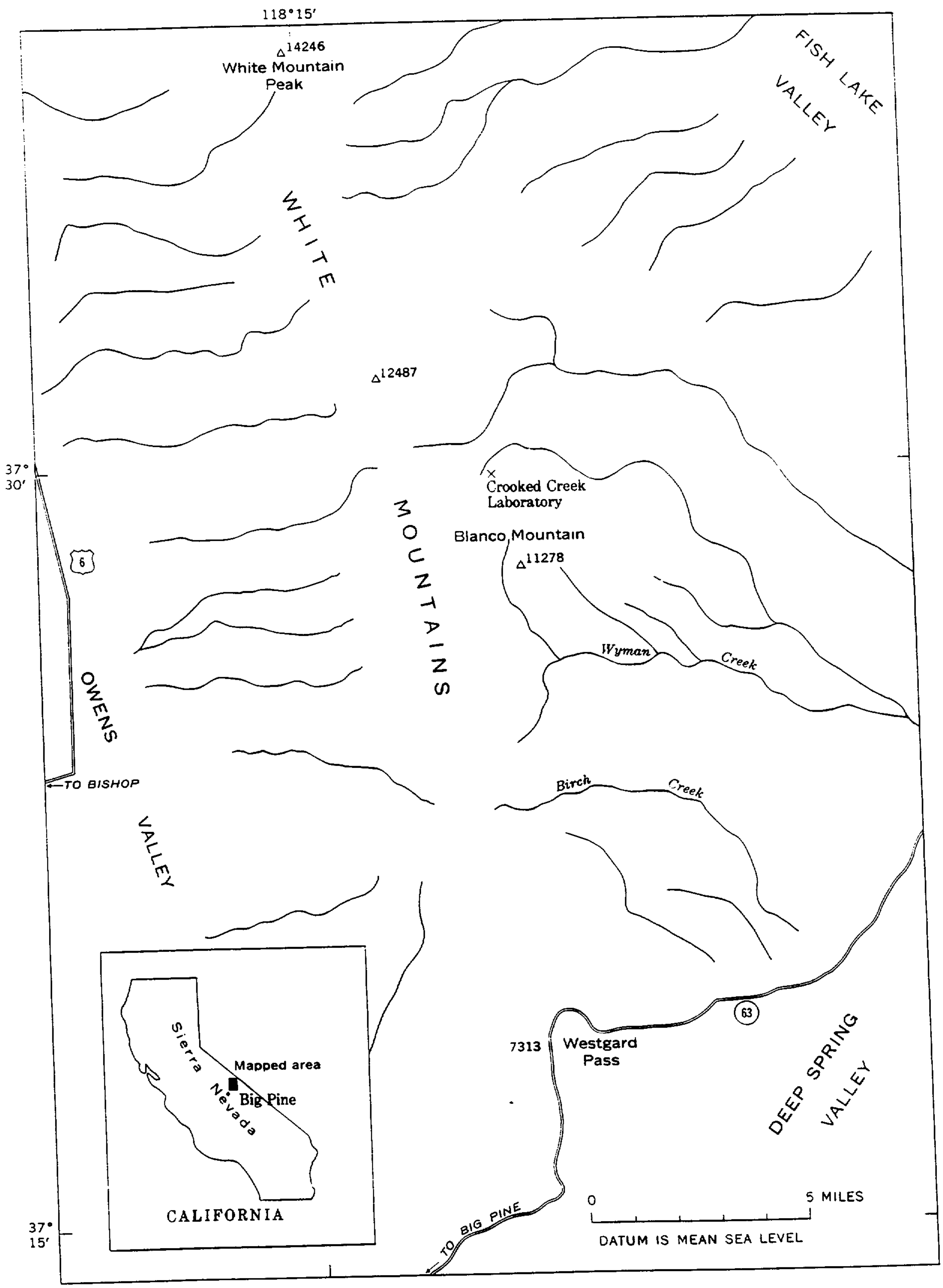

FIGURE 233.—Study area, southern White Mountains.

scarp faces the eastern scarp of the Sierra Nevada across Owens Valley, a deep structural depression. The range is bounded on the northeast by Fish Lake Valley and slopes gently to the southeast into Deep Spring Valley. The linear crest of the range, rising 2,000–10,000 feet above the basin floors, reaches its maximum altitude at White Mountain Peak (alt 14,246 ft).

The southern White Mountains are composed mainly of folded sedimentary and metamorphic rocks of Precambrian and Early Cambrian age (Nelson, 1962, Stewart, 1966) and of intrusive granitic rocks of probable Mesozoic age (Nelson, 1963). These are locally overlain by thin Tertiary basalt flows and associated alluvium and pyroclastic beds (Nelson, 1963). The major structural features are a broad south-plunging anticline and a granitic batholith that underlies much of the eastern and northern parts of the range. The structure is very complex. There are many faults, some of large displacement, and faults of several different ages, or periods of movement, can be distinguished locally.

REED DOLOMITE

Within the area studied the Reed Dolomite of Precambrian age (Stewart, 1966) is composed entirely of dolomite (Nelson, 1962). Bedding is seldom visible because the rock shows little compositional variation or textural change. Gentle to moderately steep dips (20°–45°) are indicated by the attitudes of the upper and lower contacts of the unit. To determine lithologic variations within the dolomite, hand specimens were collected at 100-foot intervals along a paced traverse across the width of the Reed outcrop east of Reed Flat (fig. 235.) The samples range from very fine grained white dolomite to medium-coarse-grained gray dolomite; some are oolitic. Thin sections were made of 5 of the 25 samples. A typical sample is composed of interlocking anhedral dolomite crystals and a few scattered silicate grains. Weathered surfaces of the rock are buff, cream-colored, or white. The light color of the weathered surfaces suggests that the dolomite has a fairly low iron content.

Intersecting joint sets, rather than bedding planes, determine the shape and appearance of bedrock outcrops (fig. 234), and the rock breaks along preferred directions controlled by joint orientation. Measurements of 23 joints at 8 localities on the knoll east of Reed Flat gave the following results when plotted on a stereographic projection: Two principal orientations at about N. 10° E., 40° W., and N. 30° E., 70° E., and a less frequent orientation at N. 80° W., vertical. The spaces between parallel joints or fractures range from 1–2 inches to several feet and seem to increase with slope of the bedrock surface.

FIGURE 234.—Reed Dolomite outcrop showing prominent jointing. Tape is extended 1 foot.

TOPOGRAPHY AND DRAINAGE

The southernmost stand of bristlecone pines in the White Mountains occupies an area 6 miles long and 3 miles wide that extends from Blanco Mountain on the north to Reed Flat on the south. Altitudes in the area generally range from 9,000 to more than 11,000 feet. Most of the Reed Dolomite terrane (fig. 235) is drained by two eastward-flowing streams—Wyman Creek on the north and Birch Creek on the south—with drainage areas of 29 and 15 square miles, respectively. The slopes bordering Reed Flat and Coldwater Flat drain into these adjacent closed basins, which have a combined drainage area of about 2 square miles.

The main divide separating this area from the Owens Valley drainage to the west is underlain by the Precambrian and Lower Cambrian Campito Formation. An undulating ridge marks the outcrop of this resistant sandstone and shale unit. Parallel to, and a mile east of, the divide is a discontinuous ridge of the equally resistant Reed Dolomite. Drainage from longitudinal valleys carved in the weak shale, thin-bedded dolomite, and limestone of the intervening Precambrian Deep Spring Formation is funneled into a few deep canyons that cut through the forested dolomite ridge. In the southern part of the area, folding and faulting of the Reed Dolomite and the underlying Wyman Formation is reflected in a series of northeast-trending dolomite spurs sepa-

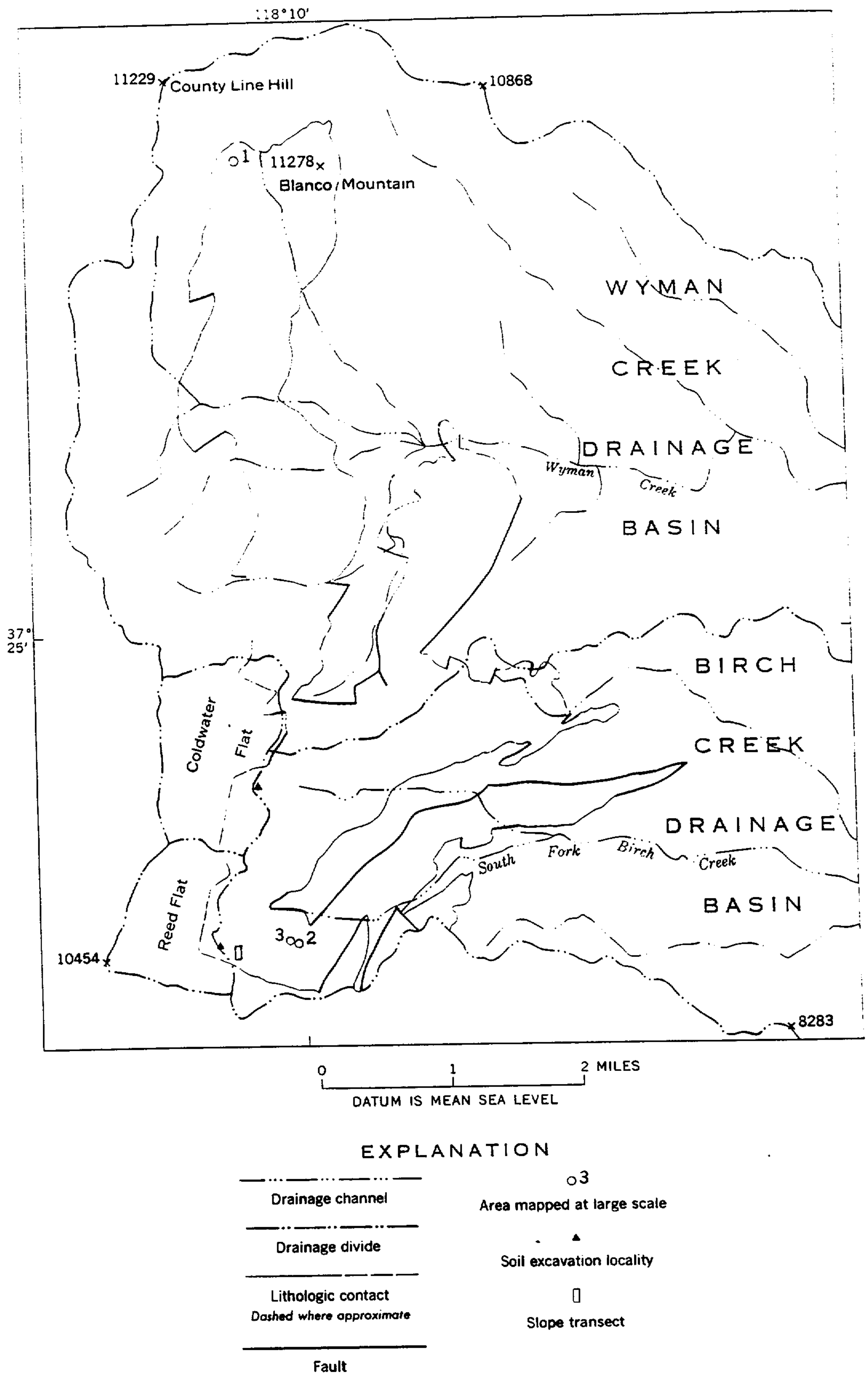

FIGURE 235.—Distribution of Reed Dolomite (shaded) in relation to drainage patterns in Blanco Mountain–Reed Flat area. Also shown is location of smaller areas mapped at large scale. Geology after Nelson (1963).

rated by valleys in the less resistant Wyman argilite and platy sandstone.

The slopes in the study area show a variety of forms and surface features: most are straight or smoothly curving, but a few are sharply faceted. Ridge crests are generally narrow and smoothly rounded, but some are surmounted by rocky pinnacles and are actually biconcave in cross profile. Outcrops, in the form of smooth surfaces and small cliffs, are typically limited to ridge crests and upper slopes. The lower slopes and valley bottoms are generally deeply mantled by colluvium and alluvium.

CLIMATE AND RUNOFF

The White Mountains are in the rain shadow of the Sierra Nevada. Eastward-moving winter storms, a major source of precipitation in the region, are depleted of moisture by the high mountain barrier to the west (D'Ooge, 1955). The higher parts of the White Mountains have a cold steppe climate, and the flanking valleys are classified as cold desserts (Kesseli and Beaty, 1959), having mean annual temperatures ranging from 56.0° F at Bishop)alt 4,108 ft) to 27.7° F at Barcroft Laboratory (alt 12,470 ft). Mean annual precipitation increases with altitude on the range, from 5.5 inches at Bishop to 15.5 inches at Barcroft, and may reach 18–20 inches near White Mountain Peak. At the higher altitudes, precipitation is mostly in the form of snow falling during October through May. Occasional intense rains are produced by summer thunderstorms.

The Crooked Creek Laboratory (alt 10,150 ft) of the University of California White Mountain Research Station is in the area, and daily weather observations have been recorded there since 1948. Shorter series of measurements, incidental observations, and estimates have also been made in the area (Kesseli and Beaty, 1959; Mooney and others, 1962). Meteorological data from Crooked Creek Laboratory are graphically summarized in figure 236.

Runoff from White Mountain watersheds is small owing to low precipitation and high potential water loss. Perennial streams are found only in those canyons that head in the highest parts of the range. Elsewhere, ground-water discharge maintains low summer flow only in some reaches of the major canyons. Most of the streams draining the White Mountains are ephermeral or intermittent; however, historical evidence discloses that occasionally heavy runoff occurs from many of these watersheds. Kesseli and Beaty (1959) summarized the records of flooding in and adjacent to the White Mountains during the period 1872–1957. Cloudbursts during the months of July and August were responsible for 40 of the 63 reported floods. Most of the other floods, distributed fairly uniformly throughout the rest of the year, apparently resulted from rapid snowmelt, often augmented by rainfall. Although the maximum 24-hour rainfall recorded at the U.S. Weather Bureau cooperative stations within the mountains during the 10-year period ending December 31, 1962, was only 1.45 inches (Crooked Creek, July 24, 1959), more than 8 inches or rain were caught in a portable rain gage during a 2-hour cloudburst in the northern White Mountains on July 19, 1959 (Kesseli and Beaty, 1959, p. 23). This downpour, concentrated in an area of 1–2 square miles, generated a debris flow that moved for more than 3 miles down a canyon to the edge of the range.

SOILS AND SURFICIAL MATERIALS

A mantle of surficial debris overlies bedrock of the Reed Dolomite throughout most of the area studied. The mantle consists of the products of the mechanical and chemical breakdown of bedrock and of a small amount of organic material. It ranges in thickness from a few inches to perhaps 30 feet and is apparently thickest on the lower slopes and the valley bottoms. Texture of the mantle ranges from pebbly loam to coarse rubble. Except locally, the mantle has not developed in place as a residual product of the disintegration of the immediately underlying rock. The thin veneer of debris on the upper slopes appears to be actively moving. The much thicker colluvial deposits on some of the lower slopes and the alluvial fill of the major canyons, derived from adjacent slopes and tributary drainage areas, are now being dissected by stream action.

SURFACE FEATURES

The debris mantle is characterized both by broad-scale textural differences associated with topographic site and by local surface irregularity and textural inhomogeneity. Areas of relatively fine soil on gentle slopes show well-developed patterned-ground features, including miniature sorted stripes, miniature sorted polygons and nets, and stone-banked terraces (terminology after Washburn, 1956). On the gentlest slopes, crude networks of pebbles surrounding elevated areas of fine soil form polygons or nets with individual cells from 3 to 6 inches in diameter. Sorted stripes consisting of 2- to 5-inch-wide bands of silt and fine sand alternating with narrower, depressed, pebble stripes occur on steeper slopes of as much as 25° (fig. 237). Stone-banked terraces, elongate parallel to the slope contours, and sorted steps, elongate downslope, are much larger features. These terraces average several feet in length and have borders, composed of pebbles and cobbles, as much as 1 foot high. The flat or gently sloping areas thus enclosed contain finer grained material sorted

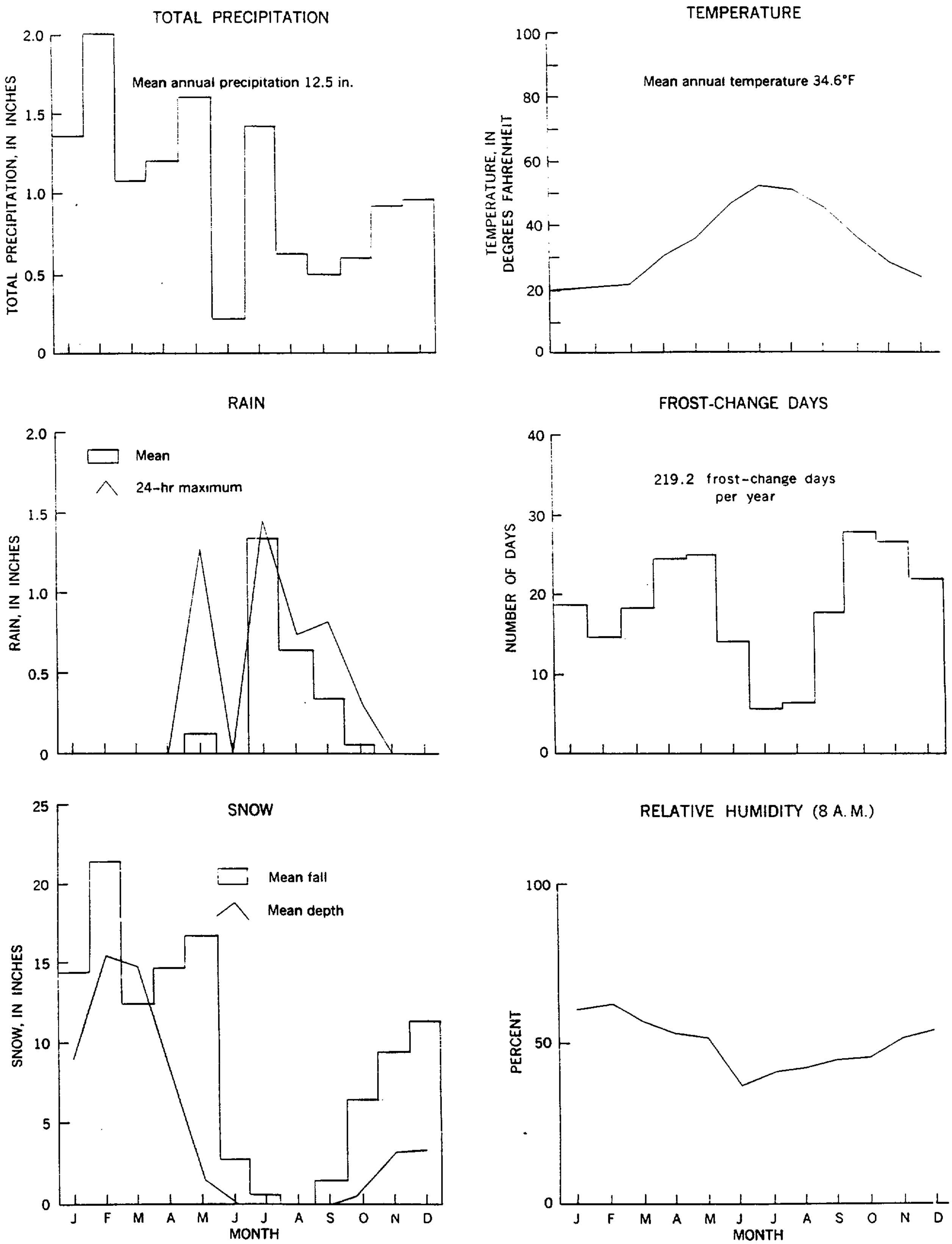

FIGURE 236.—Summary of climatic data from Crooked Creek Laboratory for 10-year period ending December 31, 1962. Frost-change days (days with maximum temperature greater than 32° F and minimum temperature of 32° F or less) calculated from original station records; all other data from Pace (1963).

FIGURE 237.—Miniature sorted stripes produced by frost action on gentle (12°) south-facing slope. Miniature polygons are found in flat areas and sorted steps, on steeper slopes.

into miniature stripes or nets. Even larger, but less regular, patterns of sorting of surface material characterize the steep sparsely vegetated slopes mantled by coarse debris. These are rock streams several feet wide and tens of feet long that have smaller fragments in the center and large pebbles and cobbles on the margins (fig. 238).

The patterned-ground features are actively developing. Tufts of grass and individual cushion plants have been overridden by small mud lobes and pebble streams. Grass, small plants, and even shrubs have been overturned and partly buried by downslope movement of the borders of terraces and steps. Rock streams have apparently been diverted by living trees and fallen logs. In a single winter, nonsorted miniature polygons formed in tire tracks that cross the silty sediment in Reed Flat.

Patterned-ground development in arctic and subalpine regions is generally attributed to frost action (Washburn, 1956). The miniature forms common in the White Mountains, more typical of tropical and subtropical mountains, are associated with shallow frost penetration, ephemaral snow cover, and numerous diurnal freeze-thaw cycles (Troll, 1958). With 219 frost-change days per year, an average snow depth of only 5 inches, and a mean minimum temperature of 22.3°F (Pace, 1963), the climate at an altitude of 10,000 feet in the White Mountains favors rapid development of patterned-ground and intense but shallow frost action.

SOIL PROFILE

Development of a soil profile in the dolomitic mantle is weak even in the most favorable locations. Soil texture and mineralogy were studied in excavations in areas of relatively deep soil, gentle surface slopes, and small surface-particle size. Litter 0–1 inch thick overlies a

FIGURE 238.—Rock stream, oblique upslope view. This elongate patch of fine-grained soil is moving downslope more rapidly than surrounding coarse rubble.

thin zone of reddish-brown soil containing numerous plant rootlets. This zone grades downward into a barren yellow to buff zone. At depths of 1–3 feet is a distinctive thin (1–4 in.) dark-brown zone filled with both dead and living plant rootlets. In contrast to the buff soil above and below, the dark-brown zone contains few pebbles and is uniform in texture.

Soil samples were collected from the walls of two excavations (fig. 235). Each composite sample represents from 6 inches to 1 foot of the profile, except in the dark-brown zone that was sampled separately. In addition, samples of the upper 6 inches of soil were collected at eight points along the slope transect described on page 359. The air-dry samples, which had no preliminary treatment, were dry-sieved through a set of screens with openings of 4.76, 2.00, 1.00, 0.25, and 0.065 mm; and the size fractions were weighed. The mineralogic compositions of selected size fractions of some samples were estimated. The content of silicate minerals was estimated from residues insoluble in hot hydrochloric acid. X-ray diffractometer methods were used for semiquantitative mineralogic analysis of the bulk samples and the insoluble residues.

The samples from all but the dark-brown zone have similar textural and mineralogic features. Nearly half the soil is composed of particles smaller than 0.25 mm, and most of the remainder, of fragments larger than 2 mm (table 1). The coarse fractions consist of dolomite pebbles; the fine fractions, of dolomite grains and minor amounts of quartz and feldspar and accessory mica, chlorite, and goethite (pseudomorphic after pyrite). The intermediate-size fractions, which typically make up less than 10 percent of total original sample weight, are composed mainly of root casts and aggregates of fine sand and silt cemented by calcite.

The dolomite (which makes up most of the soil), the goethite, and some of the silicate grains are derived from the mechanical breakdown of the Reed Dolomite. Some of the silicate grains could have come from small outcrops of sandstone and shale of the Deep Spring Formation upslope from all the localities examined. Alternatively, windblown silt could have been added to the accumulating colluvial mantle.

TABLE 1.—*Grain-size distribution of samples of dolomitic soil in the White Mountains*

[Distribution of weight fractions (percent) by size (millimeters)]

Sample	Size range					
	<0.062	0.062–0.25	0.25–1.0	1.0–2.0	2.0–4.76	>4.76
SURFACE SAMPLES (TO 6-IN. DEPTH) FROM SLOPE TRANSECT						
14	10	28	5	2	5	50
15	6	20	3	1	6	64
16	6	20	6	2	6	60
17	10	23	8	2	6	51
18	9	26	9	6	13	37
19	9	33	6	5	10	37
20	5	25	6	5	12	47
21	5	29	8	6	15	39
SOIL HORIZONS SAMPLED IN EXCAVATIONS						
Upper						
4	10	22	10	2	2	54
5	9	16	6	3	5	60
8	16	18	6	3	3	49
9	7	43	10	4	10	26
10	12	19	9	6	13	41
11	3	32	7	4	10	44
Dark brown						
6	29	31	18	6	15	0
12	10	41	17	6	8	18
Lower						
7	21	22	8	3	5	41
13	2	33	6	5	11	43

The dark-brown zone is composed principally of aggregates of fine-grained calcite, but it contains a few dolomite pebbles and some fine-grained dolomite. Because this zone is parallel to the ground surface even in areas where the mantle is being incised by stream channels, and because it is locally connected to the upper dark zone by inclined layers of similar soil, it is thought to represent a true soil profile horizon that has developed in place, rather than a buried soil or accumulative layer.

The cement of the aggregates and casts and the coating on pebbles seen throughout the soil is interstitially precipitated calcite. Calcite precipitation probably takes place in the late spring and summer, when the moisture content of the soil is reduced by evaporation and plant transpiration. The original source of the calcium carbonate is apparently the clastic dolomite making up most of the soil. Dolomite ($CaMg(CO_3)_2$) dissolves congruently in water but rarely precipitates from dilute aqueous solutions under surface conditions (Garrels and others, 1960). Although seasonal precipitation of calcite alone from water originally containing dissolved dolomite would lead to progressively higher concentrations of magnesium in soil solutions, no evidence was found for the presence of secondary magnesian compounds in the soil. Perhaps periodic flushing by downward-moving water removes this dissolved magnesium.

A textural feature common to nearly all the soil samples is the bimodal distribution of particle sizes. If secondary aggregates in the intermediate size classes are disregarded, half of a typical sample is composed of dolomite pebbles and cobbles and half of very fine sand-size and silt-size dolomite and silicate grains. The two principal size classes reflect two distinct modes of rock breakdown—the large multigranular particles, separation along joint and fracture surfaces, and the small dolomite fragments, dislodgement from individual crystals along cleavage planes.

The relative proportions of the two kinds of clastic particles are related to the kind of process that produces them. Frost shattering—the result of the constrained expansion of freezing water—is capable of dislodging particles in both size classes. The abundance of course debris, the meteorological evidence of frequent freeze-thaw cycles, and the widespread development of patterned ground suggest that frost action is a primary mechanical weathering process in the White Mountains.

The growth of tree roots in fractures has clearly resulted in the dislodgement of large bedrock masses from cliffs. Similar wedging action by plant rootlets may contribute to the breakdown of soil particles. Interstitial crystal growth, colloid plucking, and other small-scale processes are probably active, especially within the soil. The processes of chemical alteration that are so active in the breakdown of silicate rocks are not operative except that of simple solution, the only such process that can affect the relatively pure dolomite.

VEGETATION

The broad pattern of plant distribution in the White Mountains is similar to that in other regions of high relief in the Southwest (Merriam, 1890). Four major vegetational zones can be distinguished (Mooney, and others, 1962): desert scrub at altitudes below about 6,500 feet; pinyon-juniper woodlawn from 6,500 to 9,000 feet; subalpine coniferous forest from 9,000 feet to upper tree line, at about 11,500 feet; and alpine above tree line.

In detail, plant distribution is related in both kind and amount to topography, rock type, and soil and slope characteristics. The subalpine coniferous forest, which includes both bristlecone pine and limber pine (*Pinus flexilis* James), is neither continuous nor homogeneous within its broad altitudinal limits. Only scattered stands of conifers are found in topographically favorable locations underlain by limestone, shale, sandstone, or granite. These patches of forest, especially at lower altitudes, are composed mainly of limber pine. The dolomite areas support relatively dense continuous stands of bristlecone pine.

BRISTLECONE PINE

The bristlecone pine grows near upper tree line in many of the high mountain ranges of the Southwestern United States (Munns, 1938). Where geomorphic changes have been sufficiently rapid, the extreme longevity of many bristlecone pines makes possible the study of local degradational rates over the past several thousand years. The great age of some individual trees of this species was first discovered by Edmund Schulman in the White Mountains (Schulman, 1956), and by 1958, 17 specimens more than 4,000 years old were known in this area. Other bristlecone-pine stands in California, Nevada, and Utah are also known to contain very old trees. Currey (1965) recently described a 4,900-year-old bristlecone pine in eastern Nevada. The White Mountains support one of the largest known bristlecone pine stands containing a large number of old trees, but relatively few trees have attained extreme ages (in excess of 4,000 years), and some areas contain many acres of only young trees (< 500 years old). The oldest tree studied in this report is 3,100 years old, and the average age of those dated is only about 1,000 years. Most of the very old trees are found in restricted sites, near the lower forest border or on rocky exposed ridge crests. The great age attained by conifers apparently growing under the most severe local conditions has been discussed by Schulman (1954, 1956).

The mature bristlecone pines have a great variety of sizes and forms. The trees in areas of high stand density are tall and straight. Each has a single stem that is circular in cross section and bark covered around the entire circumference. In contrast, the very old trees are isolated or are in more open stands. They are typically squat and gnarled and have many dead branches and large areas of exposed deadwood. The bristlecone pines are not large because they grow slowly, adding only ½–2 inches of wood along a given radius in 100 years. The tallest specimen reported in the White Mountains (Billings and Thompson, 1957) is only 60 feet high. The Patriarch, a multiple-stemmed tree near upper tree line, is 37 feet in circumference, although it is only 1,500 years old (Schulman, 1958, p. 358).

Living bristlecone pines are rarely overturned. There are many standing dead trees, however, and dating of the outermost growth rings shows that some died more than 1,000 years ago. These trees apparently fall only after the supporting roots have decayed or been undermined by deep erosion. Some long-dead trees, firmly rooted in bedrock fractures, have weathered to mere stubs. The extent to which dead roots have been preserved depends on the length of time that they have been exposed—small branch rootlets are still present on roots that have been rapidly and recently uncovered. At the other extreme, the root systems of a few long-dead trees have been reduced to formless stubs projecting a few inches outward from the base of the stem.

The cool semiarid climate and the dense resinous nature of the wood seem to be responsible for the unusual persistence of the exposed deadwood. The stems and branches of standing trees and the roots lying above the ground surface are usually sound. Dead roots, fallen logs, and branches partly buried in the soil have rotted. Conditions seem to be most favorable for decay on the relatively moist north-facing slopes, which have denser vegetation and are littered with organic debris.

TREE-RING DATING

Precise ages can be asigned to individual growth increments in the secondary xylem of bristlecone pines in the White Mountains. The dating method involves the counting and correlation of annual rings exposed in cross sections or in cores taken with an increment borer. The method is based on the number of rings and on year to year variations in ring width that are correlative among most of the trees in the area.

During the summer growing season, new wood normally forms in a concentric sheath around a root or stem axis through activity of the cambial layer, which is immediately beneath the bark. Wood formed early in the season is light colored and possesses large thin-walled cells; wood formed toward the end of the growing season is much darker and has small thick-walled cells. A distinct annual layer is thereby defined, each layer appearing as a ring in transverse section. (See fig. 239.) The widths of rings formed in successive years differ. Certain years are characterized by narrow rings, not only at different points in the same tree, but also in most nearby trees. Thus, a common response to some factor affecting the total seasonal growth is indicated. In semiarid regions the availability of soil moisture is thought to be a determining factor: relatively thin rings may represent dry years (Fritts, 1966; Schulman, 1956). The "sensitive" growth records of some bristlecone pines show large year to year fluctuations in ring width. Trees with more uniform growth have "complacent" records. Sensitivity is associated with a low average growth rate and is characteristic of trees growing on rocky exposed sites or near the lower forest border; it is also typical of old trees. The relation of site to ring-width variability in bristlecone pines in the White Mountains was illustrated by Fritts (1966).

Locally absent or "missing" rings are also associated with slow growth and high sensitivity. Such rings occur only locally, if at all, in many trees and may not be present in a particular sample. Rings which are absent in the growth records of sensitive trees are found to correspond to relatively narrow rings in more complacent records. False rings, representing more than one period of growth in a calendar year, can be distinguished from true annual rings (Glock, 1937, p. 10) and are rare in the White Mountains (Schulman and Ferguson, 1956, p. 137); they have been noted only in the wood of very young trees.

Cross dating (Douglass, 1914) is the correlation of distinctive sequences of wide and narrow rings (fig. 240). Simple ring counting yields precise dates only if no rings are missing from the sample, which must be from a living tree and must include the outermost ring as a dating control. However ring sequences in a sample can be cross dated with those in a dated sample from the same, or from a different, tree. This permits the dating of virtually any piece of wood from an area, provided that dated samples with overlapping or concurrent growth records exist. To utilize the cross-dating properties of sensitive growth records, and yet retain the precise dating possible with complete, but complacent, records, a chronology is made. This is a graph of the variation of average ring width with time and is constructed from the growth records of many trees in an area of homogenous ring-width variation.

A chronology for the period from A.D. 300 to A.D. 1954 was used in this study. It is based on the work (largely unpublished) of Edmund Schulman and C. W. Ferguson in the White Mountains. The chronology is similar to that published by Schulman (1956, p. 52), which is reproduced here in figure 239. Less precise control in the period prior to A.D. 300 is provided by samples from specimens with growth records extending back to about 2000 B.C. Distinctive sequences in these samples were dated by ring count and used to cross-date old samples that do not overlap the period covered by the chronology. Dates prior to A.D. 300 obtained in this study are thus subject to an error due to the uncertainty in the number of locally absent rings in the control specimens. Experience in dating younger samples shows that 5–10 percent of the rings may be missing from growth records of highly sensitive trees. The older specimens can be more precisely dated when an extended chronology becomes available.

Through the use of cross dating and the building of a local chronology, the tree-ring dating method can be made very precise in terms of the reproducibility of the results obtained by independent study. But the validity of the calendar dates assigned to individual rings depends on the assumption that the growth increments represented in the chronology are annual rings. At least one line of evidence suggests that they are. Only one ring has been formed each year by most of the bristlecone pines in the 10-year period since the first samples were collected by Schulman, as shown by comparison of samples collected in 1963 with the published chronology (Schulman, 1956, p. 52). In the Reed Flat area the outermost rings in some of the bark-covered stumps of cut trees have been dated in the mid-1860's by cross dating with living trees in the vicinity; this date is corroborated by the fact that bristlecone timbers were used in a nearby mine first located in 1862 (Norman and Stewart, 1951). Because the rings formed during this period are annual rings and do not differ qualitatively from those of earlier periods, it is felt that accurate dates can be assigned to growth rings in the wood of bristlecone pines.

Although the potential accuracy of the ring-dating method is great, definite limitations are inherent in it. Some trees, during long periods of extremely slow growth, have added only one-half an inch of new wood in 100 years. Such intervals are difficult to date because the component rings are only a few cells in width. Resolution of individual rings is poor, and cross dating is almost impossible. It is also difficult to cross date samples in which numerous rings are locally absent. These problems can be partly overcome by sampling sectors of relatively rapid growth within a specimen and by cross dating the samples in intervals of maximum growth rate.

The dating procedure did not include the actual measurement of ring width in wood samples. The razor-cut surface of the mounted sample core, daubed with turpentine, was first scanned under low magnification for distinctive ring patterns of known age. Because the main objective was the dating of the specimen itself rather than the study of its growth record, the older part of a sample or the oldest sample from a given speci-

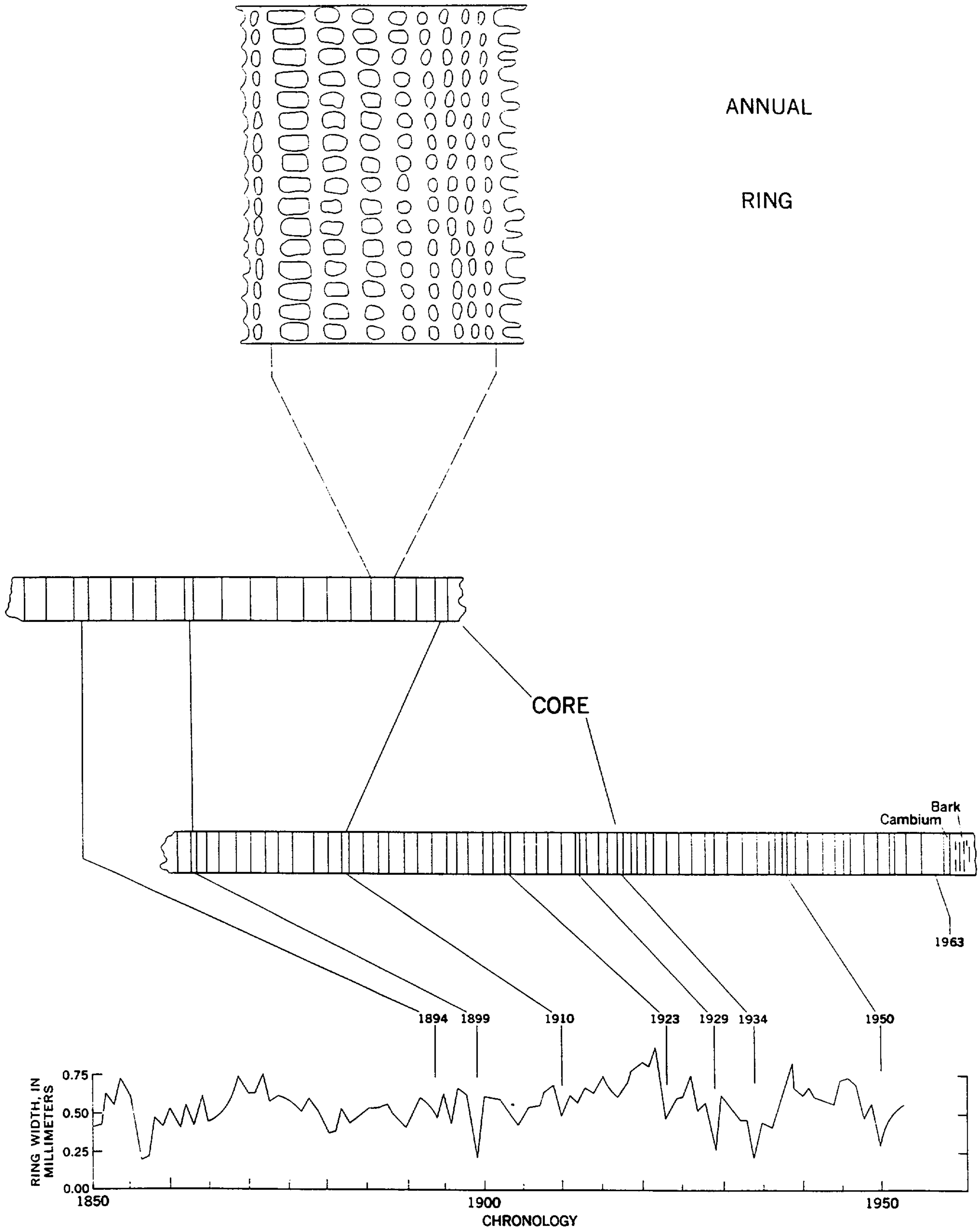

FIGURE 239.—Cross dating between portions of two cores, and chronology with diagrammatic enlargement of transverse section through annual ring. Chronology for White Mountains after Schulman (1956, p. 52).

men, was studied first. If no obvious correlation was possible and if the sample included the outermost ring of a living tree, the sample was approximately dated by ring count. Frequently this led to the recognition of cross-dating sequences in which one or more rings are microscopic or locally absent. If not such outer control were present, as with samples from dead trees or logs, a skeleton plot was made showing the relative spacing of narrow rings (Glock, 1937, p. 17). By comparing the skeleton plot with similar plots made from dated samples, or with the chronology, cross dates were often obtained. Wood samples from nearly 200 specimens with an average age of over 1,000 years were dated by these methods.

AGE ESTIMATE

Weathering, erosion, and decay have destroyed the older wood of the stems and roots of many of the bristlecone pines. Therefore, determination of specimen age requires an estimate of the timespan represented by the missing wood as well as the dating of that wood which is still sound. This estimate is based on the probable amount of radial growth missing and on the inferred average growth rate during the period.

The original center of secondary growth (stem or root axis) can be approximately located by inspection of the remaining wood. In the old trees with greatly reduced ratio of cambial area to total circumference, the growth layers formed after initial cambial reduction are not continuous and are not concentric about the axis. However, as shown by well-preserved specimens, even these trees grew at a normal rate during an early period of up to several hundred years, forming an inner core 3–12 inches in diameter. Where portions of this early wood are preserved, the stem or root axis can be located at the intersection of projected branches or branch rootlets or at the intersection of the radii of curvature of concentric rings (fig. 240). Thus, the approximate distance from the end of radially directed increment core to the axis can be estimated.

Also, the average growth rate during the period represented by the missing wood is a source of uncertainty in the age estimate. Samples of sound wood show that most of the trees have an early period of relatively rapid diametral growth. For example, along one radius at a height of 4 feet, the main stem of a 3,000-year-old specimen added 3 inches of wood in the first 40 years of growth, but only 9 more inches in the succeeding 800-year period. However, this is an unusually rapid growth-rate decrease. The growth rate shown by the wood in the inner 1 or 2 inches of a sample was generally used to estimate the timespan represented by the missing wood near the axis.

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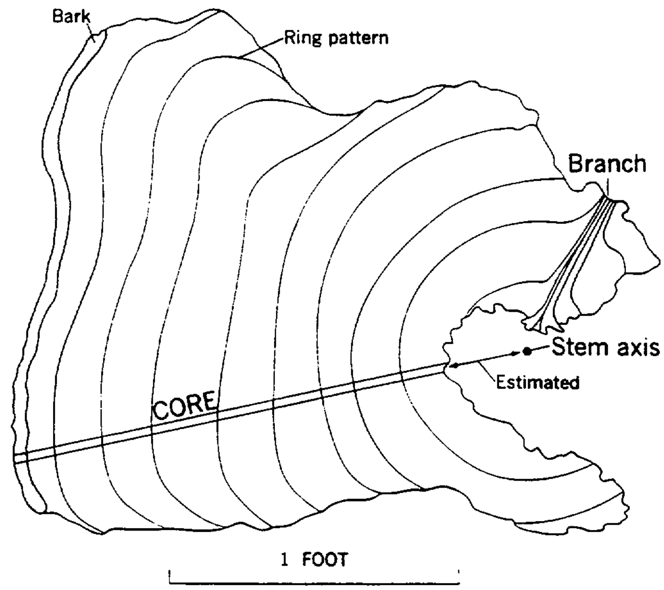

FIGURE 240.—Transverse section of eroded stem showing the geometrical basis for age estimation. The pattern of growth layers results from reduction of the ratio of cambial to total circumference. An early period of concentric diametral growth is indicated by the form of the inner rings. Many exposed roots show the same general features.

The estimated uncertainty in the age assigned to each specimen used in the study is given in tables 2, 3, 4, and 5; it averages about 5 percent of the determined age and is greatest for very old trees with large amounts of wood missing. The uncertainty in the age determinations is comparable in magnitude to the uncertainties in the other measured quantities used in this work.

ROOT EXPOSURE AND SLOPE DEGRADATION

Exposed roots are direct evidence of degradation: unless a tree is overturned, its roots can become exposed only through removal of the enclosing soil. However, this evidence has been little used to investigate degradational rates except where wind erosion is involved. Seybold (1930) described the exposure of pine roots to a depth of 5 feet in 80 years by shifting of dune sand in Holland; Hueck (1951) used the exposure of the root systems of shrubs to estimate rates of aeolian denudation in Patagonia. Deep root exposure is rarely seen on slopes degraded by mass-wasting and through erosion by surface runoff. Degradation proceeds too slowly to cause significant lowering of the ground surface within the relatively short lifetimes of most trees. The uncovering and exposing of root systems, however, affects trees of several species in the White Mountains, including a 1,000-year-old limber pine and a 1,700-year-old juniper (*Juniperus* sp.), as well as the old bristlecone pines. Root exposure is the direct consequence of shallow root development and the great age of these trees.

ROOT SYSTEMS

Bristlecone-pine roots can be seen in excavations and on overturned trees as well as exposed along the ground surface in the White Mountains. The root systems of mature trees are extensive but shallow. Mapping of roots exposed on the wall of a pit showed that more than 75 percent are concentrated in the uppermost foot of soil (Harold C. Fritts, written commun., 1965). Small roots penetrate to depths of several feet, but vertical taproot development is rare. In common with trees in other areas (Stout, 1956), rapid longitudinal growth apparently takes place early in the life of a bristlecone pine. Several major roots extend outward from a center at the base of the stem. Individual roots are largest at the stem junction, and most taper to a diameter of less than an inch within 10 feet; but some sparsely branched roots were seen that extend 20 feet or more with little change in size. The root systems of trees growing in coarse rubble or rooted in bedrock fractures are less regular.

The close relationship of growing roots to the overlying ground surface is also demonstrated by exposed root systems that parallel the profile of the topography that existed at the time of root development. Where individual roots crossed preexisting topographic irregularites, such as those along ridge crests or at the edges of cliffs and steep banks, the exposed roots retain the original irregular form. Conversely, where local relief has developed on a previously smooth slope, as adjacent to trees with asymmetrically exposed root systems (described below), the root system shows the original planar form.

EFFECTS OF EXPOSURE

The roots of woody plants grow in two ways—longitudinal extension by activity of the apical meristem is soon followed by secondary growth around the primary axis through the addition of successive layers of secondary xylem by the cambium (Esau, 1953). Only the terminal parts of the young branch rootlets absorb soil water. The sheaths of secondary wood that make up most of a mature root serve first for conduction of fluid and later as supporting tissue. The structure of mature roots is thus very similar to that of the stems and branches.

Uncovering of a trunk root near the stem of a bristlecone pine apparently has little immediate effect; however the terminal, water-absorbing parts of the root system function only within the soil; they die when exposed, as can be seen along roadcuts and in excavations. Many of the naturally exposed roots dealt with in this study are also dead. The roots on the downhill side of a tree are uncovered more rapidly and more completely than those projecting uphill or to one side. Many of the root systems in this downhill sector have not survived exposure.

BUTTRESS ROOTS

The development of a buttress form by individual lateral roots is a direct result of exposure (LaMarche, 1963). These roots are high but relatively narrow in transverse section. A buttress root is bark covered only on the bottom and owes its asymmetrical form to secondary growth radially downward from the root axis. Only the narrow strip of bark along the base, with its underlying cambium and conductive tissue, connects vertical or inclined branch roots with the stem. Initial reduction of the cambial area follows the uncovering of the upper surface of the root. Continuous concentric growth rings can be seen around the axis of a well-preserved buttress root, but the growth layers that formed after cambial reduction are limited to the lower side of the root and terminate at the sides. This discontinuity in the form of the growth layers marks the approximate time of the initial root exposure.

All stages of buttress root development are seen. The degree of asymmetry depends on the diameter of the root when it is first exposed and on the period of time since its initial exposure, as well as on the average growth rate. Uncovering of a shallow root normally takes place several hundred years after longitudinal growth. This interval is the time required for the removal of the overlying soil and is related to the original depth of root development and to the local degradational rate. Rapid diametral growth is also a factor in early exposure of the upper surface of a root. The buttress form can be developed only by living roots; the roots of trees that died before exposure do not show this feature (fig. 241).

Uncovering of roots is not a recent phenomenon in the White Mountains, as is shown by the existence of buttress roots of different ages, stages of development, and depths of exposure. Root exposure and buttress root development have been regularly associated with increasing tree age during at least the past 3,000 years, as it will be shown subsequently.

PROBLEMS OF MEASUREMENT

CHOICE OF DATUM

Only the axis, or center of radial growth, of an exposed root can be validly used to estimate the position of the ground surface as it existed at the time of root development. The top of a very shallow root may be uncovered simply as the result of increase in diameter with time. Although most developing roots are buried to a certain depth in soil that must be removed before the roots are uncovered, this depth is not known for exposed roots. For any exposed root, all that is known is

FIGURE 241.—Stump of 350-year-old bristlecone pine that died about A.D. 1350. Many such standing snags in the Reed Flat area have been cut for poles. Lack of buttress root development shows that root exposure has occurred since the tree died.

that its axis developed within the soil and that the position of the root axis marks the minimum possible level of the original surface.

The depth of root exposure is the vertical distance from the root axis to the underlying ground surface (fig. 242). Use of an arbitrary figure representing the assumed initial depth of burial might improve the estimate of local slope degradation for a single tree, but this may be unnecessary in an area where a large number of trees are studied. As shown in a subsequent section entitled "Degradational Rates," data based on measurements of the depth of root exposure can be extrapolated to estimate the average depth of root development. In two separate areas this depth is shown to have been about one-half a foot, remarkably similar to observed depths of concentration of rootlets.

The point of inflection of the basal flare of a tree (fig. 242C) is commonly misidentified as representing the original ground level at which root exposure occurred. This impression may be fortified by a pronounced change in the character of the wood or bark at this point. However, this typical feature of mature forest trees bears no relation to degradation. Clearly the inflection point will migrate upward with respect to even a static ground surface as a consequence of increasing stem and root diameter. If the inflection point is mistakenly used as the datum for measuring degradation, the degradational rates will be overestimated (fig. 243).

ASYMMETRICAL EXPOSURE

Asymmetrical root exposure causes large discrepancies between maximum depths of root exposure and actual slope degradation. The root systems of most bristlecone pines on debris-mantled slopes have not been uniformly around each tree. Typically (fig. 244), there

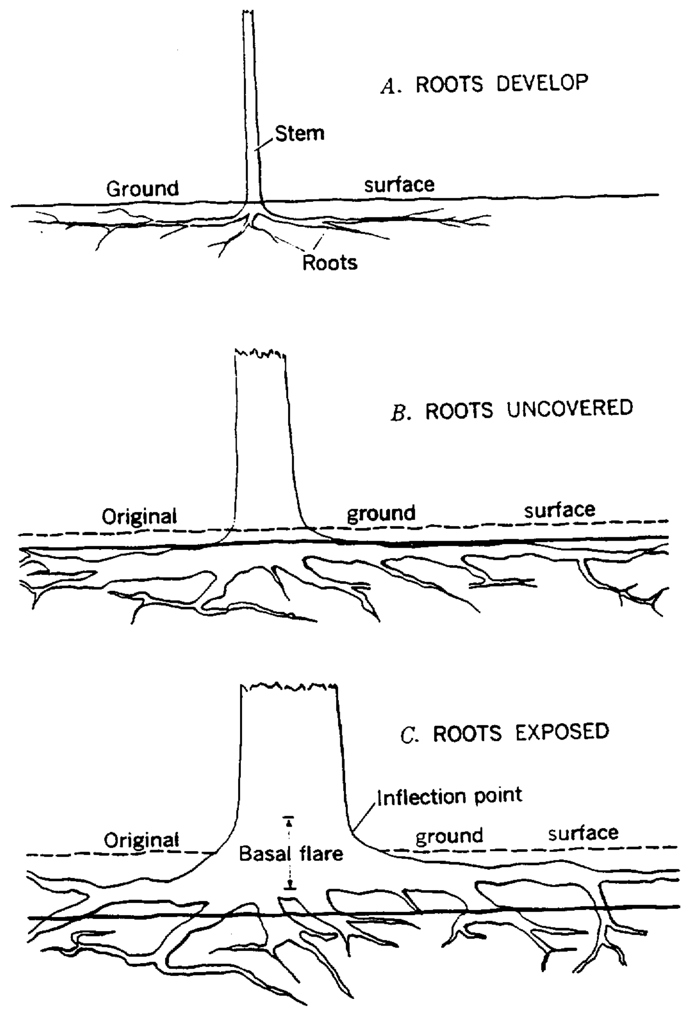

FIGURE 242.—Stages in development and exposure of a root system.

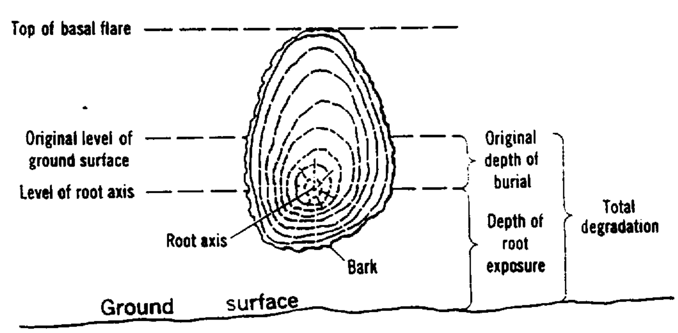

FIGURE 243.—Cross section of exposed root near stem showing relation of root exposure to degradation.

exists a gently sloping terrace on the uphill side of an old tree, and a concave hollow on the downhill side. Correspondingly, the roots upslope from the stem may be little exposed or may be buried, whereas those on the downslope side are deeply exposed. The ground surface may drop 6 feet in a horizontal distance of only 3 feet where the surrounding slope is at an angle of 35° or less. As shown by the data in table 4, the maximum depth of root exposure is commonly three to four times greater than the slope degradation.

The prominent topographic discontinuity is caused by the damming effect of the trees and develops where the stem and roots impede the downslope movement of surficial rock debris. Material accumulates above the barrier, forming the terrace. The hollow results from the net removal of surficial debris downslope from the tree, and in many places bedrock is exposed in the hollow. Microrelief features and the orientation of pebbles in the surficial mantle show that the downslope flow lines are divided in the vicinity of such an obstruction and that material moving downslope passes on either side of the tree. Such topographic changes are not associated with deep root exposure in two situations: (1) where the root system extends only upslope or downslope, the exposed roots do not interfere with debris movement (fig. 245), and (2) where the roots of a tree growing on a ridge crest extend down opposite slopes subparallel to the directions of movement and show correspondingly symmetrical exposure (fig. 246).

FIGURE 244.—Terrace and hollow due to damming effect of old tree. Maximum depth of root exposure is about 4 feet. Note rock fragments spilling over top of root at stem base.

FIGURE 245.—Root system symmetrically exposed because roots extended directly upslope. Centers of roots are alined parallel to slope but lie about 2 feet above surface—a measure of degradation subsequent to establishment of tree.

FIGURE 246.—Root system exposed symmetrically because of location on ridge crest. Roots extend down opposite slopes subparallel to directions of movement of rock debris; damming effect is further reduced because volume of debris is small.

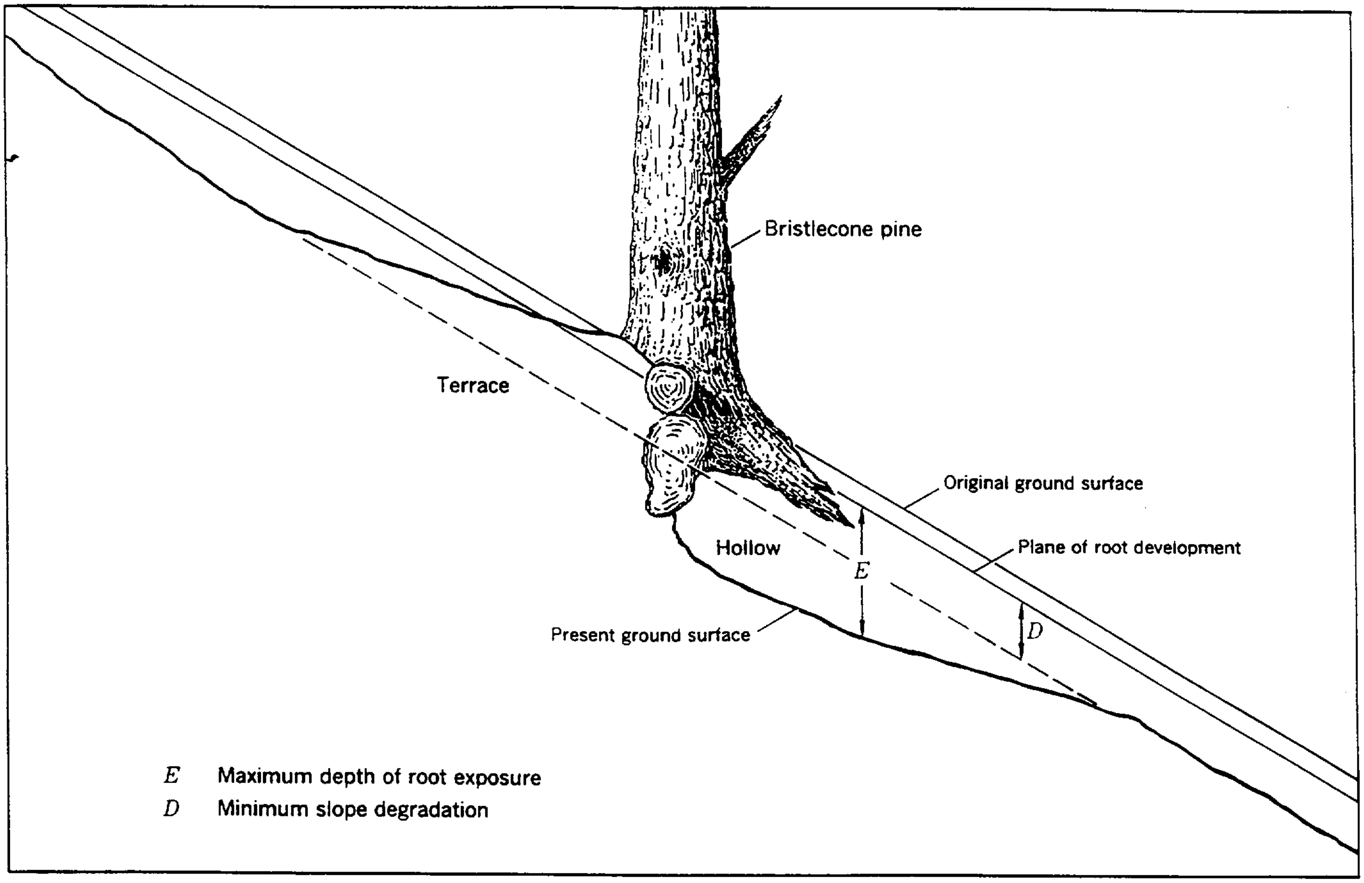

FIGURE 247.—Slope profile in the vicinity of a tree with asymmetrically exposed roots. Shows terrace and hollow, approximate location of original ground surface, and basis for measurement of minimum slope degradation.

Asymmetrically exposed root systems also can be used to estimate slope degradation if the surrounding slope is smooth and regular. In a study of two selected areas, a downslope profile at a scale of 1 inch equals 10 feet was made in the vicinity of each tree having an asymmetrically exposed root system associated with terrace and hollow development. Figure 247 shows that a line passing through the axis of the highest exposed roots lies above, but is parallel to, the line formed by projection of the present surface from points above and below the tree. The vertical distance (D) between the two lines approximates the minimum slope degradation (it does not include the original depth of burial) in the vicinity of the tree since the development of the root system. The vertical distance (E) between the root axis and the underlying ground surface is the maximum depth of root exposure. This depth is always found in the hollow on the downslope side and is always greater than the overall depth of degradation.

CALCULATION OF DEGRADATIONAL RATES

The study of an individual tree and its exposed roots can yield the maximum depth of root exposure and the period of time since the tree's initial root development. A rate of exposure calculated from these data generally will not be equal to the local rate of degradation during the same period. One source of error is the uncertainty as to the original depth of root development, for the vertical distance from the axis of an exposed root to the present ground surface is only a minimum estimate of the total depth of material removed. This error is fairly large for young trees that have only incipient root exposure; the calculated rate of root exposure will be less than the actual rate of degradation. Where the root systems of trees growing on slopes have been asymmetrically exposed, the maximum depth of exposure may be much greater than the actual slope degradation. The increase in degree of asymmetry with size and age of tree introduces a large discrepancy between local degradational rates and the maximum rates of root exposure of many older trees. However, the study of individual old trees will give rates of root exposure that approximate degradational rates if the root exposure has been symmetrical and if the axes of the highest exposed roots are used. An improved estimate of the local degradational rate, as indicated by the depth of root exposure of a single tree, can also be obtained, if the initial depth of root development can be inferred.

DEGRADATIONAL RATES

LOCAL RATES

Evidence of the progressive change in ground-surface altitude provided by the exposed roots of bristlecone pines was used to estimate rates of degradation in areas underlain by the Reed Dolomite. The problems of measurement and interpretation initially met with led to the refinement of methods used during the rest of the investigation. Early work was concentrated in 1-square-mile area near Reed Flat (fig. 235). Attention was focused on trees with deeply exposed roots and on those occupying special topographic sites.

Either a direct determination of root age or an estimate based on stem age was made for each tree. In 1962, 99 trees were sampled in the Reed Flat area and elsewhere in the White Mountains; some of the specimens were not dated, and some are on other substrates and are not included in the results. The age determination, depth of root exposure, and local slope of the ground surface are listed in table 2 for each of the specimens, and the results are graphically summarized in figure 248. The measured depths of root exposure range from 0 to 4.5 feet, and the estimated ages, from about 200 to 2,500 years. A general increase in the maximum depth of exposure with increasing age can be

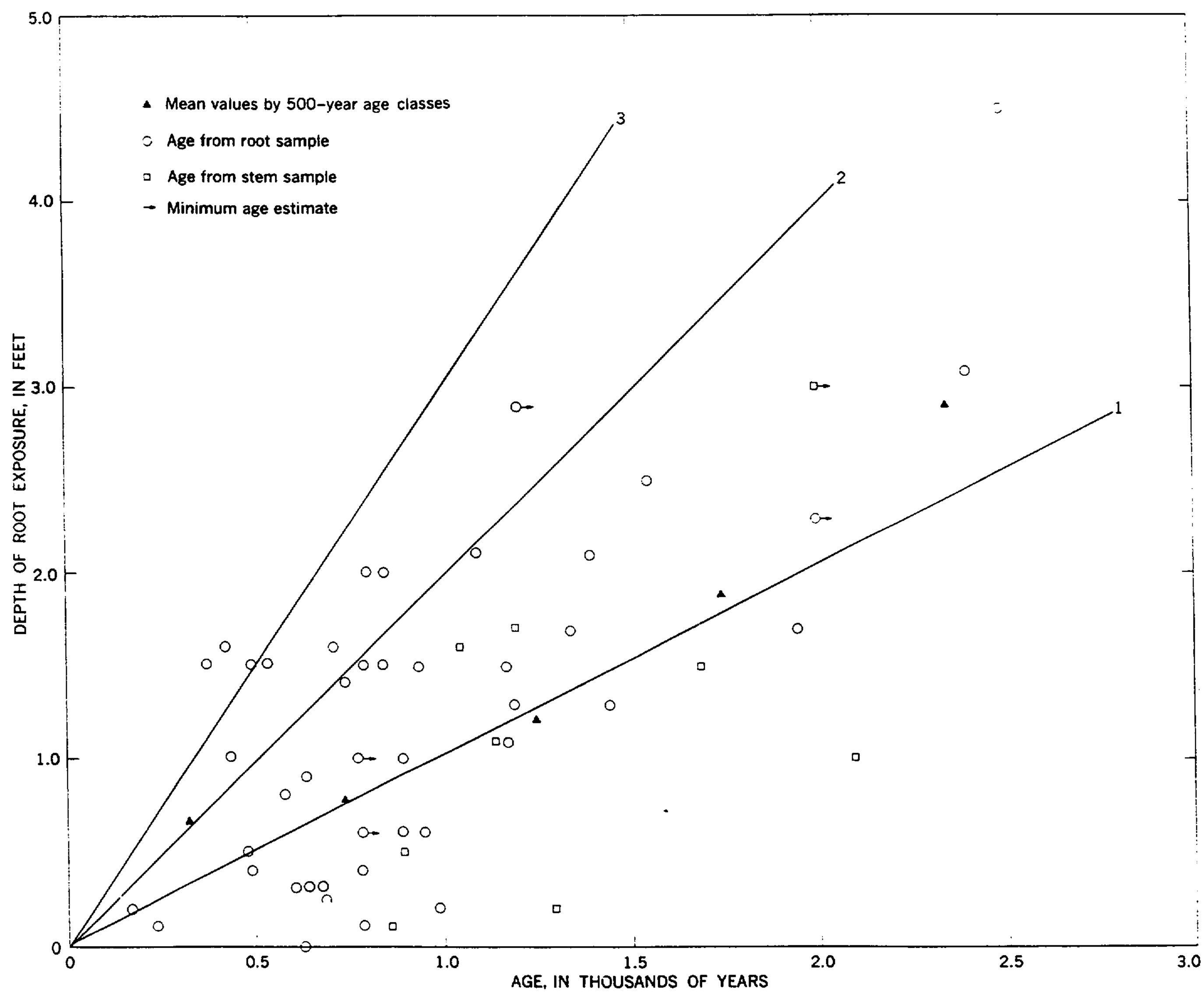

FIGURE 248.—Relation of root exposure to age and probable range of local degradational rates.

seen, but there are great differences in the rates of root exposure indicated by these data. The differences reflect not only different local rates of degradation, but also the effects of differences in the symmetry of exposure and in the original depth of root development.

TABLE 2.—*Age, root exposure, and site data for trees in scattered localities in southern White Mountains*

Specimen	Age estimate (centuries)		Depth of root exposure (feet)	Slope (degrees)
	Age	Uncertainty		
Root age from root sample				
1	9.0	0.5	1.0	33
2	3.8	.1	1.5	28
3	11.7	.1	1.5	12
	12.1	.3	1.7	12
	14.0	.3	2.1	12
	14.5	.2	1.3	12
	15.5	.5	2.5	12
5	7.5	.5	1.4	26
6	[1] 12.1+	----------	2.9	32
7	6.2	.1	.3	28
	6.2	.1	.3	28
9	25.0	2.0	4.5	36
11	10.0	1.5	.2	2
12	8.5	.3	2.0	24
	4.4	.1	1.6	24
13	5.3	.1	1.5	17
14	2.5	.2	.1	8
15	[1] 8.0+	----------	1.0	40
17	8.1	0	2.0	30
19	8.5	.4	1.5	26
20	13.5	1.0	1.7	20
22	5.0	.2	.5	14
23	12.0	2.0	1.3	25
24	2.0	.1	.2	32
57	9.5	1.0	1.5	25
58	[1] 8.0+	----------	.5	10
61	6.5	.5	.3	8
62	8.0	.2	.4	9
63	6.4	0	.9	16
64	11.9	.1	1.1	20
67	9.0	.5	.6	18
68	[2] 7.1	.1	1.6	26
	[2] 7.8	0	1.5	26
69	4.5	1.0	1.0	19
71	[2] 9.5	1.0	.6	20
73	6.0	.2	.8	21
74	7.0	.1	.3	20
75	6.5	.3	0	6
	8.0	.5	.1	6
78	5.0	.2	.4	9
79	7.0	.4	.2	9
80	19.5	1.0	1.7	21
81	[3] 20.0+	----------	2.3	24
84	5.0	.3	1.5	16
91	24.0	2.0	3.1	23
97	[1] 11.0	----------	2.1	36
Tree age from stem sample				
21	1.8	0	----------	17
51	8.8	0	0.1	5
59	13.6	.5	.2	8
60	6.5	1.0	----------	10
65	11.5	.1	1.1	22
70	21.0	1.0	1.0	20
76	17.0	1.0	1.5	16
95	[3] 20.0+	----------	3.0	30
96	9.2	0	1.5	23
98	12.0	.2	1.7	30
99	[3] 10.5	.3	1.6	25

[1] Sample incomplete.
[2] Dead tree. Age based on cross dating.
[3] Dead tree. Minimum-age estimate equals total number of rings counted.

SLOPE TRANSECT

The possible effects of topographic position on root exposure were studied in trees along a line that extends directly up a north-facing slope from the base of the knoll east of Reed Flat to the crest of the adjacent ridge. Each standing tree within 5 feet of the line was sampled for an age determination, and the depth of root exposure was observed; the results are listed in table 3. The slope profile, tree ages, and root exposure are shown graphically in figure 249.

TABLE 3.—*Age, root exposure, and site data for trees on slope transect, listed in order of increasing distance from base of slope*

[Ages based on stem samples]

Specimen	Age estimate (centuries)		Depth of root exposure (feet)	Slope (degrees)
	Age	Uncertainty		
28	4.0	----------	([1])	7
29	1.9	----------	----------	11
30	.8	----------	----------	3
31	6.2	----------	----------	10
32	1.5	----------	----------	18
33	1.9	----------	----------	18
34	.5	----------	----------	25
35	2.0	----------	----------	28
36	10.2	0.1	0.3	28
37	5.5	.3	----------	30
38	7.5	.5	----------	32
39	6.5	.4	.3	29
40	1.9	----------	----------	31
41	6.5	1.5	.1	32
42	5.5	.2	----------	35
43	6.0	.5	.6	34
44	7.0	.1	.4	36
45	[2] 15.0+	----------	----------	36
46	12.5	.5	----------	34
47	10.5	.4	.9	33
48	6.1	.2	.8	30
50	14.0	2.0	----------	28
52	9.0	.2	.2	36
53	10.0	.5	1.4	25
54	17.0	1.0	----------	29
55	7.0	.4	.1	18
56	6.5	.3	.1	16

[1] Indicates no roots exposed.
[2] Dead tree. Minimum age equals total number of rings counted.

The lower part of the slope, extending about 500 feet to the base of the main slope, is gently rolling; the average slope is about 10°. The line of profile crosses two depressions marking incised channels. The trees in this area are widely spaced, and the ground cover is relatively dense. The main slope, rising 300 feet in a horizontal distance of 500 feet, has a nearly linear profile with a slope of 30°. The surface of the ground is smooth, but the coarse soil is loose and readily dislodged. Litter, including the stems of fallen trees, is abundant. The upper slope is distinctively convex in profile. Its ground surface is much rougher than that of the main slope below. Numerous outcrops and small cliffs protrude through the thin patchy veneer of surficial debris.

A striking relationship between tree age and location is shown in figure 249. The 6 trees on the lower slope have a mean age of 220 years; the 10 trees on the main slope, 520 years; and the 11 trees on the rocky upper slope, near the ridge crest, more than 1,000 years.

Comparison of tree age with depth of exposure shows that the roots of trees less than 500 years old have not yet been exposed, owing to either slow degradation or to

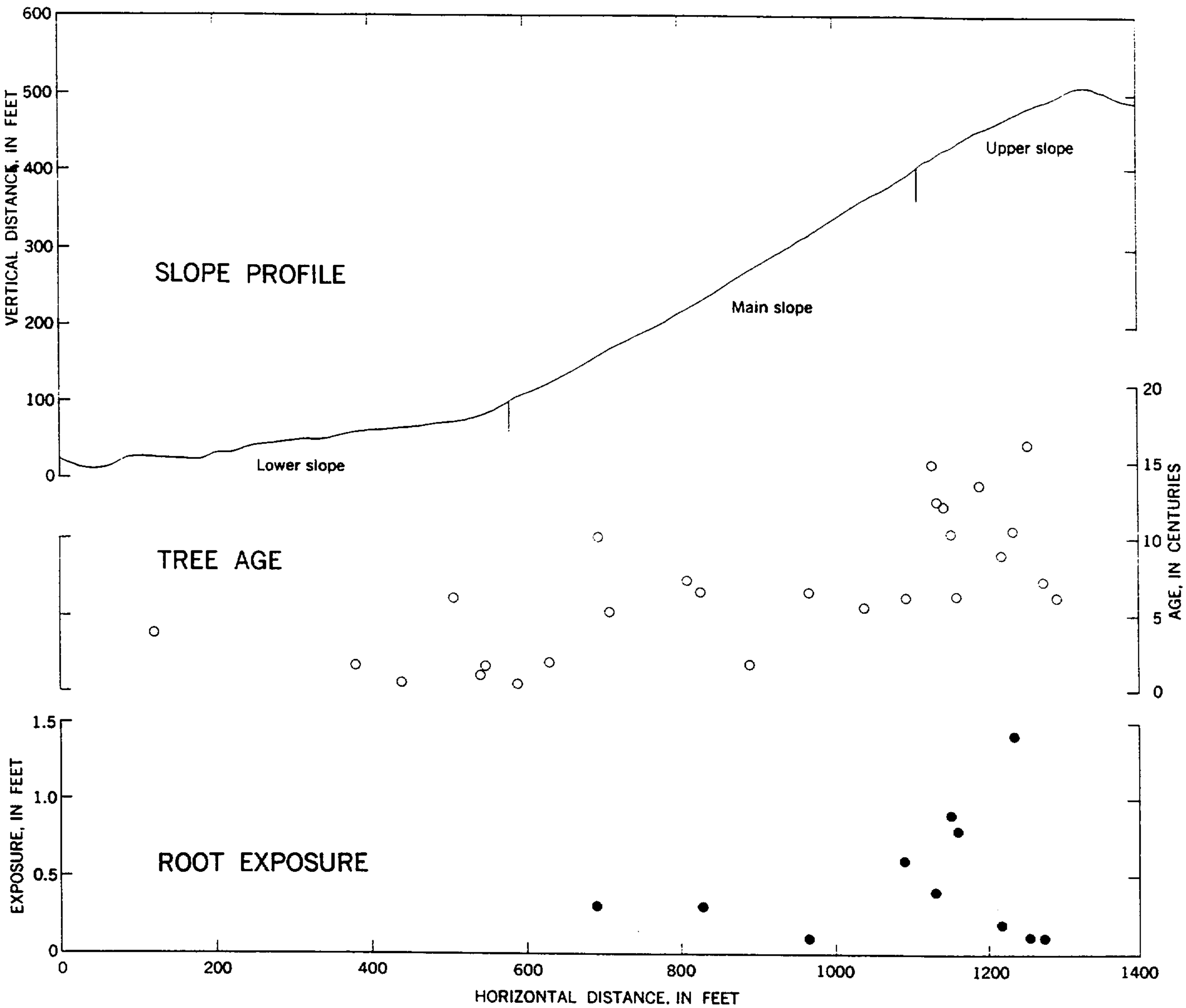

FIGURE 249.—Slope profile, tree age, and depth of root exposure along slope transect.

great depth of development. Incipient exposure, where the roots on the downhill side are partly uncovered, is characteristic of trees in the 500- to 1,000-year age range. Only the fairly old trees have deeply exposed roots; however, the oldest trees do not show the greatest exposure. Roots of two of the oldest trees, 1,400 and 1,700 years old, respectively, are not now exposed. These specimens, which are in the area of irregular topography immediately below the ridge crest, have been partly buried by lobate rock streams.

Although local rates of degradation, suggested by the depth and symmetry of root exposure, are apparently greatest on the upper slope, the conclusions that can be drawn from observation of an individual specimen are valid only for the limited area around that tree. Further, the restricted distribution of trees old enough to show significant root exposure precludes strict comparison of degradational rates at different points along the transect. The average rate of degradation on this slope is probably less than half a foot per 1,000 years.

SELECTED AREAS

The initial reconnaissance study of individual bristlecone pines showed that deep root exposure is generally associated with great age. It suggested that the rate of exposure is proportional to the local degradational rate but also depends on the depth of root development and the degree of symmetry of exposure. The great range in rates of exposure seems to be related to differences in degradational rates in different parts of the landscape.

Inconsistencies in the results of study of nearby trees showed, however, that bias in specimen choice could lead to results that are not representative of an area much larger than that included within the root system of a single tree.

The purposes of the second phase of the study were to convert measurements of root exposure to estimates of slope degradation, to characterize local topographic environment closely, and to obtain unbiased samples of the trees in selected areas as a basis for generalization of the results. The approach used included the large-scale planetable mapping of two areas that represent contrasting slope types. The maps (plates 10 and 11) show the general outlines of exposed roots and of fallen trees, in addition to the topography. All the standing trees in one area and a large random sample in the other were studied. Each of the areas was selected because it has old bristlecone pines; the average age of 71 trees in the two areas is 1,100 years.

A third area, significant because it is incised by closely spaced drainage channels, was mapped at a smaller scale. The exposed root systems of six trees on low steeply sloping interfluvial ridges were mapped in great detail. These specimens were selected because they have deeply exposed roots; the trees have a mean age of 1,450 years.

AREA 1

This area of about 2 acres is one-half a mile northwest of Blanco Mountain (fig. 235) and lies at an altitude of 10,500 feet. It is the west end of a hill of Reed Dolomite that rises abruptly from a gentle sagebrush-covered slope (fig. 250). A broad swale at the base of the hill slopes to the south, where it deepens and contains a first-order drainage channel. The center of this topographic depression is also marked by a strong contrast in both vegetation and soils: on one side of the depression is the dolomite slope with its sparse ground cover and scattered bristlecone pines, whereas on the other side is an unforested flat whose soil is composed of sandstone and shale from the slopes of County Line Hill, to the west.

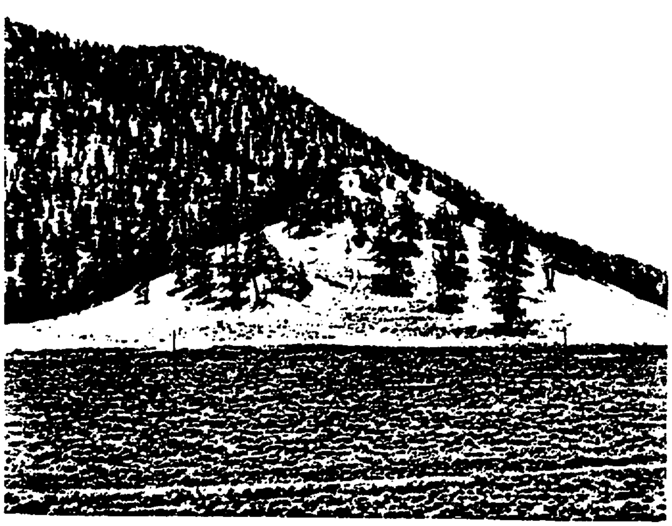

FIGURE 250.—Area 1, as viewed from the west; Blanco Mountain is in background. Note abrupt change in type of soil and vegetation at base of triangular slope.

The mapped area (pl. 10) includes the western slope of the hill and a broad north-sloping shoulder. The linear rocky crest is 100 feet above the base of the slope. Below the irregular cliffs along the crestline, the slope has a fairly smooth concave profile and an average slope of 20°. The ground surface of the hillcrest and of the subsidiary spurs is dolomite bedrock that has local accumulations of coarse rubble. Rock outcrops are numerous, and the mantle is thin over large areas of the shoulder and the upper slopes. The mantle is thicker and more continuous on the lower slopes.

The mantle is fairly coarse textured and contains pebble- to cobble-sized angular dolomite fragments. The average surface-particle size, measured along each of four downslope transects, ranges from 14 mm, on a 10° slope on the shoulder in the northern part of the area, to 33 mm, on a 22° slope extending down from the main hillcrest (fig. 251). There is an irregular decrease of grain size in the swale at the base of the slope, where the soil is a dolomitic sandy loam with few pebbles.

The surface of the debris mantle on the slopes is uneven. The steeper part of the west-facing slope has poorly sorted stone-banked terraces, presumably related to frost action, but there are no miniature patterned-ground features. Terrace and hollow development is locally prominent adjacent to standing trees and to some of the large wood fragments that litter the slopes.

Three main groups of bristlecone pines can be distinguished. One group grows on the north-facing slope on the shoulder of the hill; the second group grows on the west-facing slope; and the third group, which includes the oldest trees in the area, grows on or immediately below the cliffs west of the hillcrest. There are 49 standing trees in the area mapped. Stem core samples were taken from all specimens, and dating provided at least a minimum age estimate for all but four trees. The trees range in age from about 10 to 2,700 years and average nearly 1,000 years.

The root systems of most of the trees are uncovered or are at least partly exposed. The deep symmetrical exposure of the roots of trees along the hillcrest (fig. 252) is especially striking. The minimum local slope deg-

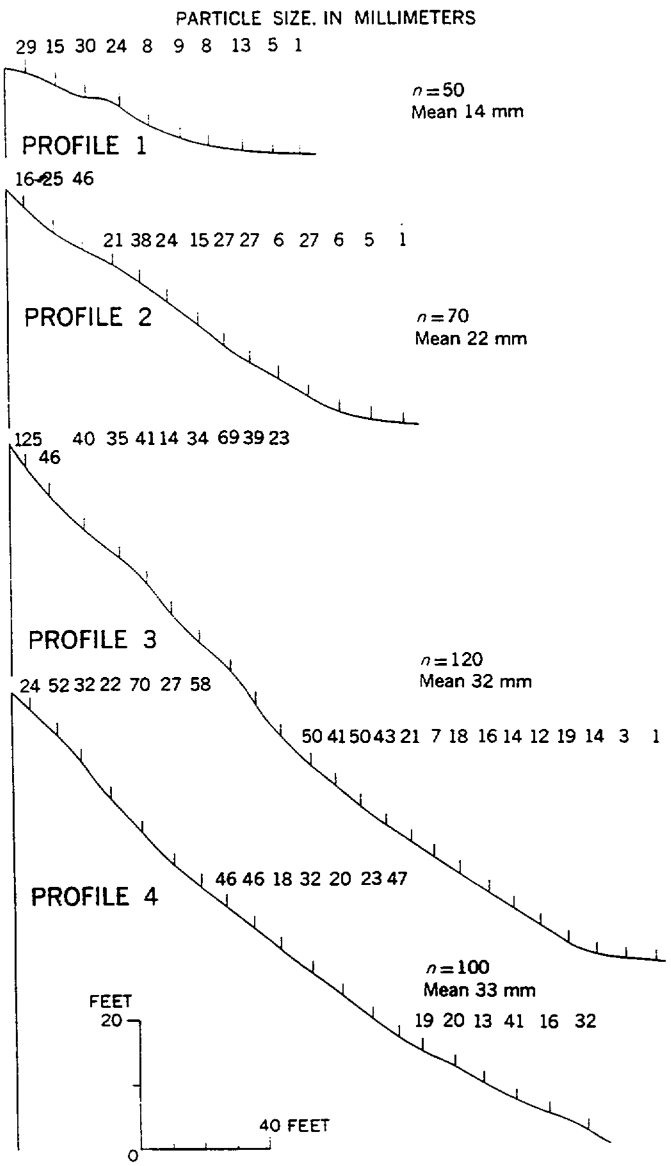

FIGURE 251.—Slope profiles and results of particle-size measurements. Each number represents mean of five measurements of intermediate dimension of rock fragments made at 2-foot intervals along line.

radation represented by the root exposure was measured directly where root systems were symmetrically exposed. It was obtained from the individually constructed downslope profiles for those specimens showing asymmetrical exposure. These data, together with age determinations, are listed in table 4.

The minimum local slope degradation is plotted against specimen age in figure 253. The points are scattered around a straight line representing a slope of 1.2 feet per thousand years, the average degradational rate. The extrapolated average depth of exposure at zero age, based on a least-squares analysis of data from 33 specimens, is one-half foot and represents the average initial depth of development of the roots. The

FIGURE 252.—Exposed root of specimen 110. Depth of root exposure shown by comparison with 18-inch hammer. Exposed bedrock is broken up. Note symmetrical exposure of root of this 2,500-year-old tree.

analysis did not include data from 10 younger trees with no root exposure nor data from 6 specimens which were not reliably dated. Even though the trees are not distributed uniformly over the entire area, the results are thought to be representative of at least the crest and the upper slope areas.

TABLE 4.—*Data for trees in two selected areas*

[Ages from stem samples]

Specimen	Age data (centuries)		*E* Maximum depth of root exposure (feet)	*D* Minimum local slope degradation (feet)
	Age	Uncertainty		
Area 1				
101	[1] 13.0+	----	1.6	1.4
102	8.5	0.2	1.2	.7
103	4.8	.1	.4	.1
104	7.4	.1	1.2	.4
105	(2)	----	1.8	1.8
106	18.7	.5	2.0	1.5
107	8.1	.2	.8	.4
108	3.7	.1	.8	0
109	6.5	.2	.1	0
110	25.0	2.0	3.2	3.0
111	27.0	2.0	3.2	3.2
112	7.6	.1	.8	.6
113	7.6	.1	.6	.3
114	9.5	1.0	.8	.7
115	7.5	.3	.4	−.1
116	7.0	.2	.5	0
117	4.5	.4	(3)	----
118	4.5	.3	(3)	----
119	7.5	.1	.8	0
120	4.8	.2	.9	.5

See footnotes at end of table.

TABLE 4.—*Data for trees in two selected areas*—Continued

[Ages from stem samples]

Specimen	Age data (centuries)		*E* Maximum depth of root exposure (feet)	*D* Minimum local slope degradation (feet)
	Age	Uncertainty		
Area 1—Continued				
121	1.0	.0	[3]	----------
122	20.0	1.0	1.7	1.7
123	21.0	1.0	.6	.6
124	9.0	2.0	.5	.5
125	18.0	2.0	1.0	1.0
126	[1] 9.0+	----------	1.0	1.0
127	20.0	3.0	2.6	2.3
128	15.5	2.0	1.7	1.7
129	.1	0	[3]	----------
130	6.5	.5	.7	.7
131	7.0	.5	1.5	1.3
132	7.1	.1	.2	.2
133	[1] 22.5+	----------	2.2	1.5
134	6.0	1.0	.4	.4
135	[2]	----------	1.3	1.3
136	5.0	.5	.8	0
137	4.5	.3	.4	−.1
138	13.0	2.0	1.3	.9
139	.1	0	[3]	----------
140	9.0	3.0	2.2	1.2
141	.4	0	[3]	----------
142	5.0	.1	.6	.3
143	[2]	----------	.3	.3
144	13.5	1.0	1.2	1.1
145	17.0	1.0	2.5	1.3
146	.6	0	[3]	----------
147	[2]	----------	[3]	----------
148	.1	0	[3]	----------
149	.2	.1	[3]	----------
Area 2				
150	5.5	0.5	[3]	----------
151	5.0	.4	[3]	----------
152	5.5	.2	[3]	----------
153	2.5	.1	[3]	----------
154	17.0	2.0	3.6	0.7
155	4.0	.2	[3]	----------
156	[4] 20.0+	----------	5.4	1.2
157	6.0	.3	.5	0
158	.8	0	[3]	----------
159	11.0	2.0	1.6	1.1
160	[1] 22.0+	----------	[3]	----------
161	9.0	.5	1.8	.2
162	18.0	2.0	3.2	.4
163	31.0	1.0	[3]	----------
164	[4] 10.0+	----------	4.0	1.3
165	30.0	3.0	5.4	1.7
166	8.1	.1	1.2	0
167	[1] 30.0	3.0	4.2	2.0
168	20.0	2.0	4.6	1.3
169	17.0	2.0	4.0	1.2
170	8.5	1.5	[3]	----------
171	18.0	2.0	4.6	1.2
172	10.6	.5	.8	.4
173	19.0	1.0	1.0	.5
174	7.5	.5	1.2	.1
175	18.0	2.0	2.0	1.1
176	[2]	----------	.5	.2
177	1.4	0	[3]	----------

[1] Dead tree. Age based on cross dating.
[2] Age not determined.
[3] No exposed roots.
[4] Dead tree. Minimum age equals total ring count.

Systematic deviations from the average degradational rate might be expected owing to the topographic inhomogeneity of the area. Figure 254 shows the estimated rates of degradation, in feet per 1,000 years, at each sampling point. These values were obtained graphically from the scatter plot of tree age and minimum slope degradation (fig. 254). Through the point representing a given specimen, a line was drawn to the −0.5-foot mark on the ordinate (the approximate initial depth of root development). This line intersects the vertical line representing 1,000 years of elapsed time at some value, D, of minimum slope degradation. The vertical distance between this point and the −0.5-foot point represents the degradation taking place in 1,000 years at each point. Most of the values are within the range from 1.0 to 1.4 feet, regardless of specimen location. The highest values are at points along the rocky crest and upper slope; there is some suggestion of a downslope decrease in degradational rate on the west-facing slope. However, because the estimated degradational rates vary widely from point to point and because these variations are not clearly related to topographic position, the author has concluded that no significant trends in slope development can be inferred from these data.

AREA 2

Area 2 is a strip extending from a stream channel in a narrow alluvial flat to the crest of the adjacent ridge. This 1-acre area is representative of the steep side slopes of major canyons incised into the Reed Dolomite. It is 1 mile east of Reed Flat in a canyon tributary to the South Fork of Birch Creek (fig. 255). The narrow alluvial flat is at an altitude of about 9,700 feet. The crest, 350 feet above the base of the slope, is the end of a long dolomite ridge. There are no shrubs and only a few herbaceous ground cover plants on the slope. The only other vegetation is an open stand of old stunted bristlecone pines (fig. 256 and pl. 11). The canyon has a "V-in-V" cross profile in this area, and the lower slopes are about 5° steeper than those above. The slopes are nearly linear in cross profile except at the narrow rounded crest.

Coarse soil forms a continuous mantle over the lower two-thirds of the slope. Bedrock is locally exposed on the upper slope and almost continuously along the crest. The surface consists mainly of large angular dolomite fragments (fig. 257) which have been sorted into rock streams or less regular elongate patches of contrasting textures. No measurements of particle size were made, but the surface material is noticeably coarser than in area 1 and is very unstable.

The slope surface has moderate local relief. On the lower part of the slope, microrelief features apparently reflect differences in the thickness of the mantle rather than bedrock irregularities. Upslope terraces and downslope hollows have developed adjacent to many of the older bristlecone pines (fig. 244). The large maximum depths of root exposure (table 4) are related to this extreme asymmetry.

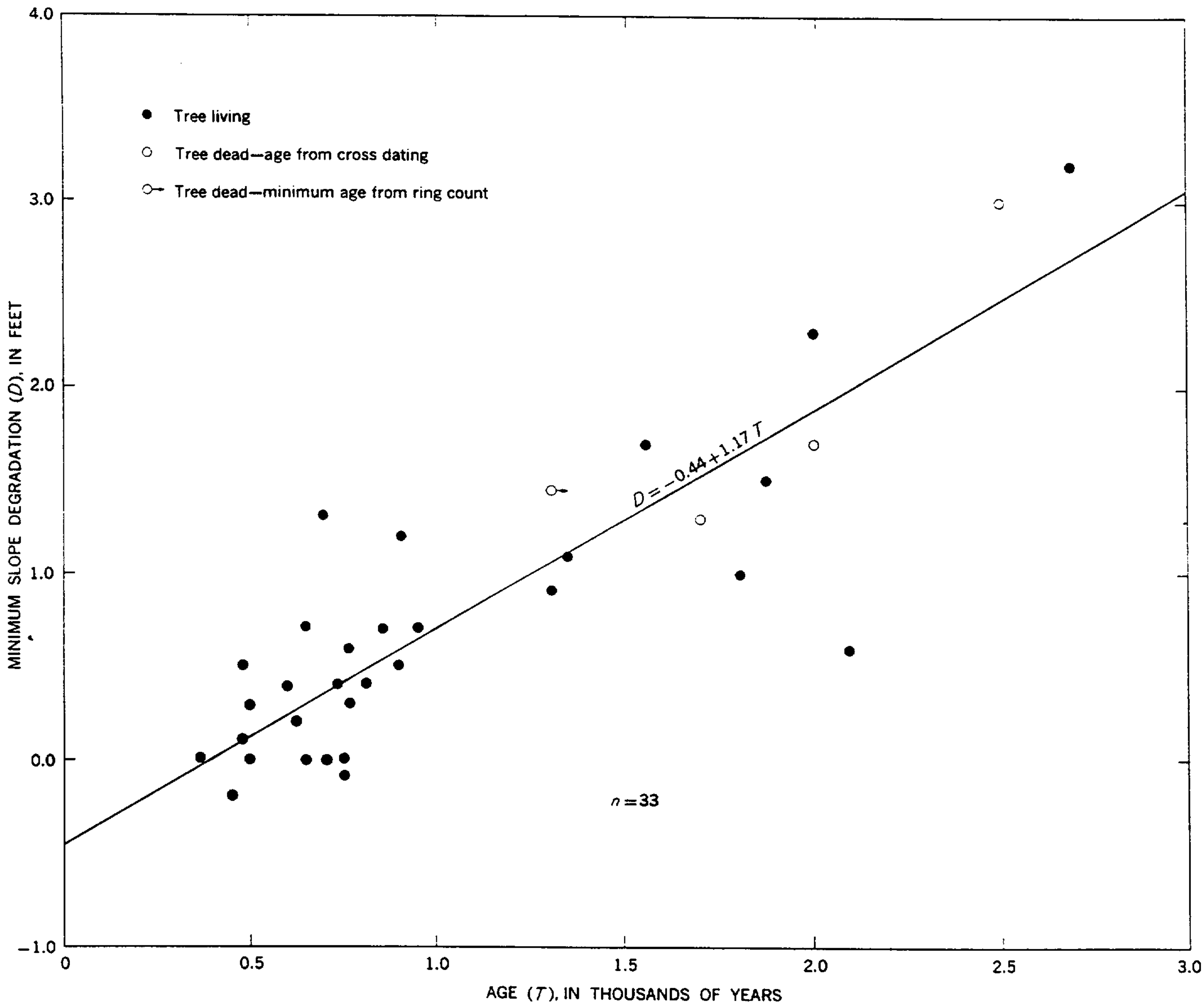

FIGURE 253.—Age and minimum slope degradation for area 1. Average age of 10 trees with no exposed roots is about 125 years. Line fitted by least squares gives average degradational rate of about 1.2 feet per 1,000 years; intercept with vertical axis at $T=0$ gives average depth of root development of about one-half foot.

All trees on the slope and the alluvial flat were included in the mapping. From a total of 80 standing trees, 28 (including 2 on the flat) were selected for detailed study by means of an overlay of randomly plotted points. A minimum-age estimate was obtained for 26 trees; they range from 80 to 3,100 years in age. Measurements of the maximum depth of root exposure, estimated local degradation, and estimated tree age are given in table 3.

The relation of local slope degradation to tree age is shown in figure 258; six trees with a mean age of only 380 years show no root exposure, and two are incompletely dated. A straight line fitted to the rest of the plotted points indicates an average degradational rate on the slope of about 0.8 foot per 1,000 years and an average depth of root development of one-half a foot.

The distribution of estimated values of local degradational rates was plotted and mapped for areas 2 and 3, which lie on opposite slopes of the same canyon (fig. 259). Most of the values for the local degradational rate at points in area 2 ranged from 0.5 to 1.0 foot per 1,000 years. Neither the crest nor the lower part of the slope are well represented by points, partly reflecting the actual distribution of old trees and partly owing to the random sampling method used. (Compare with fig. 256.) A stratified sampling procedure would have been a more effective method of study. Little evidence was found to suggest a systematic downslope change

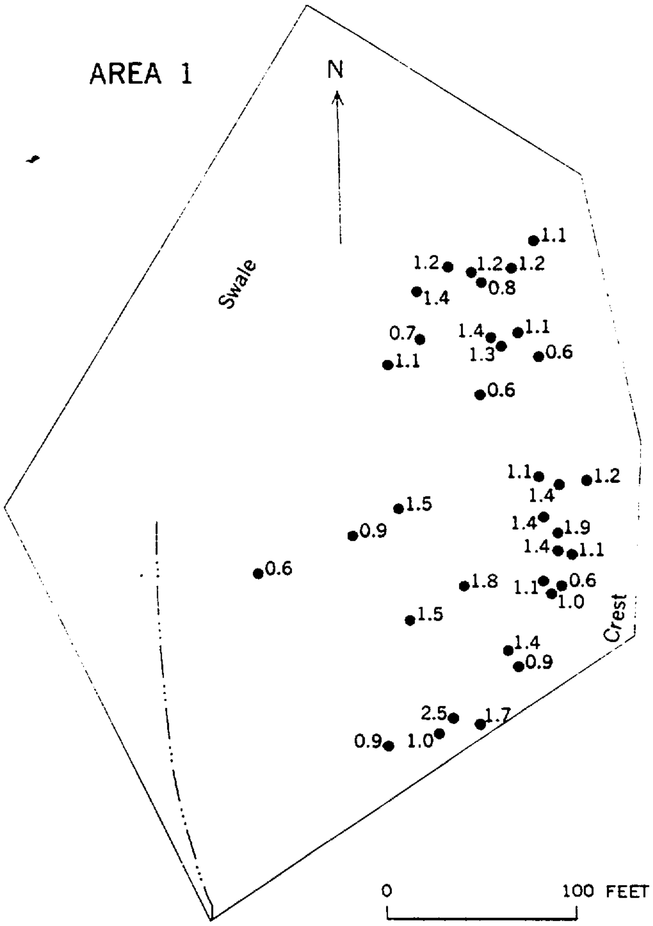

FIGURE 254.—Distribution of values of estimated local degradational rates, in feet per 1,000 years, in area 1.

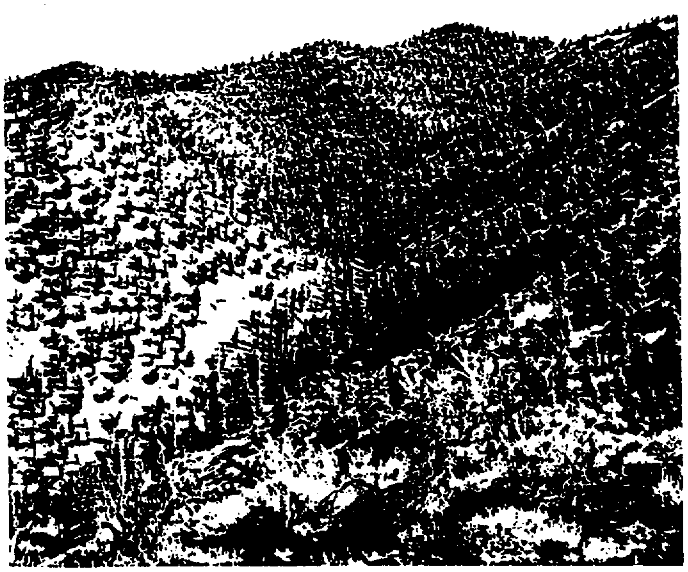

FIGURE 255.—Valley tributary to the South Fork of Birch Creek. View is toward the south. Area 2 extends from channel in center of photograph up the light-colored slope to the ridge crest at left; area 3 is on lower part of opposite slope.

FIGURE 256.—Upper part of area 2. View is toward the southeast. Low density of trees and absence of ground cover are typical of stands of old bristlecone pines.

FIGURE 257.—Surficial mantle in area 2. Scale shown by 6-inch rule. Beneath surface, angular dolomitic rubble has matrix of finer soil.

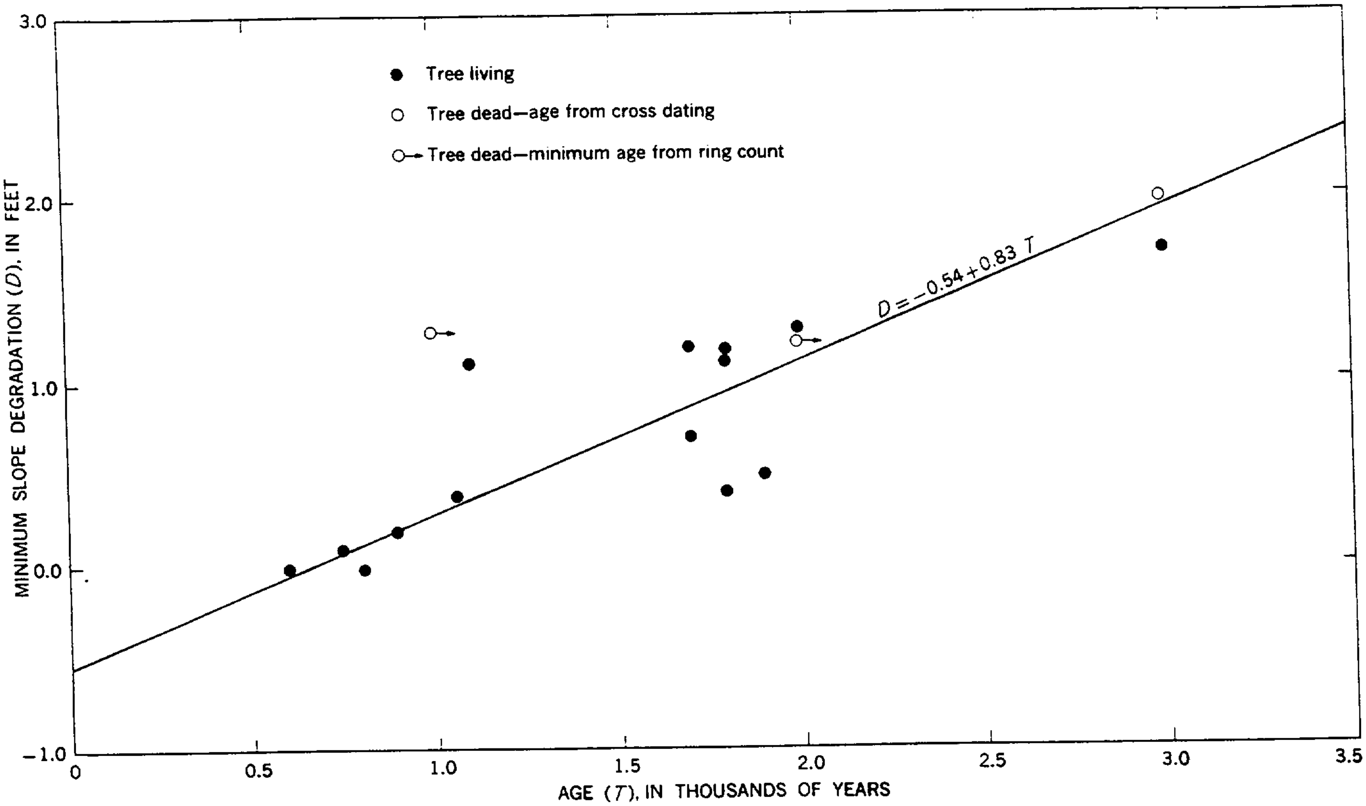

FIGURE 258.—Age and minimum slope degradation for area 2. Average age of six trees with no exposed roots is about 375 years; data for two trees on alluvial flat at base of slope are not included. Line fitted by least squares gives average degradational rate of about 0.8 foot per 1,000 years; intercept with vertical axis at $T=0$ gives average depth of root development of about one-half a foot.

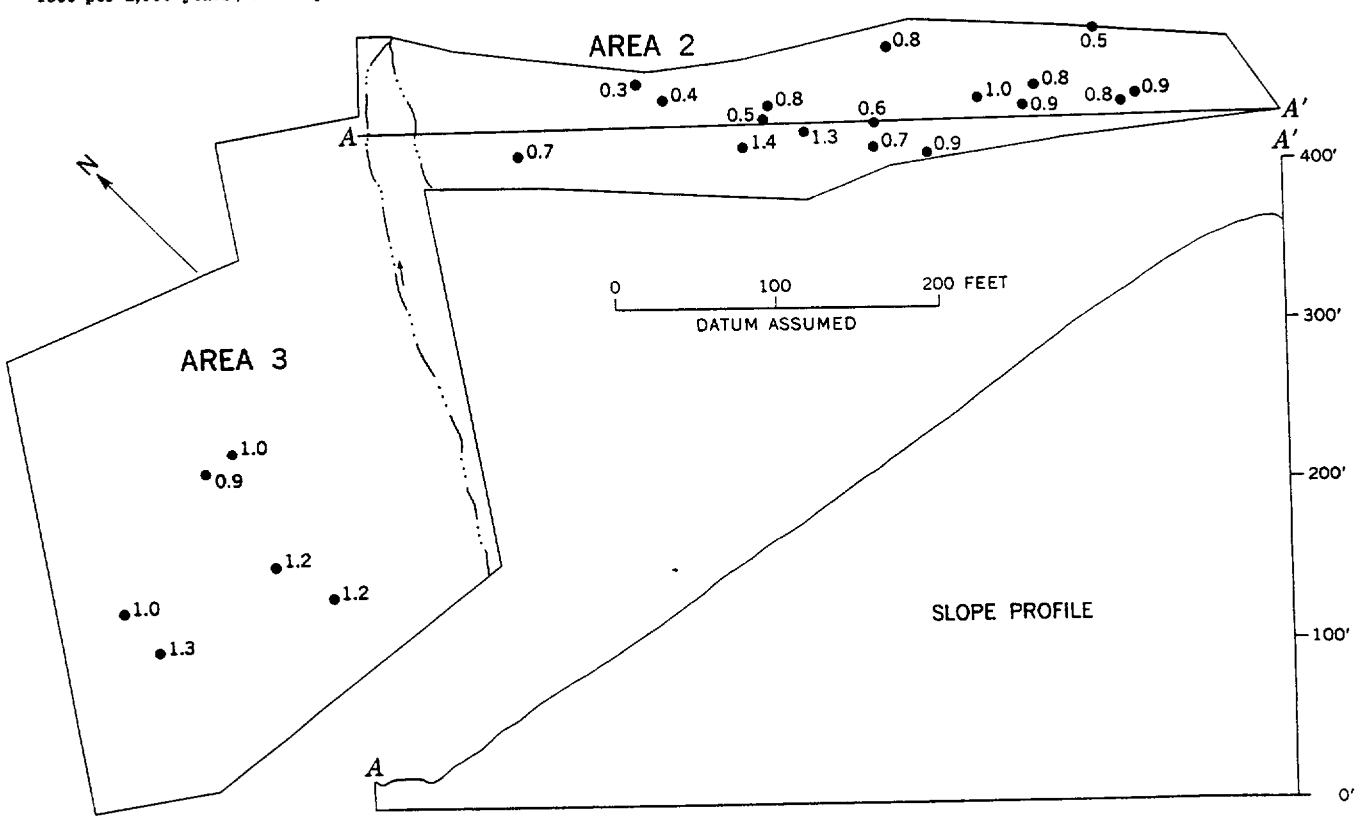

FIGURE 259.—Distribution of values of estimated local degradational rates, in feet per 1,000 years, in areas 2 and 3, and slope profile of area 2.

in degradational rate in the upper two-thirds of the area. Three specimens in the lower third give relatively low values of local degradational rates, perhaps indicating that the rates have been lowest in the lower part of the area, above the slightly oversteepened slope at the base.

AREA 3

Area 3 is distinctly different from those previously discussed. Although it is nearly opposite area 2, on the southeast-facing slope of the same canyon, area 3 does not have the same smooth to irregularly hummocked appearance. Instead, it appears to be corrugated because it is incised by steep straight drainage channels (fig. 260) in smoothly rounded miniature valleys. The channels head higher up on the slope, about 200 feet from the ridge crest. A map of a 2-acre area on the lower slope, with an average slope of 28°, is shown in figure 261.

Bristlecone pines and a sparse cover of shrubs and smaller plants grow on the slope. Some of the older trees growing on low, rounded interfluvial ridges show deep and extensive root exposure (fig. 262). The root systems of six of these trees, which range from 1,100 to 1,900 years in age (table 5), were mapped in detail (fig. 263), and the depth of root exposure was measured at many points on each. The average and maximum depths of exposure and the estimated ages are given in table 5.

FIGURE 260.—Part of area 3, viewed upslope. Shallow swales and rounded interfluvial ridges give slope a corrugated appearance. Trail in foreground.

TABLE 5.—*Age and root-exposure data for trees in area 3*

Specimen	Age data (centuries)		Root exposure		
	Age	Uncertainty	Number of measurements	Mean (ft)	Maximum (ft)
183	13.5	0.5	14	0.9	1.9
184	19.3	.3	14	1.3	2.5
185	11.0	2.0	9	.8	1.7
186	13.3	.5	16	1.1	2.3
187	13.0	1.0	17	1.2	2.4
188	17.5	.5	15	1.2	2.4

The exposed root systems generally parallel the present ground surface; thus, the valley-and-ridge topography must have existed as much as 1,900 years ago, when the root system of specimen 184 was developing. The symmetry of exposure, however, is different from that shown by trees on unchanneled slopes. The depth of exposure here varies radially from the base of the stem, reflecting the bilateral symmetry in the directions of movement of material away from the sloping miniature crest. The depth of exposure is least immediately upslope from the stem, where a narrow terrace exists; it is greatest on the downslope side. The results are summarized graphically in figure 264. For each specimen, the maximum depth of exposure is about twice the average depth of exposure, reflecting the asymmetry discussed above. The average depth of root exposure is a fair measure of the local degradation of the crest in the vicinity of each tree. As shown in figure 264, a trend line through paried values of age and average depth of exposure for these trees is flatter than one originating at zero time and zero exposure. This trend suggests that the degradation of this slope has not proceeded uniformly with time.

COMPARISON

Measurements of root exposure, minimum slope degradation, and elapsed time obtained by the same methods and based on comparable samples can be directly compared for areas 1 and 2. The results have previously been reduced to estimates of local degradational rates for each area (figs. 254, 259). The frequency distribution of this measure of degradational rate in the two areas is shown in figure 265. The modal value for area 1 is clearly greater than that for area 2, corresponding to the average degradational rates (obtained by least-squares analysis) of 1.2 and 0.8 feet per 1,000 years, respectively.

The rocky crestal areas and relatively short gentle slopes of area 1 are being degraded at a significantly greater rate than the long steep valley side slope represented by area 2. Confidence intervals can be computed (Wallis and Roberts, 1956) for the regression lines fitted to data from each area. In figure 266, the 95-percent confidence bands for the lines do not overlap

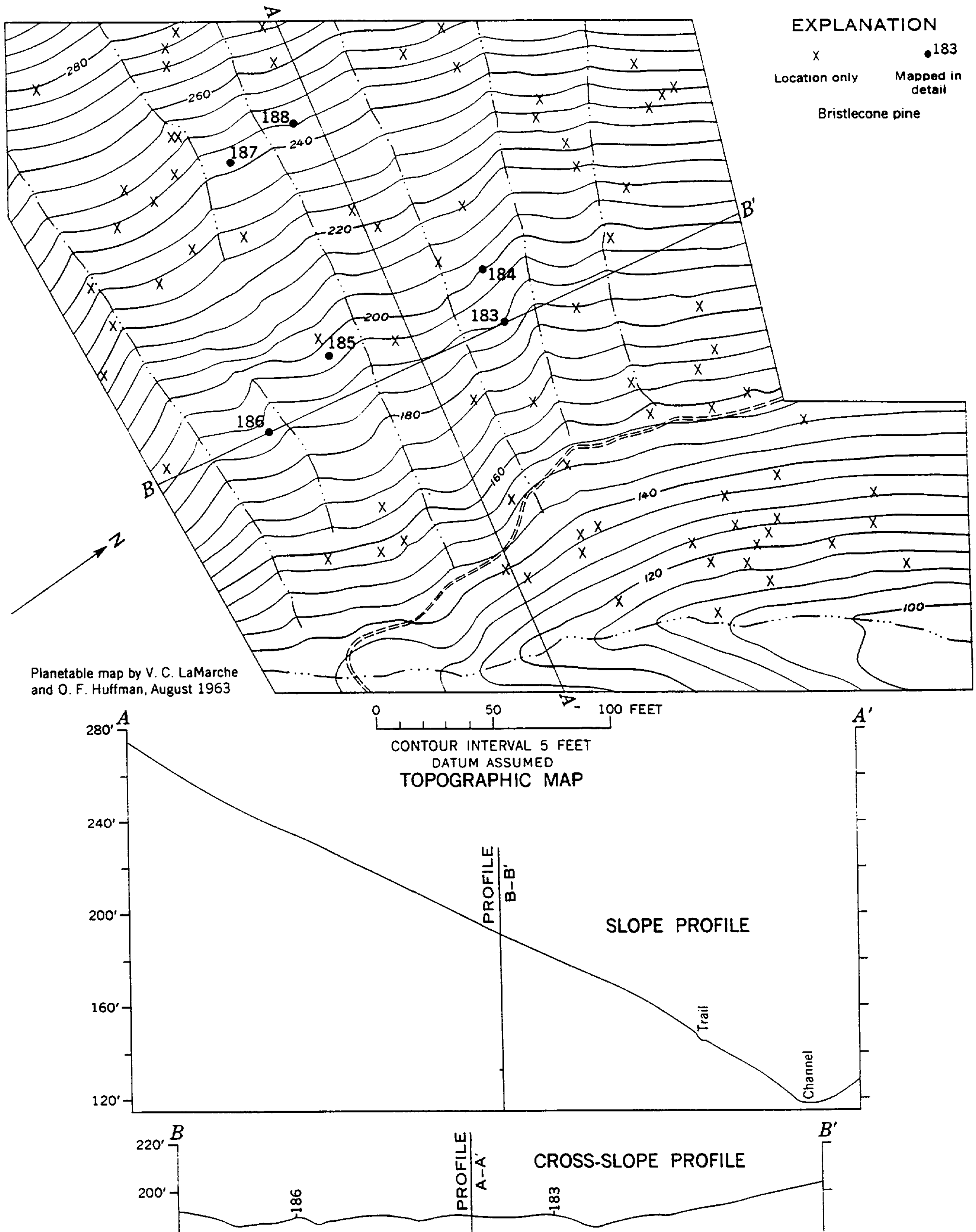

FIGURE 261.—Location of trees studied in area 3, and profiles of area 3.

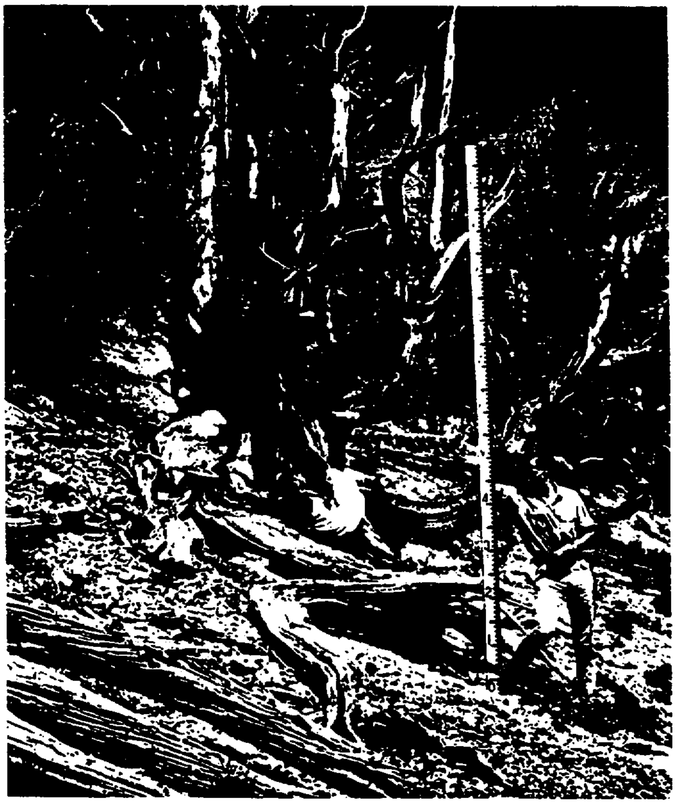

FIGURE 262.—Specimen 184 in area 3. Depth of exposure of root in foreground is about 2.5 feet, shown by comparison with stadia rod. Tree, which is 1,900 years old, is on crest of low ridge that extends down the main slope.

except near their point of convergence, at low values of the variables.

RELATION TO TOPOGRAPHY

Differences in the long-term degradational rate from place to place within an area underlain by a homogeneous formation are clearly related to differences in topography and reflect variations in the intensity of degradational processes. The local rate of degration is not solely dependent on the slope of the ground surface but is also related to the geomorphic setting of the point of observation. Comparison of data obtained in two areas showed that a gently sloping knoll may be degraded more rapidly than a long steep slope (table 6). Grouping of many local estimates of degrational rates by slope and site classes (table 7) substantiates these results. In general, rocky ridge crests, upper slopes, and steeply inclined spurs are being degraded more rapidly than the long valley side slopes. Furthermore, where degradational rates in crestal areas apparently increase with increase in slope angle, the main slopes are degraded at fairly constant rates that do not vary systematically with slope angle.

TABLE 6.—*Summary of degradational rates and topographic characteristics in three selected areas*

Area	Number of specimens dated	Sampling method	Average[1] slope (degrees)	Degradational rate (ft per 1,000 yr)	Topographic character
1	43	Total	20	[2] 1.2	Rocky knoll.
2	26	Random	38	[3] .8	Long smooth slope.
3	6	Selective	28	[4] 1.1	Gullied slope.

[1] Mean of measurements, vicinity each specimen.
[2] From least-squares analysis of data from 33 trees.
[3] From least-squares analysis of data from 15 trees.
[4] Estimated from mean 1,000-year degradation.

TABLE 7.—*Degradational rates for slope classes in crestal areas and on main slopes*

[Rates estimated from mean values of age and root exposure for specimens listed in tables 1 and 2]

Slope	Number of observations	Age (thousands of years)	Exposure (ft)	Estimated degradational rate (ft per 1,000 yr)
Crestal Areas				
Gentle	9	0.65	0.2	0.3
Moderate	16	1.00	1.0	1.0
Steep	13	1.13	1.5	1.3
Very steep	2	1.70	2.8	1.6
Main slopes				
Steep	13	0.87	0.7	0.8
Very steep	6	.86	.4	.5

The dolomite areas being degraded most slowly, if at all, are the gentle, lower slopes of high ridges, illustrated in figure 249. Direct evidence of degradational rates in this topographic setting cannot be cited, because the maximum ages of trees at these sites are low. The trees apparently do not survive long enough to show significant root exposure, although several bristlecone pines on gently slopes (<10°) have attained ages of about 1,000 years. Low rates of slope degradation can also be inferred from the development of a soil profile in the surficial mantle of these areas.

Of special geomorphic interest is the evidence of the breakdown of bedrock in progressive and relatively rapid degradation of the ridge-crest areas. The crests of high ridges on Reed Dolomite range in character from angular and irregular to gently rounded and fairly smooth. Bedrock outcrops are abundant, and the soil is coarse and patchy. Small cliffs—steep bedrock faces as much as 10 feet high and 50 feet long—have formed on the upper slopes of most ridges and along the crests of steeply inclined spurs. The shape and the appearance of such cliffs are controlled by the spacing and orientation of joints. Overturning of trees has accompanied

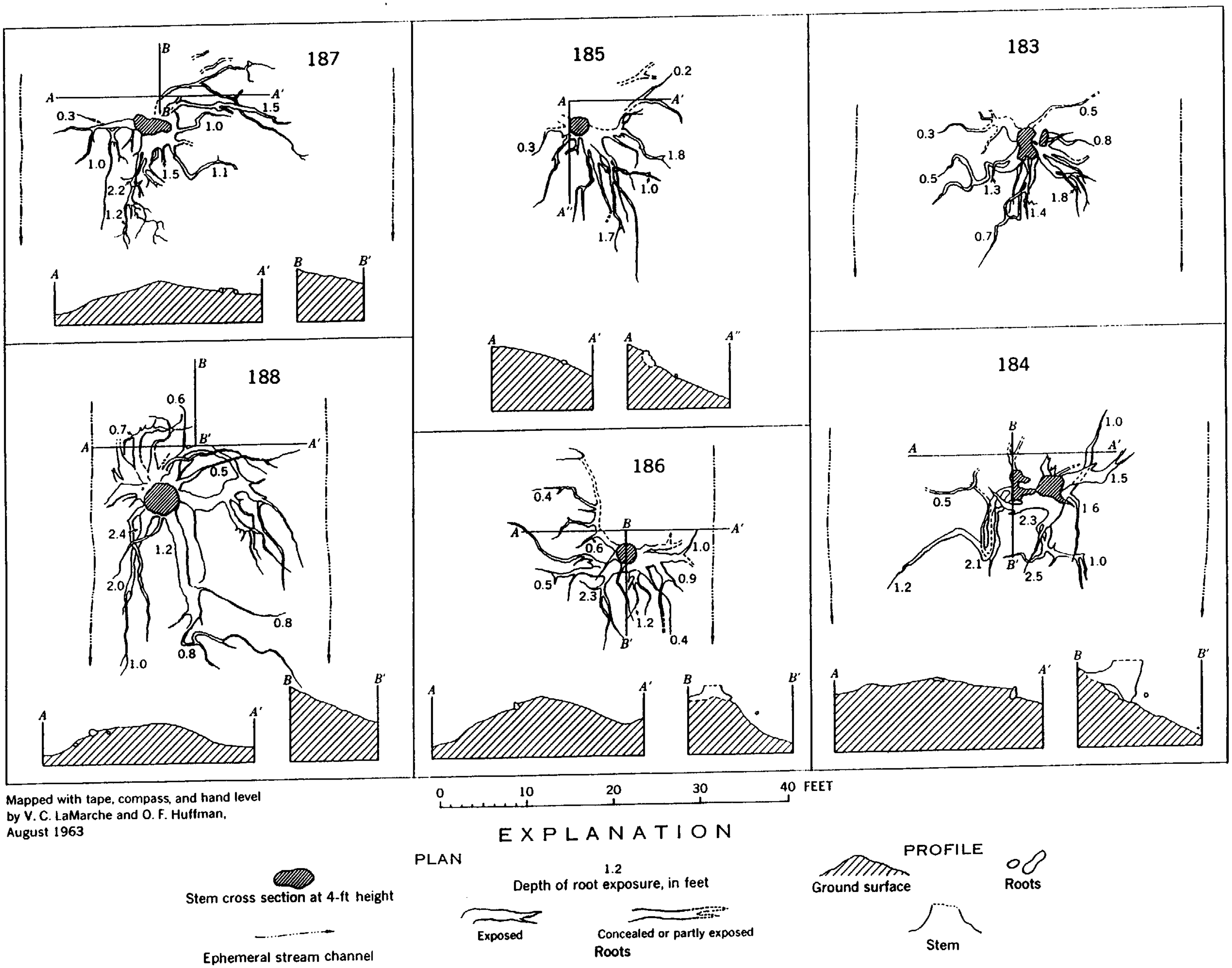

FIGURE 263.—Exposed roots of six trees in area 3, and profiles in vicinity of five of the trees.

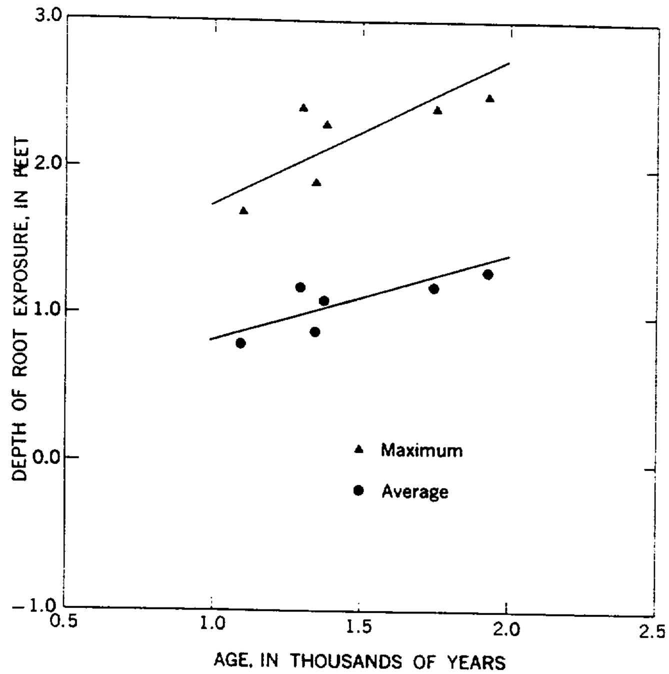

FIGURE 264.—Comparison of average and maximum depths of root exposure of trees in area 3. Average values approximate slope degradation.

the dislodgement of bedrock masses, showing that large-scale mass movement is occurring locally. Less catastrophic cliff retreat also takes place at a rate similar to that of debris-mantled slopes. The roots of a tree near upper tree line, 12 miles north of Reed Flat, extend 20 feet down a 45° cliff. These roots, which apparently followed fractures, have well-developed buttress forms and are exposed to a depth of 1.5 feet. A talus slope with fragments as much as a foot in diameter mantles the foot of this low bedrock face. The buttress root of another tree, about 800 years old, is exposed to a depth of 1 foot along a 40° bedrock surface above a high talus slope. Root exposure is seen above steeply inclined but thinly mantled bedrock surfaces and gently sloping outcrops, as well as along cliffs. The trees are firmly rooted and cannot have been elevated relative to the underlying rock. The surfaces are too steep, in many places, to have had a thick veneer of soil or rubble at the time of root development. Thus, root exposure must be due to the breakdown and removal of bedrock.

The steep embankments bordering the channels incised into the alluvial and colluvial valley fill are retreating more rapidly than valley side slopes of comparable steepness. The roots of two trees (specimens 2, 17) growing along the edges of embankments in the

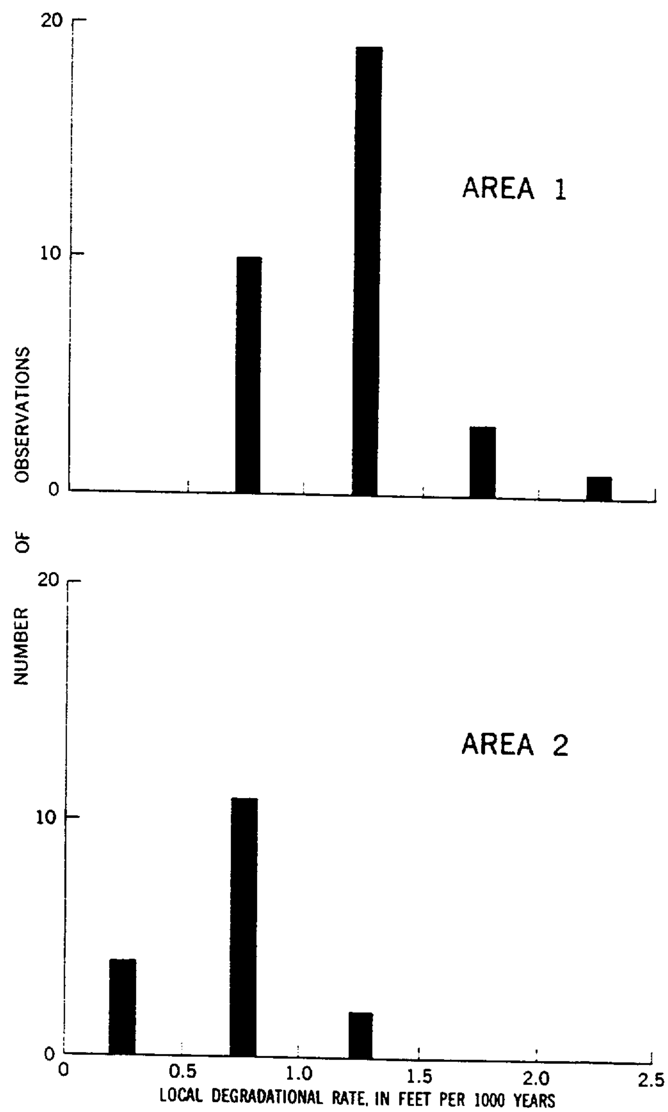

FIGURE 265.—Comparison of degradational rates in areas 1 and 2, as indicated by frequency distributions of local values of degradational rates.

Reed Flat area were studied in detail. The root systems have been differentially exposed—the roots projecting down the steep bank have been deeply exposed, but those projecting upslope have not yet been uncovered. Although youthful in appearance, these steep-walled inner valleys (which locally form a ramifying gully network) are not recent features of the landscape. Not only do 800-year-old roots parallel the banks, but trees 1,000 years old or more grow within the local areas of erosional topography. On the basis of present rates of development, however, channel cutting in the headwater areas of the White Mountains probably began less than 10,000 years ago.

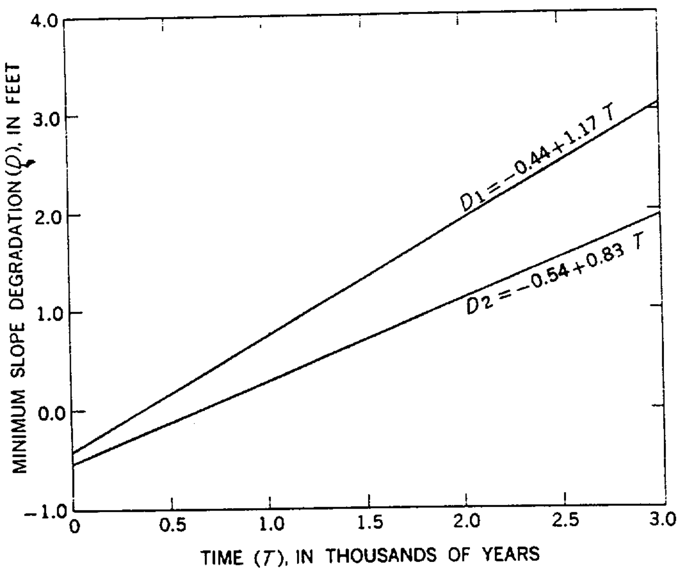

FIGURE 266.—Comparison of degradational rates in areas 1 and 2. Heavy lines represent least squares fit to scattered data. Shaded areas represent 95-percent confidence bands for lines.

DEGRADATIONAL PROCESSES AND EVIDENCE OF MOVEMENT

The land surface at some places in areas underlain by the Reed Dolomite has been lowered a few inches to several feet in the past 3,000 years; consequently, a large volume of rock debris must have been removed from these areas to account for the calculated slope degradation. The significance of mechanical weathering in the breakdown of bedrock can be inferred from the texture and mineralogy of the surficial mantle. Textural and microrelief features of the mantle suggest that downslope movement was rapid. Also, evidence indicates that large volumes of sediment are moved in stream channels during rare floods. In most of the area the movement of rock particles must take place at or near the surface of the mantle of surficial debris that overlies the dolomite bedrock. The massive, competent character of the rock and the absence of a mechanically weak, chemically weathered upper bedrock zone preclude bedrock creep and large-scale slumping. Neither chemical solution, whose action is minimal under the cool dry conditions, nor wind erosion seem to be significant mechanisms. The shallow mass-wasting and rapid erosion that occur during infrequent cloudbursts apparently cause most of the degradation.

Evidence of movement of weathering products on the dolomite slopes is abundant, but the effects of erosion and mass-wasting are difficult to distinguish. Movement of rock debris by flowing water concentrated in channels may be more significant in the long-term degradation of the Reed Dolomite slopes than is indicated by the low drainage density of about 6 miles per square mile. In a few local areas there are numerous closely spaced drainage lines. Runoff from infrequent intense storms possibly causes the headward extension of existing streams and the development of gullies on previously smooth slopes. Because the recurrence interval of flood-producing rainfall at any given point in the White Mountains seems to be about 50–100 years, according to historical evidence, such gullies would be healed by mass movement and slope wash in the intervening periods.

DEBRIS DAMMING

The terraces and hollows adjacent to old bristlecone pines are evidence that differential downslope movement of material has taken place. Similar features are the terraces that extend upslope from the trunks of fallen trees that lie across the slope and act as debris dams (fig. 267). The terrace surface is nearly horizontal, even where the surrounding area slopes steeply; and at many places, soil seems to be spilling over the top of the obstruction. An attempt was made to date such logs in order to estimate rates of accumulation; however, this was found to be impractical because the trees commonly remain standing several hundred years after they die. The date of the outermost ring in a log is a poor guide to the length of time that the log has been on the ground. The fact that such ephemeral features as logs do act as temporary barriers to downslope movement shows that the movement is frequent or continuous

FIGURE 267.—Log that forms debris dam on slope; longitudinal view. Ground surface drops about 1 foot across this barrier to downslope movement of rock debris.

and that it is shallow; there is no evidence that debris is moving beneath these logs, and only on the steepest slopes do the fallen trunks appear to be moving downslope. The material composing the terraces could thus have been transported by shallow mass-wasting or by surface runoff or both.

ASYMMETRICAL ROOT EXPOSURE

The maximum depth of root exposure in the hollow below an old bristlecone pine is a measure of the rate of movement of rock debris on the slope. The results of measurements of the maximum depth of exposure for trees with asymmetrically exposed roots are given in table 3. The rate of root exposure was calculated for each area by least-squares analysis of these data. Although the degradational rate is greater in area 1 than in area 2, the maximum rates of root exposure are about 1.0 and 1.7 feet per 1,000 years, respeotively; these rates reflect the extreme asymmetry of root exposure in area 2. Although the significance of the results is not immediately clear, the differences must be related to the differences in the slope gradient in the two areas; the average slope angle, measured in the vicinity of each of the specimens on which the results are based, is only 20° in area 1 but is 38° in area 2. Another notable difference is the distance downslope from the ridge crest to the points at which the measurements were made; this averages 200 feet in area 2 but only about 100 feet in area 1. However, within each area, there is no discernible tendency for the rate of root exposure to increase either with increasing slope of the local ground surface or with distance downslope.

A possible interpretation is that different processes are dominant in the two areas. Thus, it may be that the terrace and hollow can result only from mass movement and that the effect of the transport of sediment by water flowing over the ground surface would be to erase this topographic inhomogeneity. The degree of asymmetry of root exposure would then depend on the balance between the opposing processes. This is an attractive alternative because of the surface characteristics of the surficial mantle in the two areas. Although there are large rock fragments on the slopes of area 1, there is no continuous veneer of very coarse debris; large areas of the ground surface are silty in texture. Further, the presence of silty dolomitic sediment in the swale at the base of the slope shows that selective transport of debris is taking place on the slope, probably by surface runoff carrying only the smaller particles. In contrast, the upper 2–10 inches of the mantle in area 2 is composed exclusively of relatively large fragments that are very loosely packed and have a large interstitial volume. A rainfall intense enough to produce runoff on the surface of the compacted, relatively fine grained soil of area 1 could be expected to flow downslope within the veneer of rubble mantling the slope in area 2 without attaining great velocity or significant above-surface depth. Such interstitial water could, however, be expected to cause downslope movement of saturated debris masses. The slope material is at the angle of repose (35°–40°) when dry; the lubricating and buoyant effects of water might cause the material to move.

DEBRIS LOBES AND FANS

Evidence for recent movement of rock debris in ephemeral stream channels is widespread in the White Mountains. Much of the sediment produced by drainage basins in the range reaches the alluvial fans along the margins of the range in the form of dense mudflows (Kesseli and Beaty, 1959; Lustig, 1965). Smaller alluvial fans extend from the mouths of tributaries into the channels of streams within the range. The lobate form, the unsorted nature of the sediment, and the large size of some fragments suggest that these alluvial fans are formed by similar flows. Direct evidence for the occurrence of mudflows was found in area 3, where a debris lobe has completely filled one of the steep miniature valleys for a distance of 40 feet (between specimens 186 and 187, fig. 263). About 30 feet in maximum width and 4 feet deep, this deposit is composed of an unstratified mixture of silt, pebbles, and cobbles. A tangle of wood debris bounds the steep lower margin. This is clearly a mudflow that stopped before reaching the main canyon bottom. Although the channel slope at this locality is about 25°, it is even greater (30°) immediately upslope; the change in gradient may explain the loss of mobility.

Much larger piles of rock and wood debris choke the channelway in a narrow canyon west of Blanco Mountain. One of the largest of these (fig. 268) is a deposit of cobbles and boulders, up to 3 feet in diameter, behind a tangle of large logs; it fills the 50-foot-wide canyon floor to a depth of 10 feet.

Several other debris jams of similar size are located downstream, and all were probably produced at the same time by a flood of catastrophic proportions. There is evidence that this flood occurred within the past 300 years. Tree-ring dating of a standing tree deeply buried by the debris shows that it died in A.D. 1640; it was probably already dead at the time of burial. One of the best preserved logs in another pile represents a tree that died about A.D. 1600, establishing the earliest possible date of the event.

FIGURE 268.—Large debris pile in canyon tributary to Wyman Creek, as viewed upstream. This tangle of logs and large boulders was apparently produced by a single flood.

SUMMARY AND CONCLUSIONS

Degradation is the decrease in altitude of the land surface that results from gradual removal of surficial rock debris. Slope degradation in dolomite areas of the White Mountains, Calif., has resulted in the uncovering and progressive exposure of the initially shallow root systems of many bristlecone pines. Root exposure has occurred in a variety of topographic sites—from cliffs and steep talus slopes to rounded ridge crests and gently sloping valley bottoms. The extensively exposed root systems of certain individual trees, as well as the deeply exposed roots of large numbers of old trees in large tracts, show that material has been uniformly removed from large areas. At many sites, the roots of young trees have not yet been uncovered, whereas older trees show depths of root exposure proportional to their ages. Thus, root exposure is the result of degradational processes operating uniformly over large areas for long periods of time.

The Precambrian Reed Dolomite is a massive homogeneous unit that underlies a fluvially eroded terrain of moderate to high relief. The dolomite bedrock is covered by a mantle of surficial rock debris except along ridge crests, spurs, and rocky knolls. Ranging in texture from pebbly silt loam to coarse rubble, the debris is produced by the mechanical breakdown of the closely jointed dolomite. Frost shattering appears to be the dominant weathering process. Miniature patterned-ground features suggest that the approximately 220 diurnal freeze-thaw cycles per year, indicated by weather records, are also effective in sorting and causing downslope creep of the surficial debris.

Bristlecone pines dominate the subalpine coniferous forest that is almost entirely limited to dolomite terrane in the White Mountains. Although noted for their great age, few bristlecone pines have attained an age of more than 4,000 years. Only trees less than about 3,000 years old are relatively abundant. Typically, the oldest trees in a given area are restricted to the crests of high ridges and to rocky subsidiary spurs. Although the older trees might reliably indicate long-term degradational rates, selective study of trees of great age necessarily introduces a bias toward a particular kind of topographic situation. Because degradational rates appear to be a function of topography, such results may not be representative. Total or random samples of bristlecone pines in two areas, even though the stands were chosen because of the great apparent ages of many individual trees, give average ages of about 1,000 years and maximum ages of about 3,000 years.

Counting and correlation of annual growth rings form the basis for reliable age determinations of bristlecone pines. The most significant source of uncertainty in estimates of the time of establishment of a tree and its root system is the frequent loss of the oldest wood through weathering and decay. The absence of certain growth rings from a sample results in age estimates that are systematically too young if dating is based on a simple ring count. Cross dating of distinctive ring patterns in such a sample and in the complete growth record of another tree will increase the accuracy of the age estimate. The cross-dating techniques may also be used to estimate the age of a log or stump, but large error can be introduced by erroneous correlations in the absence of the approximate dating control provided by a ring count based on the outermost ring of a living tree.

The basis for relating root exposure to slope degradation is the shallow depth of initial root development that characterizes certain conifers. Root systems of many bristlecone pines and of a few old trees of other species in the White Mountains have been uncovered and exposed as a consequence of increasing age on sites subject to degradation. The axis of a root, which must have been within the soil at the time of longitudinal growth, is the only unequivocal datum for the measurement of root exposure. The top of a shallow root may become exposed through diametral increase alone. The sharp inflection of the basal flare, low on the stem of a tree, bears no relation to degradation, but is a normal feature of mature forest trees.

Local degradational rates can be calculated by combining a measure of root exposure with an estimate of tree age for each of a number of individual trees. However, the depth of root exposure, measured vertically from the root axis to the underlying ground surface, will be less than the actual degradation by an amount equal to the original depth of root burial. This factor would thus lead to underestimation of individually calculated degradational rates; it would affect the results from study of younger trees with little root exposure much more than those from older trees with roots exposed to depths of several feet.

A much more significant source of error is related to the asymmetrical exposure of root systems. The maximum depth of root exposure may be several times the actual slope degradation, and the disparity will tend to increase with time. An upslope terrace and downslope hollow are microrelief features associated with old trees on sloping terrain. These features reflect the damming effect of the tree itself—the stem and roots impede the direct downslope movement of surficial debris. The result is deep exposure of roots that extend downslope but little exposure or actual burial of roots directed upslope. The depth of root exposure can be averaged over the affected area to give a more reliable estimate of local degradation. When this procedure was followed on a steep (38°) slope (area 2), a sample of 14 trees showed that the maximum depth of exposure increased about twice as rapidly as the degradation of the surrounding area. These problems of measurement, combined with the possibility of bias in selective sampling, cast doubt on the significance of degradational rates calculated only from observations of age and maximum root exposure of individual trees.

Even casual observation of deeply exposed roots can indicate the order of magnitude of degradational rates. More accurate estimates must be based on careful measurements related to a valid index of both present and preexisting ground levels. The inferences that can be drawn from examination of exposed roots depend on observations of the relationships of developing root systems to the contemporary land surface. Furthermore, study of the response of the roots to uncovering and exposure may provide additional information on the local topographic history. Finally, the trees themselves are static features in a changing landscape, and they can induce pronounced local topographic changes that must be considered in quantitatively relating exposed roots to degradation.

Despite the problems of measurement, the grouping of the scattered observations of tree or root age and uncorrected depth of root exposure by topographic character of the individual sites gives at least a rough comparative estimate of degradational rates. The numbers obtained are probably significant only in their relative magnitudes. Degradational rates are greatest, perhaps 3–4 feet per 1,000 years, where the landscape is changing most rapidly—on the steep banks adjacent to channels now being incised into alluvium and colluvium that fills the valleys. The undissected surface of this fill represents the gentle ($< 10°$) lower slopes of the flanking ridges. Here, degradational rates are too low to be directly measured but must be less than about 0.5 foot per 1,000 years. In contrast, there is much evidence for rapid degradation of rocky ridge crests and upper slopes. Furthermore, the degradational rate seems to increase with increasing slope, from about 0.3 foot per 1,000 years (slope $< 10°$) to about 1.6 feet per 1,000 years (slope $> 30°$). Because root exposure tends to be symmetrical in crestal areas, this result probably reflects real differences in degradational rates rather than the effect of slope angle in increasing the asymmetry of exposure. The long comparatively steep (30°–40°) slopes that extend from the valley floors to the crests of the main ridges are apparently being degraded more slowly (0.4–0.8 ft. per 1,000 yr.) than the crestal areas (1.2 ft. per 1,000 yr.). Because such slopes make up a major part of the terrain underlain by the Reed Dolomite, the average degradational rate for the entire area must also be less than 1 foot per 1,000 years.

The most accurate estimate of the long-term rate of slope degradation based on study of exposed roots is obtained through unbiased (total or random) sampling of a fairly large number of specimens within a small area. Measurements of root exposure are reduced to estimates of minimum slope degradation by correcting for the local topographic changes induced by the presence of the tree itself. Results of study of two contrasting areas, using this approach, reinforce conclusions based on analysis of data from individual trees scattered over a large area. A rocky knoll, representative of crestal and upper slope areas, has been degraded at the average rate of 1.2 feet per 1,000 years during the past 2,500 years. Study of trees in a long narrow strip extending from a canyon bottom to the adjacent ridge crest showed that it has been degraded at a rate of only 0.8 foot per 1,000 years in the same period.

The extent of slope degradation indicated by the widespread exposure of root systems of trees in the White Mountains requires the movement of large volumes of rock debris from the slopes to the stream channels. The accumulation of material behind logs and the pronounced damming effect of standing trees show that such movement does take place. Relatively rapid movement is suggested by the fact that the appearance of an obstruction is reflected in the microtopography within a few hundred years.

Removal of the debris produced from individual slopes, and perhaps a significant amount of slope erosion, may take place at infrequent intervals. Historical evidence shows that cloudbursts in White Mountain watersheds have generated floods that appeared as mudflows on alluvial fans flanking the range. Small debris lobes and alluvial fans and large bouldery deposits in channels within the study area illustrate that large volumes of coarse dolomitic debris can be transported in single flood events. However, from the straight-line variation of degradation with time in each of two areas and from evidence from scattered observations of gradual and progressive root exposure provided by many buttress roots, it appears that degradational rates have not fluctuated greatly within the past 3,000 years. The landscape seems to be roughly adjusted to the nearly steady transportation of the products of rock weathering on this scale in time, even though major erosional events may recur only infrequently. A summary of the kind and scope of processes that are inferred to be significant in the degradation of the Reed Dolomite terrane in the White Mountains is given in table 8.

TABLE 8.—*Qualitative summary of major transport mechanisms*

Process	Frequency	Scope	Rate of movement	Associated features	Associated events
Creep	Continuous	Ridge-crests and slopes.	Slow	Rock stream.	Diurnal temperature change and freeze-thaw cycles.
Solifluction	Seasonal			Patterned ground.	
Erosion	Occasional	Slopes and channels.	Rapid	Debris piles.	Snowmelt and cloudburst runoff.

The magnitude of degradational rates in the White Mountains generally corresponds to the results of calculations based on indirect evidence of degradational rates in comparable areas. From data on sediment and dissolved loads of 17 streams draining mountain basins in semiarid and subalpine regions, Corbel (1959) calculated an average denudational rate of 0.3 mm per year, or about 1 foot per 1,000 years. Schumm (1963), in a recent review of rates of denudation of small drainage basins, suggested a maximum long-term denudational rate of 3 feet per 1,000 years in the early stages of the erosion cycle in semiarid areas underlain mostly by sedimentary rocks.

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Yield of Sediment in Relation to Mean Annual Precipitation

W. B. Langbein and S. A. Schumm

Abstract—Effective mean annual precipitation is related to sediment yield from drainage basins throughout the climatic regions of the United States. Sediment yield is a maximum at about 10 to 14 inches of precipitation, decreasing sharply on both sides of this maximum, in one case owing to a deficiency of runoff and in the other to increased density of vegetation. Data are presented illustrating the increase in bulk density of vegetation with increased annual precipitation and the relation of relative erosion to vegetative density.

It is suggested that the effect of a climatic change on sediment yield depends not only upon direction of climate change, but also on the climate before the change. Sediment concentration in runoff is shown to increase with decreased annual precipitation, suggesting further that a decrease in precipitation will cause stream channel aggradation.

Introduction—The yield of sediment from a drainage basin is a complex process responding to all the variations that exist in precipitation, soils, vegetation, runoff, and land use. This study is aimed only toward a discernment of the gross variations in sediment yield that are associated with climate as defined by the annual precipitation. Such a study may contribute to an understanding of the effects of climatic change on erosion and of the regional variations in sediment yield. Data on sediment yields are now available in sufficient number for this kind of study, although still quite deficient in geographic coverage. Two major sources of sediment data exist. Records collected at about 170 gaging stations of the U. S. Geological Survey, where sediment transported by streams is measured, is one source of data; whereas, the other source of data is provided by the surveys of sediment trapped by reservoirs. Both kinds of data are used in this study.

Precipitation data—Precipitation is used as the dominant climatic factor in the study of sediment yield, because it affects vegetation and runoff. However, the effectiveness of a given amount of annual precipitation is not everywhere the same. Variations in temperature, rainfall intensity, number of storms, and seasonal and areal distribution of precipitation can also affect the yield of sediment. For example, *Leopold* [1951] in an analysis of rainfall variation in New Mexico, found that despite the absence of any trend in annual rainfall, changes in the number of storms produced a significant influence upon erosion. Although analyses of these effects are beyond the scope of this study, the effect of temperature, which controls the loss of water by evapotranspiration, can be readily taken into account. As is well known, the greater the temperature, the greater are the evapotranspiration demands upon soil moisture; hence, less moisture remains for runoff. More precipitation is required for a given amount of runoff in a warm climate than in a cool climate. Therefore, instead of using actual figures of annual precipitation, it is preferable to use figures of precipitation adjusted for the effect of annual temperature. However, in lieu of carrying out these extended computations, it appears possible to use the data on annual runoff which already reflect the influence of temperature. Annual runoff data are available for all the gaging station records and for most of the reservoir records. Because of the well-established relationships between annual precipitation and runoff, it is readily possible to estimate precipitation from the runoff figures.

We shall define effective precipitation as the amount of precipitation required to produce the known amount of runoff. Figure 1 shows a relationship between precipitation and runoff based on data given in Geological Survey Circular 52 [*Langbein*, 1949]. This graph has been used to convert known values of annual runoff to effective precipitation, based on a reference temperature of 50°F. In a warm climate, with temperature greater than 50°, the precipitation so estimated would be less than the actual amount of precipitation; in a cool climate, the effective precipitation so estimated would be more than the actual amount. This is the desired relationship.

Sediment-station data—In recent years a number of records of sediment yield, as measured at sediment-gaging stations, have become available. Annual loads were computed for about 100 stations giving preference to the smaller drainage areas in any region. All parts of the country

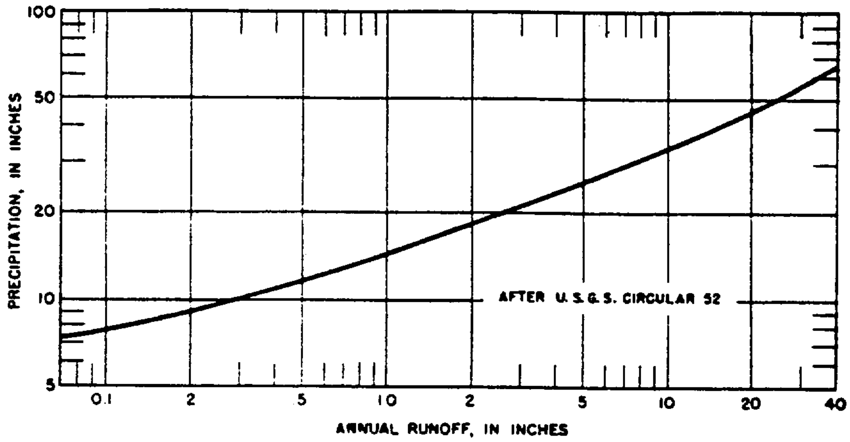

FIG. 1 – Relation between annual precipitation and runoff for a mean temperature of 50° F

where sediment records are collected, are represented.

The annual sediment loads were first arranged according to effective precipitation. They were next assembled into the class groups shown in Table 1, and the arithmetic averages were then computed for each group. Within any group the loads may vary tenfold, reflecting geologic and topographic factors not considered in this study. Each group mean is subject to a standard deviation of about 30 pct. The group averages are plotted in Figure 2. The curve shown was fitted to the data, subject to the condition (1) that it did not depart more than one standard deviation (30 pct) from any of the plotted group means, and (2) that it show zero yield for zero precipitation.

There is considerable opportunity for bias in the figures for load, because the relatively few records prohibit any high degree of selectivity. Few of the rivers drain areas in their primeval environment and moreover, land use can greatly affect the sediment yield. Farming, grazing, road construction, and channelization tend to increase sediment yield; reservoirs impound and, therefore, delay the movement of sediment. If these effects are uniform countrywide, then the overall results might be free of bias in the statistical sense, even though the absolute magnitudes may not be representative of primeval conditions. However, there is considerable variation, particularly with respect to intensity of agricultural operations, which perhaps are most intensive in the midcontinent region. The effects of various kinds of land use upon erosion vary with climate, physiography, soil type, and original vegetation. One surmises that the effect of cultivation is greater in the humid region, where effective pre-

TABLE 1 – *Group averages for data at sediment stations*

Range in effective precipitation	Number of records in each group	Average effective precipitation	Average yield
inch		inch	tons/sq mi
Less than 10	9	8	670
10 to 15	17	12.5	780
15 to 20	18	17.5	550
20 to 30	20	24	550
30 to 40	15	35	400
40 to 60	15	50	220

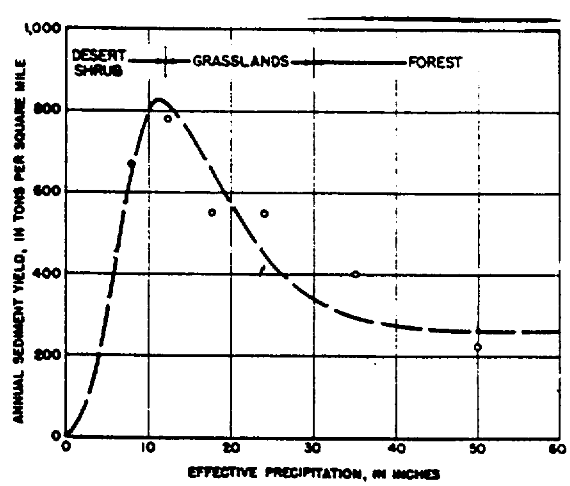

FIG. 2 – Climatic variation of yield of sediment as determined from records at sediment stations

cipitation is more than about 30 inches, because of the great contrast between original forest cover and tillage. The erosive reaction of some soil types to cultivation is evident for some small drainage basins in the humid region, which have sediment yields that approach or exceed those usual even in the arid country and are far above those to be expected within their particular range of annual precipitation. For example, sediment yield from small drainage basins (0.1 to 1.0 sq mi) in the loess hills of Iowa and Nebraska is very high, largely because of poor conservation practices on wind deposited soils. These rates "are among the highest found anywhere in the country" [*Gottschalk* and *Brune*, 1950, p. 5].

Another source of bias is the relatively non-uniform distribution of sediment-gaging stations. Most are in the central part of the country, whereas virtually none is available in the Pacific Coast Region, in New England, or in the Gulf Region.

Reservoir sediment data—Although preference was given to the smaller drainage areas in using gaging-station records of suspended sediment, opportunities for choice in this regard were severely limited. Fortunately, surveys of sedimentation in reservoirs are more numerous, so that there was opportunity to be more selective in choosing reservoirs below small drainage areas, which on that account were presumed to be more indicative of sediment yield nearer the source. Data on reservoir sedimentation were compiled by the *Federal Inter-Agency River Basin Committee* [1953]. Rates of sedimentation were obtained from surveys of sediment accumulation, expressed as an annual rate in acre feet or tons per square mile of drainage area. For those reservoirs where the bulk density of the deposits was determined, the annual rates per square mile are given in terms of tons, otherwise the rates are given in terms of acre feet. In these cases, volumes in acre feet were converted into tons by assuming a density of deposit of 60 lb/cu ft, an average of reported densities. In selecting reservoirs, preference was given to those with capacities exceeding 50 ac ft/sq mi of drainage area, in order to select those which trap a large portion of the sediment that enters the reservoir.

Reservoirs with less than five square miles of drainage area appear to have highly variable rates of sedimentation. For very small areas, rates of sediment yield are greatly influenced by details of land use and local features of the terrain [*Brown*, 1950]. For this reason, reservoirs having drainage areas between 10 and 50 sq mi were used. Because no reservoirs in desert areas were listed in the Inter-Agency compilation, data for desert reservoirs were obtained from unpublished records collected by the U. S. Geological Survey. However, because these reservoirs were on drainage areas of ten square miles or less, rates of sediment yield for these desert reservoirs were adjusted downward to obtain equivalent rates from drainage areas of 30 sq mi, according to the 0.15 power rule explained below. The sediment data we arranged according to effective precipitation an grouped as shown in Table 2.

Group averages of the reservoir data are plotte in Figure 3. The general shape of the resultin curve is quite similar to the one obtained from th records of suspended sediment measured at rive stations. The most evident difference is that th yields are about twice those indicated by th sediment-station records. There are significan differences between the two kinds of records The sediment-station records do not include be

TABLE 2. - *Group averages for reservoir data*

Range in effective precipitation	Number of reservoirs in each group	Average effective precipitation	Average yield	Remarks
inch		inch	tons/sq mi	
8–9	31	8.5	1400	15 reservoirs in San Rafael Swell, Utah, and 16 in Badger Wash, Colo.
10	38	10	1180	26 reservoirs in Twenty-mile Creek basin, Wyo., 7 in Cornfield Wash, N. Mex., and 5 general.
11	12	11	1500	General
14–25	18	19	1130	General
25–30	10	27.5	1430	General, including debris basins in Southern Calif. considered as one observation.
30–38	20	35.5	790	General
38–40	11	39	560	General
40–55	18	45	470	General
55–100	5	73	440	General

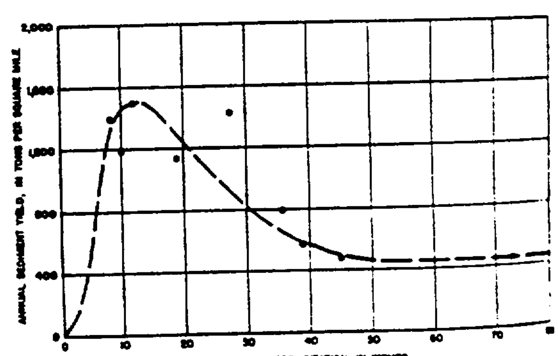

FIG. 3 - Climatic variation of yield of sediment as determined from reservoir surveys

load, which, being the coarser fraction of the load, is trapped by a reservoir. The effects are variable depending on relative amounts of bed and suspended loads at gaging stations and on the trap efficiency of the reservoirs. Moreover, reservoirs are generally built in terrain that offers favorable sites, which means drainage basins with steep slopes and hence higher rates of net erosion. However, in the comparison made here most of the difference is probably due to the effect of size of drainage area. Several studies have shown that sediment yields decrease with increased drainage area, reflecting the flatter gradients and the lesser probability that an intense storm will cover the entire drainage basin. Assuming that the graphs shown by *Brune* [1948] are correct for this effect, rates of sediment yield are inversely proportional to the 0.15 power of the drainage area. Noting that the drainage areas used for Figure 2 average about 1500 sq mi and those for Figure 3 about 30 sq mi, the sediment yields for reservoir data should average about $(1500/30)^{0.15}$, or 1.8 times that for the sediment-station data. This correction applied to the reservoir data would very nearly account for most of the difference between the curves of Figures 2 and 3.

Figures 2 and 3 appear to show a maximum sediment yield at about 12 inches annual effective precipitation, receding to a uniform yield from areas with more than 40 inches effective precipitation. The lack of data for climates with less than 5 inches of annual precipitation makes it difficult to determine the point of maximum yield with accuracy. Available data indicate, however, that it is at about 12 inches or less.

In a similar study of erosion rates and annual precipitation for large rivers of the world (Fig. 4), *Fournier* [1949] notes that the drainage basins are located on a parabolic curve in relation to their climatic character. For example, the upper limb of the parabola (greater than 43 inches) is formed by rivers typical of a monsoon climate: Ganges, Fleuve Rouge (Hung Ho), Yangtze, and some basins of southeastern United States; the middle segment of the curve between 24 and 43 inches of rainfall is formed by drainage systems located in regions with essentially equally distributed annual rainfall, as the Atlantic coastal rivers of the northeastern United States; the lower limb of the curve below 24 inches is formed by rivers draining regions of the more continental steppe or semiarid climates: Vaal, Indus, Rio Grande, Hwang-Ho, Tigris, and Colorado. Fournier con-

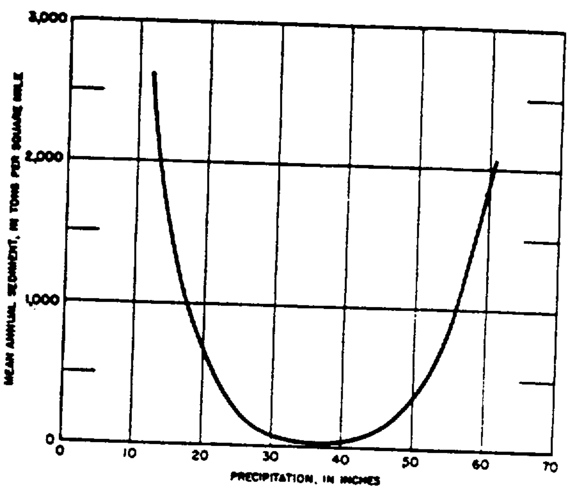

FIG. 4 – Relation of sediment yield to precipitation [after *Fournier*, 1949]

cluded that the regions of maximum erosion are those in which monthly rainfall varies greatly, the monsoon and steppe climates.

The midpart of his curve shows an annual yield of only five to seven tons per square mile which Fournier attributes to basins in which rainfall is uniform throughout the year such as those in the northeastern United States. These figures are much below that indicated by the few available records in that region which range from a minimum of about 40 tons/sq mi for Scantic River in Connecticut to 370 tons/sq mi for Lehigh River in Pennsylvania.

The lower limb of Fournier's curve terminates at a precipitation of about 12 inches, reaching an annual yield of about 2500 tons/sq mi. Although rates as high and even higher occur in many areas in the arid country, the figure of 2500 tons/year seems somewhat high as an average. The upward trend cannot continue if there is zero sediment yield (in rivers) for zero precipitation; the curve seemingly must reverse its upward trend and swing downward towards the origin.

The upper limb of Fournier's curve (above 43 inches precipitation) shows sharply increasing sediment yield with increasing precipitation, a trend that is not evident in Figures 2 and 3. However, it is possible that additional information in such areas of great rainfall as northern California and the Pacific Northwest may introduce an increasing trend in this part of those graphs.

Analysis of the climatic variation in sediment yield—The variation in sediment yield with climate can be explained by the operation of two factors each related to precipitation. The erosive influence of precipitation increases with its amount, through its direct impact in eroding soil and in generating runoff with further capacity for erosion and for transportation. Opposing this influence is the effect of vegetation, which increases in bulk with effective annual precipitation. In view of these precepts, it should be possible to analyze the curves shown in Figures 2 and 3 into their two components, the erosive effect of rainfall and the counteracting protective effect of vegetation associated with the rainfall.

These opposing actions can be represented by mathematical expressions of the following form

$$S = aP^m \frac{1}{1 + bP^n} \qquad (1)$$

in which S is annual load in tons per square mile, P is effective annual precipitation, m and n are exponents, and a and b are coefficients. The factor aP^m in the above equation describes the erosive action of rainfall in the absence of vegetation. The die-away factor $1/(1 + bP^n)$ represents the protective action of vegetation. The factor aP^m increases continuously with increase in precipitation, P, whereas the factor $1/(1 + bP^n)$ is unity for zero precipitation, and decreases with increases in precipitation.

Eq. (1) can not be evaluated by the usual least-squares method. Hence it was evaluated by trial and error, graphical methods yielding the following approximate results.

$$S = \frac{10P^{2.3}}{1 + 0.0007P^{3.33}}$$

for sediment station data and

$$S = \frac{20P^{2.3}}{1 + 0.0007P^{3.33}}$$

for reservoir sediment data.

The factor $P^{2.3}$ describes the variation in sediment yield with constant cover. Analyses of measurements of rainfall, runoff, and soil loss made on small experimental plots operated by the Department of Agriculture [*Musgrave*, 1947], indicate that, other factors the same, erosion is proportional to the 1.75 power of the 30-minute rainfall intensity. However, it is rather difficult to draw a connection between the intensity of 30-minute precipitation and annual precipitation. Inspection of *Yarnell's* [1935] charts indicates one relationship exists in the eastern part of the country and another in the western areas. However, in both areas 30-minute intensities vary with annual rainfall to some power greater than unity. Hence, one can conclude that erosion will vary regionally to some power of the annual precipitation greater than 1.75.

The second factor, $1/(1 + 0.0007\ P^{3.33})$, equals $S/aP^{2.3}$. This function, as graphed in Figure 5, purports to isolate the variation in sediment yield caused by differing degrees of vegetative cover. This function varies as shown in Table 3.

There is a good deal of information on the relation between different vegetal covers and rates of erosion in a given climate. However, most of this information deals with cultivated lands and

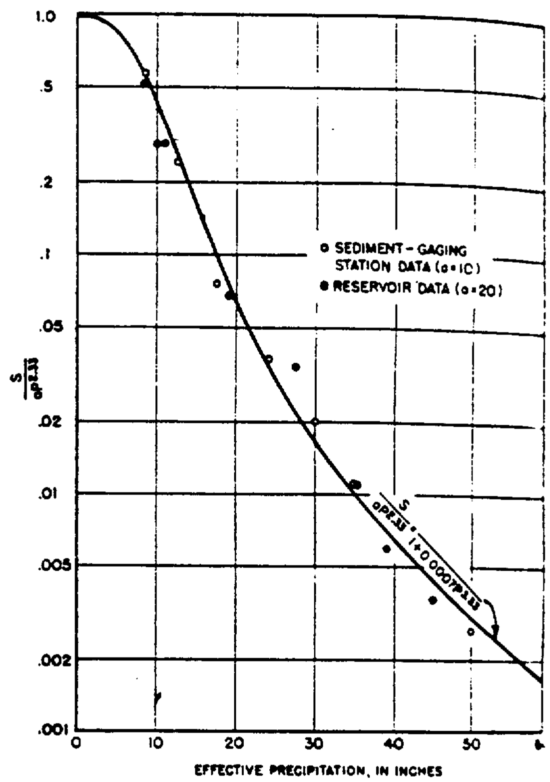

FIG. 5 – Decrease in relative sediment yield with increasing precipitation

TABLE 3 – *Variation in sediment yield associated with vegetative cover*

Effective precipitation	Vegetative cover[a]	$\frac{1}{1 + 0.0007\ P^{3.33}}$
inch		
7	Desert shrub	0.69
13	Desert shrub	0.23
20	Grassland	0.06
30	Grassland	0.017
40	Forest	0.006
50	Forest	0.003

[a] Associated with effective precipitation.

few of the vegetal data are in quantitative terms. *Musgrave* [1947] attempted a quantitative evaluation of relative erosion based on data collected at experimental watersheds in the Pacific Northwest. The results agree quite well with the results given in Table 3.

Cover	Relative erosion
Row crops or fallow	1.0 to 0.60
Small grains, grass hayland, crested wheat grass	0.05
Pasture, excellent condition, and forests	0.01 to 0.001

Formula (1) may be generalized as

$$S \propto R/V \qquad (2)$$

where R is annual runoff, and V is mass density of vegetation. In any given region the two factors operate separately; thus, sediment loads may vary with runoff depending on land use and vegetal conditions. For example, *Brune* [1948] shows that, for a given land condition in the Midwest, sediment yield increases with runoff, and that, for a given runoff, sediment yield varies enormously with percent of tilled land. The present study, however, treats of the broad climatic variation in which both runoff and vegetation are each uniquely related to effective precipitation.

With increasing precipitation, sediment yield varies as shown on Figures 2 and 3, but runoff increases as shown on Figure 1. The ratio between sediment yield and runoff is a measure of the concentration. This quantity is generally reported in parts per million (ppm) by weight and may be computed by dividing sediment yield in tons per square mile by runoff computed in tons per square mile. Figure 6 shows results of this computation for the data in Table 2. The concentration decreases sharply with increasing precipitation.

Annual precipitation, as indicated by the annual runoff, is used as the sole climatic measure. We have considered differences in precipitation intensity and its seasonal distribution only so far as these influences are reflected in the amount of annual runoff. For example, low precipitation regimes are characteristically more variable than those of humid regions [*Conrad*, 1946], and, indeed, the short-period excesses in intensity show up in the runoff. However, we repeat, as we wrote in our introduction, that although climatic influences on sediment are more complex, a good deal can be learned from consideration of the annual precipitation.

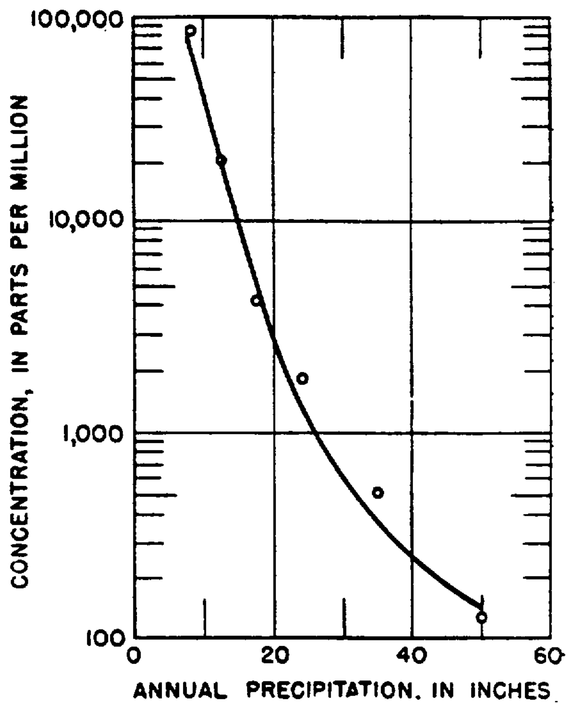

FIG. 6 – Variation of concentration with annual precipitation

Precipitation and vegetation—There can be no question of the highly significant effect of vegetation on erosion. For this reason, we have assembled information on climatic variation and vegetal bulk. The information on vegetal bulk contained in Table 4 was obtained mainly from published sources, ranging in reliability from carefully weighed quadrats to forest statistics and two estimates based on examination of photographs (for references, see Table 4). However, considering the more than 1000-fold variation in vegetal weight, as between desert shrubs to forests, great precision does not seem to be needed for the rough kind of study that seems possible at this time. Some of the data on vegetal weights were given directly in pounds per acre or equivalent. The forest data were obtained by dividing the reported cubic-foot volumes of saw-timber and pole-timber trees, given in millions of cubic feet for each state, by the respective forest area in acres. Unit weights of 45 lb/cu ft were used for hardwoods, 35 for soft woods, and 40 for mixed forests.

Table 4 also includes data on mean annual precipitation and temperature applicable to each case. The climatologic data were not usually given in the references cited and were obtained from U.S. Weather Bureau reports.

Figure 7 shows a plot of precipitation against

TABLE 4 - *Climatologic data and data on weight of vegetation*

Location	Type of vegetation	Mean annual precip.	Mean annual temp.	Weight of vegetation	Reference for vegetal bulk
		inch	°F	lb/ac	
Las Vegas, Nev.	Desert shrub	5	65	100	*McDougal* [1908, pl. 28]
Salt Lake Desert, Lakeside, Utah	Desert shrub	8	50	400	*McDougal* [1908, pl. 24]
Clark Co., Idaho	Sagebrush	12	40	891	*Blaisdell* [1953]
Fremont Co., Idaho	Sagebrush	12	40	1,273	*Blaisdell* [1953]
Coconino Wash, Ariz.	Grass	15	45	1,886	*Clements* [1922]
Burlington, Colo.	Grasses	17	52	2,251	*Weaver* [1923]
Phillipsburg, Kans.	Grasses	22	52	3,230	*Weaver* [1923]
Lincoln, Nebr.	Grasses	27	51	4,467	*Weaver* [1923]
Sandhills, Nebr.	Wheat grass	18	49	4,000	*Smith* [1895]
Lincoln, Nebr.	Grasses	27	51	6,224	*Kramer* and *Weaver* [1936]
Fraser forest, Colo.	Lodgepole pine	25	32	43,000	*Wilm* and *Dunford* [1948]
Rocky Mt. States	Conifers	28	38	54,000	*U. S. Forest Service* [1950]
Northeast Central States	Mixed forest	30	43	64,000	*U. S. Forest Service* [1950]
Northeast States	Hardwood forest	42	45	55,000	*U. S. Forest Service* [1950]
Southeast States	Mixed forest	51	60	48,000	*U. S. Forest Service* [1950]
Pacific Coast States	Conifers	64	47	150,000	*U. S. Forest Service* [1950]
Serro do Navio, Amapa Terr., Brazil	Hardwood forest	120		870,000	Field estimate by M. G. Wolman, 1956

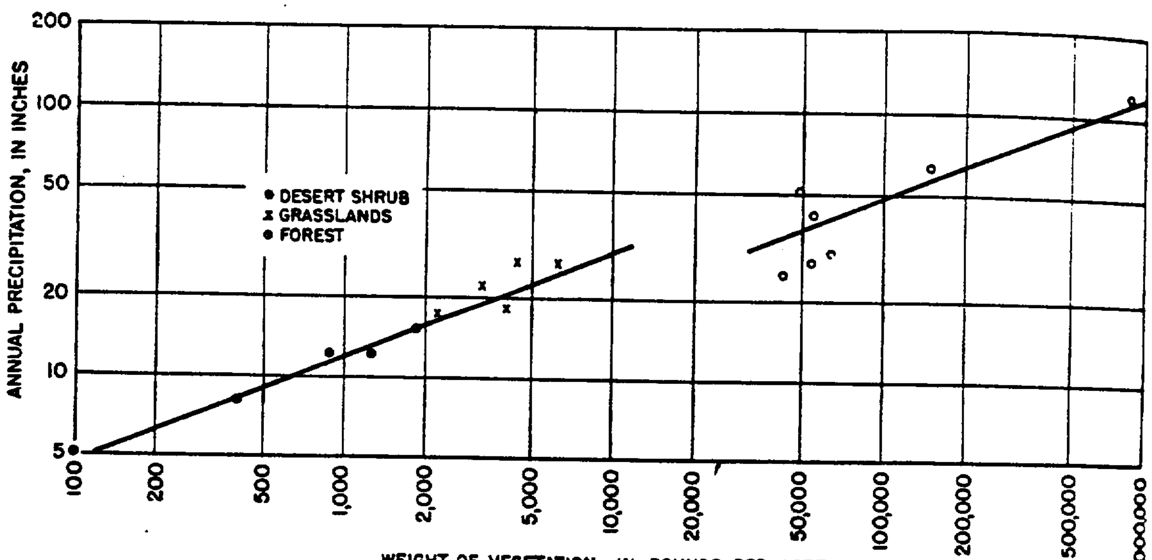

FIG. 7 - Relation between precipitation and weight of vegetation per unit area

vegetation weight. For the data available, the correlation seems quite high with a decided break between forest and nonforest types. The graph indicates that for equivalent rainfall, forests have about five times as much weight as grasses. With a longer life span, trees should understandably show greater total weight in place, although perhaps the annual growth (= annual decay for equilibrium) would be less than for grasses.

The seeming fact that desert shrubs are on the lower continuation of the line defined by the grasses seems anomalous. In arid and semi-arid regions the increase in vegetal bulk with rainfall rather simply reflects increasing opportunity for a greater number of plants, greater opportunity for each plant to reach maximum development for the species environment, and opportunity for growth of larger species. However, this does not explain the variation of forest bulk with rainfall greater than needed to satisfy optimum evapotranspiration demands for the climate. Forests are areas of water surplus in the climatic sense, yet vegetal density seems to vary with precipitation and temperature. Among the eastern states for example, the vegetal bulk per unit area in Maine and North Carolina are about the same. The lesser annual precipitation in Maine appears to be compensated by a lesser temperature; whereas, in North Carolina higher annual precipitation is compensated by a higher temperature. The forested areas of Washington, Oregon, and California have about the same temperature; the forest densities seem to follow precipitation as follows:

State	Precipitation inch	Vegetation lb/ac
Washington	80	177,000
Oregon	60	158,000
California	53	120,000

The variation in unit weight shown in Figure 7 is made up of two components, one due to variation in weight among different communities of the same vegetation type, and that due to variation in weight among different types. The latter is very likely the dominant factor in the relationship on Figure 5. Beyond a certain limiting precipitation, say that for which precipitation is adequate to meet all evapotranspiration requirements, differences in vegetal bulk may reflect not so much growth factors as differences in plant types or associations. The heavy vegetal bulk in the Pacific Northwest, for example, may be the reflection of a difference in plant type rather than a direct effect of precipitation on growth.

We are considering here only gross relations, ignoring rather important variations that might be due to differences in species, topographic setting, or moisture conditions that might favor or discourage growth. For example, there are patches of timber in the valley bottoms, in the Great Plains, with weight densities far exceeding that of the grasslands. The data used to define this relationship are admittedly crude and subject to bias. The forest statistics, for example, generally exclude bark, leaves, flowers, fruit, and most branches. The ratio of these parts to the whole tree decreases with age. The existing data are for stands in various degrees of maturity, and most existing data exclude roots. The ratio of roots to aboveground growth is variable among different kinds of plants and may be a large source of error.

Then again, although one might conceive that the maximum amount of plant material should theoretically be correlative with climate, other factors such as aspect, depth, and nature of soil are of major influence. Ideally, vegetal den-

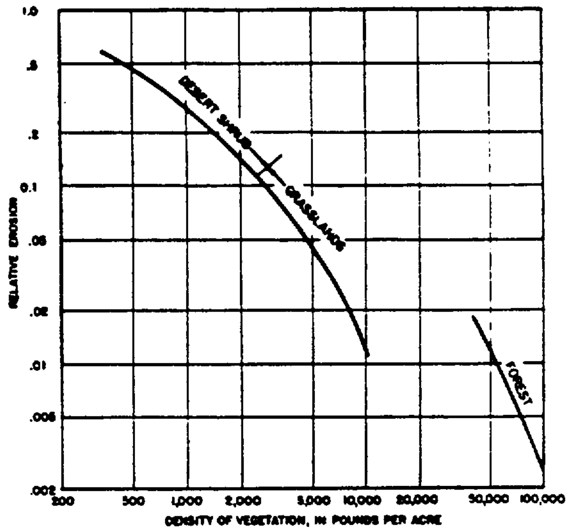

FIG. 8 – Relative erosion compared with density of vegetation

sities should be studied locally to arrive at a normal density for the regional climate. However, this kind of study would be beyond the scope of this discussion. Only the evident fact that vegetal densities are so variable over the range of climates experienced in this country makes it at all possible to use the existing data.

Interpreting the graph in Figure 5 as an indication of relative erosion associated with vegetation, as shown on Figure 7, the relationship shown on Figure 8 can be drawn. According to this graph, a relative change in vegetal density is effective on erosion throughout the climatic range, although the break between trees and grass suggests that per pound, grass is more effective in retarding erosion than trees.

Erosion and climate change—Examination of Figures 2 and 3 may be useful in visualizing not only variations in rates of net erosion between climatic zones in the United States but also the probable change in rates of erosion and stream activity during a climatic change.

Within the 0- to 12-inch precipitation zone an increase in annual rainfall would apparently be followed by an increase in erosion and vice versa; whereas, between about 12 to 45 inches of rainfall, erosion should decrease with increased precipitation. Above 45 inches of precipitation, erosion should remain about constant with increased precipitation, although Fournier's curve (Fig. 4) shows a marked increase in sediment yield above 43 inches of precipitation.

The direction of a change in sediment yield with changing rainfall appears to be dependent on the amount of precipitation before the change. For example, in a drainage basin located in a region with mean precipitation ranging from about 10 to 15 inches, a change either to a wetter or drier climate might result in a decrease in erosion, in the one case owing to increased density of vegetation and in the other case owing to a decrease in runoff. The above discussion assumes unchanged temperature, but perhaps a change in mean annual precipitation would be accompanied by an inverse change in mean annual temperature, further enhancing its effects.

A change in stream character and activity, with climate change, can probably be understood best in relation to the changes in the ratio of sediment load to discharge as precipitation increases or decreases. Referring to Figure 6, it is apparent that as annual precipitation decreases, the concentration of sediment per unit of runoff increases. This suggests quite strongly that, other factors being the same, the increasing sediment loads associated with increasing dryness will cause aggradation, in an amount depending on the magnitude of the climatic change. *Mackin* [1948, pp. 493–495] has summarized changes to be expected in stream activity with changes in load and discharge. In every case, an increase in load or decrease in discharge with constant load results in aggradation and vice versa.

The decrease in annual runoff with decreased precipitation will necessitate an adjustment of stream gradient and shape according to established principles [*Leopold* and *Maddock*, 1953], such that the width and depth of the channel should decrease and gradient increase. These changes are consistent with aggradation. Of course, an increase in precipitation might be expected to result in degradation as sediment concentration decreases. The increased discharge will result in an increase in channel width and depth and a decrease in gradient. Numerous exceptions to the above generalizations can be cited, especially when glaciation, deforestation, cultivation, or a change in base level become important.

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