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Title: MORPHOMETRIC PROPERTIES OF NIVATION HOLLOWS ON HART MOUNTAIN, LAKE COUNTY, OREGON

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Charles L. Rosenfeld

Hart Mountain is a basaltic fault block mountain in the semi-desert region of the northern Basin and Range province in south-central Oregon. Geomorphic processes associated with lingering snowpatches have formed nivation hollows, which are small scale depressions in the hill-sides. The lingering snow in the hollows prohibits shrub growth. Bedrock scarps, present in some of the hollows, show indications of chemical alteration. Rills are present below most of the hollows, indicating that surface runoff from these sites occurs.

Average hillslope, which controls the shear stress placed on soil particles, is statistically related to morphometric attributes defining the size and angles of the hollows. Simple linear regressions and the nonparametric Kendall's rank correlation coefficient (τ) and Theil's C test for the regression line slope suggest

that average hillslope is directly related to the morphometric attributes of the hollows.

Heat transfer controls the areal distribution and duration of snowpatches. A relative insolation factor and elevation are taken as surrogates for heat transfer. These surrogates are likewise correlated with the morphometric attributes of the hollows. Both the elevation and the relative insolation factor suggest an inverse relationship between heat transfer and the size of nivation hollows.

The hollows on Hart Mountain appear to have been formed by accelerated nivation processes during the Pleistocene and are currently being modified by less intense nivation.

Morphometric Properties of Nivation Hollows on Hart Mountain, Lake County, Oregon

by

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MORPHOMETRIC PROPERTIES OF NIVATION HOLLOWS ON HART MOUNTAIN, LAKE COUNTY, OREGON

I. Introduction

"Nivation" is a term which describes a group of geomorphic processes which are related in a complex and little understood manner to lingering or perennial snowpatches. The term "nivation" was introduced in 1900 by Mathes and a number of studies have addressed the processes and landforms of nivation since that time. While these studies have examined nivation in a variety of climatic regimes, none of the studies were undertaken in the high desert regions of the Basin and Range. Few articles describe nivation landforms in a quantitative manner, and none have attempted to link morphometric attributes of the landforms to process quantitatively.

The specific problems addressed in this study of nivation in the high desert region of the northern Basin and Range are the following:

(1) What is the extent to which snowpatches affect landform development in the study area?

(2) Do relationships exist between climatic forces and the morphometric attributes of nivation landforms?

(3) Is nivation presently active in the study area, or are the landforms relicts of the Pleistocene?

(4) Has the intensity of nivation changed during the Holocene?

A. Selection of Hart Mountain as the Study Area.

Field reconnaissance during June, 1979 revealed well developed nivation hollows on Hart Mountain occupied by snow, while surrounding areas were snow-free. This suggests nivation is active in this area. However, many periglacial landforms (stripes, polygons, frost heaved blocks, etc.) are evident in this area as well as in many other areas of the northern Great Basin, and well known changes in the climatic regime of this region are evidenced by pluvial lake shorelines and associated landforms (Gilbert, 1890; Flint, 1971; Bentley, 1974; Weide, 1974; Embleton and King, 1975 v. 1). The presence of relict periglacial and pluvial landforms suggests a distinct possibility of changes in the climatic regime during the Quaternary which could result in changes in the intensity of nivation.

Hart Mountain provides an excellent location for this study because it is a tilt block mountain of nearly homogeneous structure and lithology; hence it seems likely that the major influence on the development of the nivation landforms is microclimatic variations.

Another factor which makes Hart Mountain a good location for this study is the absence of glacial landforms such as glacial troughs, cirques, etc. which may obscure the influence of paleo-nivation. Field work for this study was undertaken during the summer and autumn of 1979.

B. Literature Review.

Controversy remains concerning the role of snow in landform development. Several authors suggest enhanced physical weathering caused by increased freeze-thaw activity is the dominant nivation process (Mathes, 1900; Russell, 1933; Embleton and King, 1975 v. 2). The presence of snow provides the water necessary for freeze-thaw action and meltwaters remove the weathered debris.

There is debate over whether or not a snowpatch can create a change in the microclimate of its vicinity which causes an increase in the number of freeze-thaw cycles; along with the presence of water, the number of freeze-thaw cycles determines the effectiveness of mechanical weathering. Gardner (1969) shows that the presence of snowpatches in the Lake Louise area of Alberta, Canada results in a general lowering of temperatures behind the snow relative to temperatures higher on the backwall and presents data that indicate more frost alternation days (a day when temperatures cross the freezing point) occur behind the snowpatch than above it. Hence, the snowpatch effects a change in the microclimate which provides an enhanced environment for freeze-thaw weathering.

However, Thorn (1976) tested the hypothesis that nivation causes increased freeze-thaw cycles in the Colorado Front Range by placing recording (at two-hour intervals) thermistors near snowpatches and at snow-free sites. The results of the Thorn study show no significant differences in the number of freeze-thaw cycles between the two sites.

From these two studies, it appears that under certain circumstances, snowpatches can cause microclimatic differences which enhance physical weathering, but this is not a necessary process associated with nivation. However, since the snow provides water to the bedrock, snowpatch sites may be more effective at exploiting changes in temperature which cross the freezing point caused by larger scale climatic fluctuations.

Controversy remains concerning the role of chemical weathering in nivation, as well. It is well known that water near the freezing point can hold an increased amount of CO_2. Williams (1949) shows that CO_2 concentrations are more than twice as high as normal and O_2 concentrations are significantly higher than normal in air samples taken from snowpatches in the Snoqualmie Pass region of the Washington Cascades. The CO_2 can be absorbed by meltwaters percolating through the snow forming carbonic acid in solution and increased oxygen may result in higher amounts of oxidation of certain minerals. Williams then suggests that since carbonic acid is a potent agent for dissolving mineral matter in rocks, chemical weathering is a significant process under snowpatches.

Embleton and King (1975 v. 2), in critiquing Williams' study, point out the following weaknesses: (1) Williams did not record the type of bedrock underlying the snowpatches observed; (2) only chemical processes associated with water containing CO_2 and O_2 are addressed; and (3) the problem of kinetics of reactions at such low temperatures is not discussed. Embleton and King suggest that chemical weathering is probably not important except possibly in calcareous regions. Another consideration is that the decay of organic matter is often the major contributor of CO_2 in areas where chemical solution is highest--pCO_2 (partial pressure of CO_2) may be increased 10 to 100 times by vegetation decay (Holland, 1978). Since the rate of decay is decreased at lower temperatures, chemical weathering is undoubtedly retarded near snowpatches compared to warmer areas.

However, Thorn (1976) analyzed weathering rinds on syenite stones in snowpatches and on snow-free sites and concluded that chemical weathering is indeed increased by the presence of snow. There are also several recent studies which show conclusively that chemical solution and precipitation are active subglacial processes (Ford, et. al., 1970; Hallet, 1976), but one should not directly correlate these to snowpatches because of the high pressures under glaciers. The thermodynamics of subglacial reactions are undoubtedly much different than for reactions under snowpatches. However, these studies of subglacial solution do show that chemical weathering can be important at low temperatures.

As in the increased physical weathering attributed to nivation, the presence of water on snowpatch sites, and the absence of water on the surrounding snow-free areas, may well be the critical factor if chemical weathering is indeed increased by nivation.

In light of the recent evidence for chemical weathering under snowpatches discussed above, the effectiveness of snow as protection for underlying materials from weathering processes appears to be in doubt. It has been suggested that the centers of hollows undergo decreased physical weathering because the snow insulates the bedrock from frost alternation, while margins of snowpatches experience increased disintegration (Russell, 1933; McCabe, 1939; Embleton and King, 1975 v. 2). Lewis (1939), however, contends that material below the snowpatch undergoes increased freeze-thaw activity. The effectiveness of freeze-thaw action below snow is undoubtedly a function of the depth of snow cover, as Embleton and King suggest.

Although Mathes (1900) suggests that the material produced by weathering near snowpatches is carried away by meltwaters which percolate into the ground in his study of the Bighorn Mountains in Wyoming, several subsequent publications contend that surface runoff of meltwaters and solifluction are the two significant mechanisms for debris removal (Ekblaw, 1918; Lewis, 1939; Washburn, 1973). Rills eminating from snowpatches are conspicuous features of many nivation landforms, although they are not always present. Solifluction lobes are also characteristic of many areas where nivation is active, especially in areas of permafrost (Embleton and King, 1975 v. 2).

Costins, et.al. (1964, 1973) show that slow movement of snow in snowpatches can play a direct role in the degradation of a landscape. The authors observed abrasion of the bedrock by movements of stones on Mount Twynam in the Snowy Mountains of Australia. Measurements of forces generated by snow movements were taken by placing rods of varying diameters through the snow into the bedrock. The rods were calibrated to stresses in the laboratory. The authors conclude from these measurements that the forces generated by slow movement of the snow are great enough to cause the movement of stones.

Rockie (1951) indicates that land use practices can influence nivation. He suggests that clean cultivation in the Palouse region of Washington and Idaho leads to the formation of snowdrifts (as snow is not trapped by vegetation); the meltwaters cause rilling, and in many cases, complete removal of the plow layer.

The primary landform resulting from snowpatches is the nivation hollow or niche (Embleton and King, 1975 v.2), which is a depression on a slope with a floor less steep than the overall slope, often covered with colluvium, and a backwall which is steeper than the overall slope and is often a bedrock scarp. Several authors (Ekblaw, 1918; Lewis, 1939; Henderson, 1956; and St. Onge, 1969) provide morphologic classification schemes for nivation hollows and snowpatches and provide hypotheses in an attempt to explain the formation of each type noted. Lewis' classification (perhaps the most widely cited) describes three types of hollows:

(1) Transverse--which have their major axes perpendicular to drainage lines. These result from frost shattering of bedrock with subsequent removal of weathered debris by meltwaters;

(2) Longitudinal--which are elongate downhill and occur where snow covers stream courses. Frost action on the banks provides fines to the stream course. These fines are removed by fluvial action;

(3) Circular-- which are attributed to frost action and erosion by meltwaters at the margins of snowpatches.

Ekblaw (1918) provides a similar classification of snowdrifts in which "dome-shaped" snowdrifts result in Lewis' "circular" hollows; "piedmont" drifts correspond to "transvers" niches; and "wedge" drifts form "longitudinal" hollows.

St. Onge's (1969) classification is also similar to that of Lewis. "Nivation hemicircles" being "circular"; "nivation hollows" correspond to "longitudinal"; and "nivation ledges" with the "transverse" category. St. Onge concludes that the type of underlying bedrock is the main controlling factor of the type of hollow that forms.

Henderson (1956) also classifies hollows on the basis of morphology. This scheme makes the distinction between niches that result solely from nivation (simple nivation hollows), and those that are polygenetic, generally involving subsequent mass wasting, in origin (compound nivation hollows).

Measurements of morphometric attributes (generally angles of floors and backwalls) are provided in certain publications (Cook and Raiche, 1962; Henderson, 1956; and Shaw and Healy, 1977), but no attempt is made by these authors to quantitatively relate these measurements to process. The Cook and Raiche article provides a quantitative description of hollows, while Henderson compares measurements of the hollows in the different categories of his classification. Shaw and Healy present angles of backwalls as evidence that slopes they studied are not the result of mass wasting alone since they exceed the material's angle of repose.

Russell (1933) contends that while bedrock affects the morphology of nivation hollows, the shape depends:

> even more on (1) the steepness of the slope on which they have been formed and (2) the length of the season during which they are occupied by snow (p. 932).

Russell suggests that the depth of the hollows are directly related to the steepness of the slopes on which they rest. The author also states, "If snow remains throughout the year, the depressions tend to become elongate horizontally" (p. 933).

Snow presence may also be critical to the formation of other periglacial landforms. White (1972) suggests snow provides weight necessary for packing, while meltwaters remove fines during the development of boulder pavements. Protalus mounds deposited over 300 m from the cliffs which provide the material can result from boulders being transported across snow surfaces (Yeend, 1972). Demek (cited by Embleton and King, 1975 v. 2) contends nivation is necessary for the development of cryoplanation terraces, as well.

C. Description of the Study Area.

Hart Mountain is a fault block mountain located in the southeastern part of Lake County, in south-central Oregon (Figure 1). This area, in the northwestern portion of the Basin and Range, is considered to be in a semi-desert climatic regime (BSk in Koppen's classification) and the natural vegetation is classified as shrub-steppe

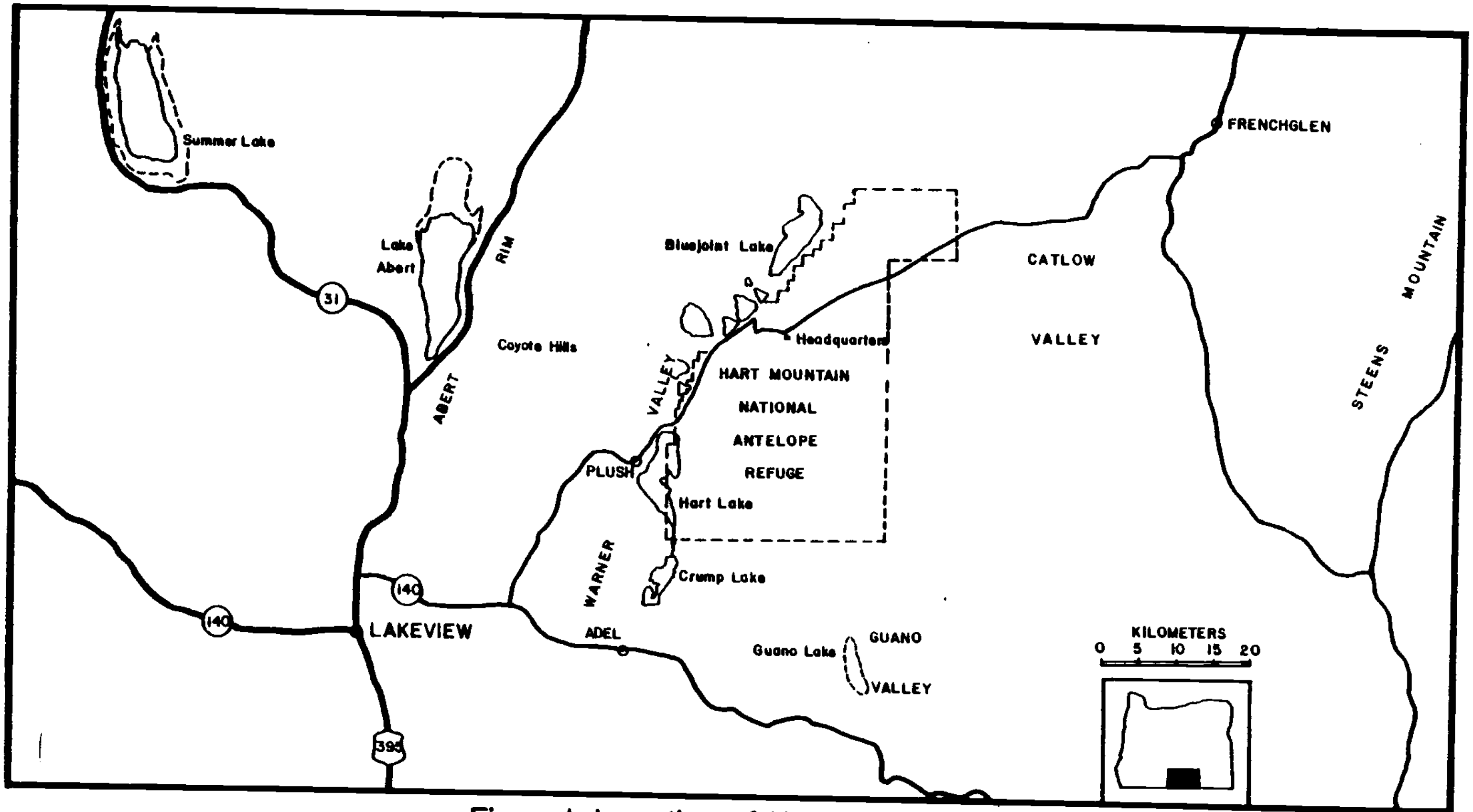

Figure I. Location of Hart Mountain

(Franklin and Dyrness, 1973). Hart Mountain is situated between Warner Valley to the west, Guano Valley south and to the east, and Catlow Valley to the east.

1. Landforms. The topography of the Hart Mountain area is dominated by two major influences (Figure 2). The most dramatic of these is the geologic structure of the region. Hart Mountain is one of several very large fault block mountains which strike SW-NE characteristic of the northern Basin and Range province. The steep west-facing scarp of the fault block rises abruptly from the floor of Warner Valley dominating the regional topography, with a maximum relief of 1084 m. The backslope of Hart Mountain dips eastward at angles of 5-10^{o}; generally, the dip decreases away from the scarp.

The basic outline of the fault block remains essentially intact with only minor amounts of fluvial dissection, except for several gorges cut along faults on the scarp which exhibit local relief of several hundred meters. Small scale faults, trending NW-SE, have also influenced the topography of the area; small, intermittent lakes occupy grabens formed by these small scale faults (Weide, 1974). The tectonic activity evidenced by the faults is considered to be very recent due to the lack of dissection and because hot springs and geothermal areas are common (Rosenfeld, 1979). Weide (1974) indicates that this area

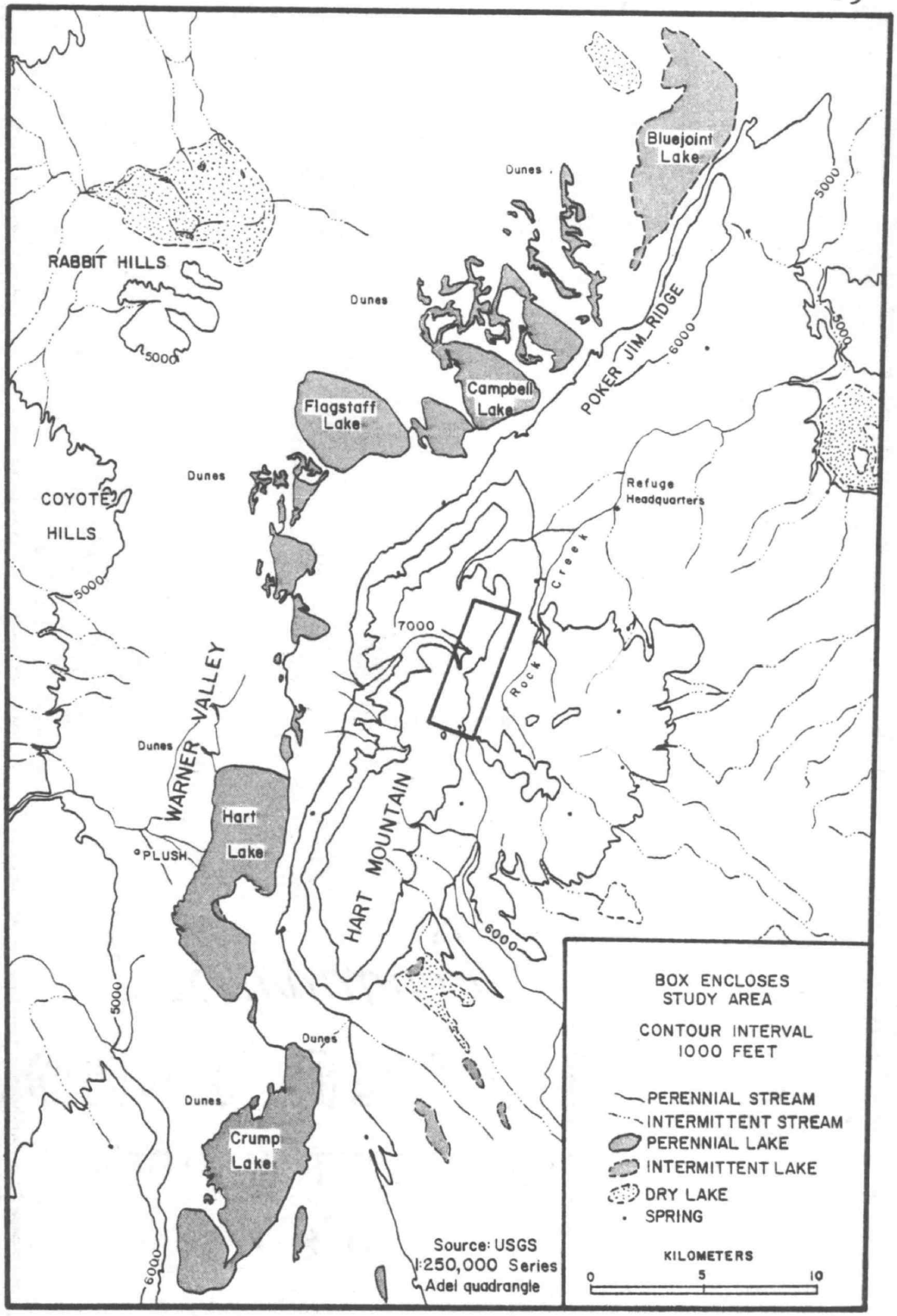

Figure 2. Location of study area

has been active throughout the Pleistocene and up to the present.

The second major influence on the landforms of this area of the Basin and Range is the changing climatic regime--of special importance is the cooler and wetter climates of the Pleistocene. Pluvial lakes were characteristic of the Pleistocene in much of the Great Basin and the Hart Mountain area is no exception (Gilbert, 1890; Flint, 1971; Weide, 1974). Pluvial Lake Warner occupied Warner Valley just east of the scarp; Hart Lake and numerous other smaller intermittent lakes presently occupy parts of the valley. The pluvial lake is responsible for a number of landform types in the valley including a well developed sequence of strand lines, which mark former lake levels which were near stable for extended periods, deltas, and dune fields, which become active in dry periods when the vegetation which stablizes them dies (Weide, 1974).

Ancient mass wasting features that developed during the pluvial are evident on the scarp. Weide (1974) noted six major landslides ranging in size from about 3 to 18 km^2. Talus slopes are common features of the scarp, while alluvial fans are present on the western side of Warner Valley.

Relict periglacial features, present in abundance on Hart Mountain, attest to a colder climatic regime in the past. According to Weide (1974), stone polygons and stripes are best developed on the eastern dip slope of Poker Jim Ridge (Figure 2); Weide cites evidence which supports a periglacial origin for these features. Block streams and apparent frost heaved blocks are also present on the central part of the mountain.

The Hart Mountain fault block is composed of nearly homogeneous volcanic rocks associated with the Columbia Plateau basalts. The surface stratigraphic sequence is composed of about 600 m of thin (3-15 m) flow units consisting of medium grained, olivine-rich porphorytic basalt (Weide, 1974). This sequence can be correlated from Abert Rim through Hart Mountain to Steens Mountain--a distance of over 130 km.

2. Climate and hydrology. The regional climate of the Hart Mountain area is in large part controlled by the Cascades which shield the moderate, moist westerly winds of the Pacific from reaching the interior of Oregon (Sterns, 1960; Lahey, 1979). This shielding from the Pacific air masses results in very low precipitation as it places Hart Mountain in a rain shadow. The lack of moisture allows greater temperature extremes to be realized since more heat can be re-radiated back to space. Table I shows the large seasonal differences in the monthly mean temperatures at the Hart Mountain National Antelope Refuge headquarters. Daily temperature ranges of 30-40° F are common during the summer

TABLE I. MEAN TEMPERATURES AND

PRECIPITATION AT HART MOUNTAIN REFUGE, 1941-1970

Temperature, °F		Precipitation, inches
January	27.3	0.92
February	30.9	0.72
March	33.0	0.90
April	40.1	0.86
May	47.3	1.84
June	53.7	1.72
July	62.6	0.36
August	61.3	0.43
September	54.9	0.48
October	45.9	0.92
November	36.1	0.94
December	29.9	0.99
Annual	43.6	11.08

Source: NOAA, 1978a

months, while diurnal ranges of 15-20° F often occur during the winter (NOAA, all cited).

In general, precipitation amounts increase with elevation in south-central Oregon, but the Hart Mountain refuge station is located on the backslope of the fault block in a local rain shadow and is drier than would be expected based solely on its elevation (Weide, 1974). Table I also shows monthly precipitation averages at the refuge station. Individual summer months which have high positive anomalies of rainfall generally receive most of the excess on one or two days of relatively intense storm activity. For example, the month of April, 1978 received 5.44" over normal. Most of this (4.95") fell on three days (4/1; 4/26; and 4/27) (NOAA, 1978b). The months of June and October, 1975 show similar patterns; both have excess precipitation of 2.50" or more and at least 2.00" fell on one day of each month (NOAA, 1975a, 1975b).

Hart Mountain is interesting hydrologically because there are many perennial streams, which are generally uncommon in south-central Oregon. These perennial streams often originate at springs, which are common.

Changes in the amount of annual moisture received are common and are evidenced by changes in the lake system of Warner Valley. Weide (1974) suggests that during wet periods the southern lakes drain northward into ephemeral lakes which subsequently dry up in dry periods.

However, Keen (1937) shows from tree ring data that while short term changes in precipitation are common, there has been no general trend to a drier or wetter climate in south-central Oregon in the last 650 years; and Keen could find no systematic variation in the moisture regime.

3. Vegetation and soils. Sagebrush communities dominate the vegetation on Hart Mountain. *Artemesia tridentata*/*Agropyron spicatum* (big sagebrush/bluebunch whaetgrass) is the most common community on xeric sites, although *Artemesia tridentata*/*Festuca idahoensis* (big sagebrush/ Idaho fescue) is generally found in association with more mesic sites in this region (Franklin and Dyrness, 1973; Frenkel, 1979). *Artemesia arbuscula* (low sagebrush), *Sarcobatus vermiculatus* (greasewood), and *Chysothamnus nauseosus* and *C. viscidiflorus* (rabbitbrush) are other common shrubs. Important grasses in this region include *Stipa occidentalis* (western needlegrass) and *Elymus triticoides* (bluejoint wild rye) (Weide, 1974).

Ceanothus are found uniquely situated above some, but not all, of the nivation hollows--these are probably associated with differences in moisture availability characteristic of the hollows. Tree species are also restricted to certain habitats. Scattered *Juniperus occidentalis* (western juniper) are confined to higher slopes near the crests of fault scarps (Weide, 1974), while deciduous trees, including *Cercocarpus* (mountain mahogony) and

Populus (aspen), are found along perennial streams at middle elevations (1500-1800 m).

Mollisols and aridisols are the dominant soil orders in south-central Oregon (Franklin and Dyrness, 1973; Frenkel, 1979) Weide (1974) indicates that aridisols are the dominant soil order in the Hart Mountain area, covering approximately 60% of the region. Aridisols are characterized by having thin, light colored surface horizons, indicating low amounts of organic matter, and have poor water retention.

Mollisols are characterized by dark colored surface horizons (top 25 cm) which have greater than one percent organic matter and greater than 50% base saturation. Weide indicates substantial areas (25%) have mollisols; while vertisols, which develop cracks upon drying and have slickensides, have developed on lake beds in the Warner Valley; and inceptisols have formed on recently deposited alluvium.

II. Morphology of Nivation Hollows

Snowpatches lingering into June were present in abundance in 1979 but those occupying the best developed hollows were located on the east side of the western divide of the Rock Creek drainage basin (Figure 2, p. 13). The nivation hollows along this ridge were studied in greater detail in July, 1979.

A. Vegetation-Morphology Relationships.

One of the most apparent characteristics of the hollows is the difference in vegetation density between them and the surrounding hillslopes. Most of the niches completely lack woody vegetation while Artemesia shrubs dominate the adjacent areas. Also, Ceanothus are conspicuous above some of the hollows while absent at others. Mairs (1977) found that the length of snow cover duration influenced vegetation communities on Steens Mountain and makes the following general comments considering the effects of the micro-environment associated with snow on plant communities:

> Generally, plants which require a longer growing season are relatively intolerant of snow cover, but if present, must also be able to withstand early spring exposure with concommitant frost, and subsequent summer drought. These plants are found near the periphery of snowbanks. Plants found near the center of a snowbank are typically intolerant of extensive frost exposure and summer drought (p. 51).

Slope breaks, while discernible, are often not sharp. The breaks in woody vegetation are located inside the slope breaks, suggesting that nivation intensity may have decreased in recent time, or that environmental conditions near the margins of the hollows are not as prohibitively restrictive to shrub growth.

B. Bedrock Morphology.

The hollows which have sharp slope breaks are also characterized by having bedrock scarps. These scarps, rather than being characterized by fresh, angular fractures, show indications of extensive chemical weathering. Chemical alteration throughout most of the smaller fragments is present and occurs to several centimeters on boulders and on the scarps. Weathering of the basalt is evident on bedrock fragments and frost heaved blocks located away from the hollows, as well, so that resolving the question of nivation-enhanced chemical weathering on Hart Mountain requires further study.

The presence of altered bedrock on these scarps suggests that physical weathering, which often produces fresh, angular fragments, is not a dominant process at present. Previous studies indicate that bedrock scarps which are present in nivation hollows are generally characterized by frost weathered rock (Gardner, 1969; St. Onge, 1969; Shaw and Healy, 1977). The bedrock scarps on Hart

Mountain were probably produced by intense physical weathering and debris removal during the colder periods of the Pleistocene, and have subsequently undergone chemical alteration.

At one of the ten hollows studied, undercutting of the bedrock scarps was evident, indicating that a process such as described by Shaw and Healy (1977) may have occurred. These authors suggest that in Antarctica, snow against the wall of a scarp is more susceptible to melting due to increased angle, and hence, increased solar loading. The meltwater produced aids the process of frost shattering. The slope is then undercut until failure occurs, at which time new snowdrifts form upslope and the bedrock is progressively cut back in a step-like fashion, with debris being deposited over the downslope steps resulting in a fairly smooth slope.

While undercutting and failing could possibly have resulted in hollow formation on Hart Mountain, evidence in this study suggests that the size of the hollows is inversely related to the amount of insolation received at a given site (Chapter V). This indicates that larger hollows form (i.e. nivation is more intense) at sites which receive less insolation rather than more, as Shaw and Healy suggest.

C. Drainage and Debris Removal.

Rills formed below most of the hollows. These rills generally converge within a short distance, although at one site, the rills do not converge until they are several hundred meters downslope. This occurs at the site of the largest hollow (864 m wide and 126 meters long) and is probably because several rill systems are required to drain a hollow of this size.

The presence of rills indicates that surface runoff from meltwaters, or due to intense summer storm activity, is an important debris removal mechanism operating in these hollows. Solifluction (or gelifluction), which is the second important debris removal mechanism of nivation, is often advocated as a major process in hollows underlain by permafrost (Embleton and King, 1975 v. 2). Since permafrost is not currently present on Hart Mountain, and since this area experiences relatively high summer evaporation potential,[1] soil saturation conditions necessary for solifluction would not be expected. Field observations support this conclusion. Gelifluction may have been a significant debris removal mechanism in the Pleistocene.

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1. Weide (1974) estimates average evaporation on the Warner Valley floor is approximately 100 cm between May and October.

D. Snow Characteristics.

Snow was present in three of the hollows examined in July. Approximately 50 cm in from the lower margin of site 3, total snow depth was six cm with ice from the soil level up to four cm and meltwater saturating the ice to one and one half cm. At the center of the hollow, total snow depth was 24 cm with ice from the ground level up to four cm, saturated to about one half a cm. Approximately 50 cm from the upper margin, total snow depth was five cm with ice up to two and a half cm and only a trace of meltwater.

At site 10, the snow surface was characterized by a sharp break in slope near the center. The upper portion sloped at 22° and the lower section sloped at 38°. The hollow's floor slopes at 26° and its backwall slopes at 39°. The floor and backwall of this hollow are separated by a sharp slope break. All slopes were measured with a Suunto clinometer.

The soil downslope from the snowpatches was saturated for several meters, but not so much as to induce solifluction. This soil can be expected to dry out rapidly after the snowpatches have completely ablated due to high potential evaporation.

E. Micro-Geomorphic Features

Micro-geomorphic features which form under snow were present in several, but not all, hollows. These include sub-nival channels, which are interconnecting ridges several centimeters high and a few centimeters wide, and nivation terracettes, which are small scale breaks in slope and the root mat which follow the contours. Sub-nival channels form by the meltwater percolating through the snow and refreezing at the snow/ice-soil interface. The refreezing results in expansion and the forcing of material to either side, forming the small scale ridges. Nivation terracettes result from basal sliding of the snow.

The micro features were present on hillslopes outside the hollows, also, indicating that nivation is active in areas which do not exhibit the specific erosion landforms normally associated with nivation.

III. Morphometric Attributes of Nivation Hollows

A. Angle Morphometry.

Overall slopes (θ) and the slope angles of the floor (ω) and backwall (ϕ) (Figure 3) were measured with a Suunto clinometer. The overall slope is taken as the slope of the straight line connecting the top of the hollow to the bottom at the middle. This is not necessarily a reconstruction of the hillslope before nivation started, but does represent the original average hillslope.[2]

The floor and backwall angles are directly correlated and significant at $\alpha = .01$.[3]

The angles on Hart Mountain are generally somewhat steeper than those at Resolute, NWT reported by Cook and Raiche (1962). They report overall hillslopes of 15-18°, backwalls of 19½-23½°, and floor angles between 3½ and 7°. Henderson (1956) reports angles of hollows near Knob Lake, Quebec which are closer to the hollows on Hart Mountain. Most of the backwall on the Knob Lake hollows are between 30 and 35° with a maximum of 45°. Overall hillslopes are 10-22°, but, again, floor angles are much lower, being 3-5°.

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2. The means, medians, standard deviations, and ranges for the slope, backwall, and floor angles are given in Table II. Site values for all attributes are presented in Appendix I.
3. Floor = -2.08 + 0.74(backwall); $t = 5.21$; $r = .8789$.

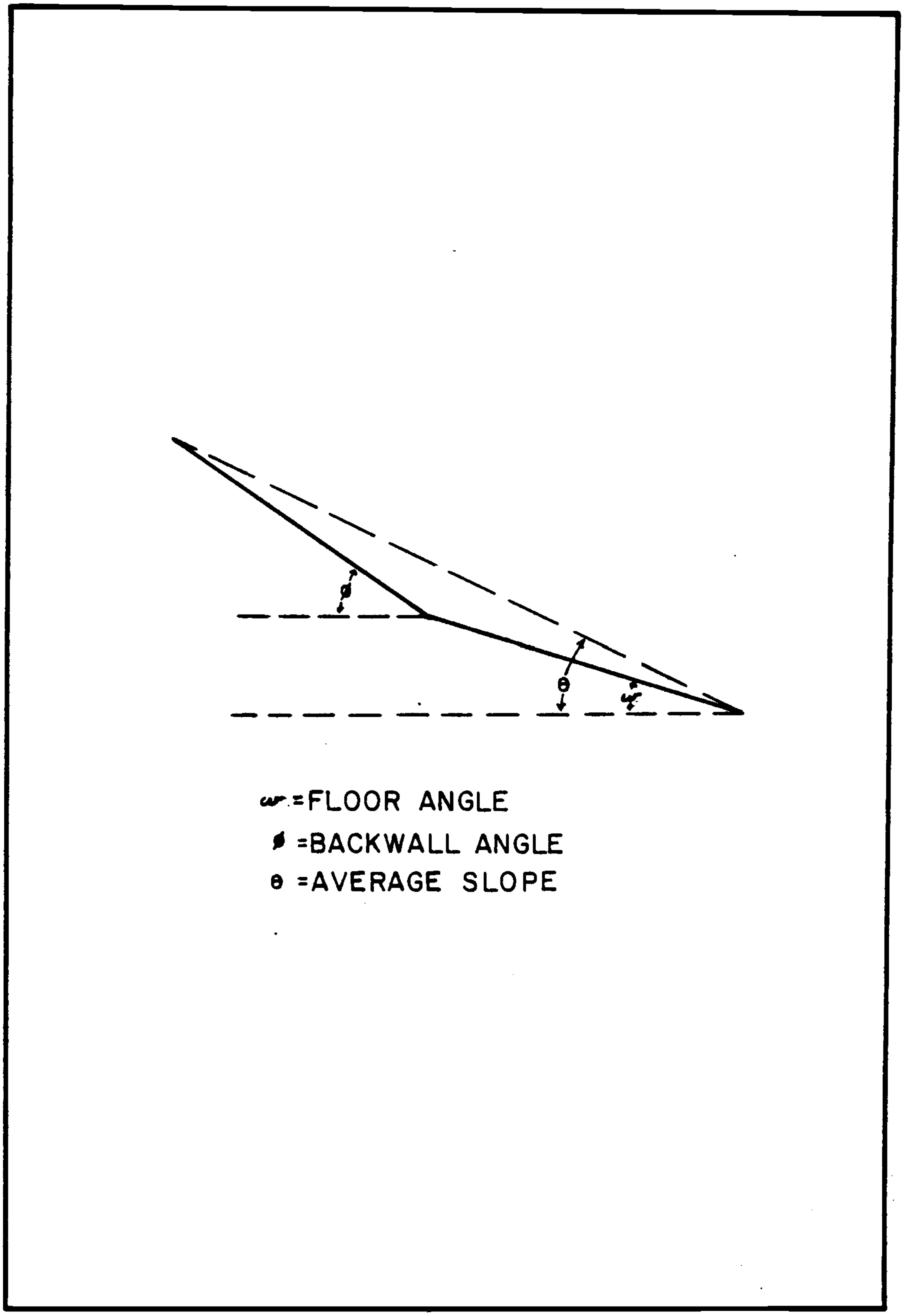


Figure 3. Angle Morphometry

TABLE II. ANGLE MORPHOMETRY

	Slope	Floor	Backwall
Mean	25*	20	30
Median	26	19.5	27.5
Standard Deviation	4.9	5.1	6.0
Range	19-33	13-28	21-39

* All values are in degrees.

Cook and Raiche (1962) indicate the angles between the plane of the floor and the plane of the backwall are in every case nearly 165°. The angles between the floors and backwalls of the hollows on Hart Mountain have a somewhat higher mean of 170°. These angles ranged from 167 to 175°.

Aspect azimuths, corrected to true north and taken at the center of the hollows with a Brunton Pocket Transit, ranged from 36° to 160° (Figure 4). Not all hollows present on Hart Moutain were studied, so nivation may be important on sites which are not east facing, but well developed west facing hollows were not apparent from field observations. The mean aspect is 101° and the median is 99°; most hollows lay in the SW quadrant. This is because the ridge along which most of the hollows studied is oriented SW-NE. No hollows are present on the west side of this ridge, but the west side is of a much lower slope than the east side.

B. Size Morphometry.

Lengths (L) and widths (W) were measured from 1: 20,000 scale black and white aerial photographs available at the Hart Mountain Refuge headquarters. Since stereo pairs were not available, the hollows were delineated based on changes in texture and pattern which were caused by vegetation differences between the hollows and surround-

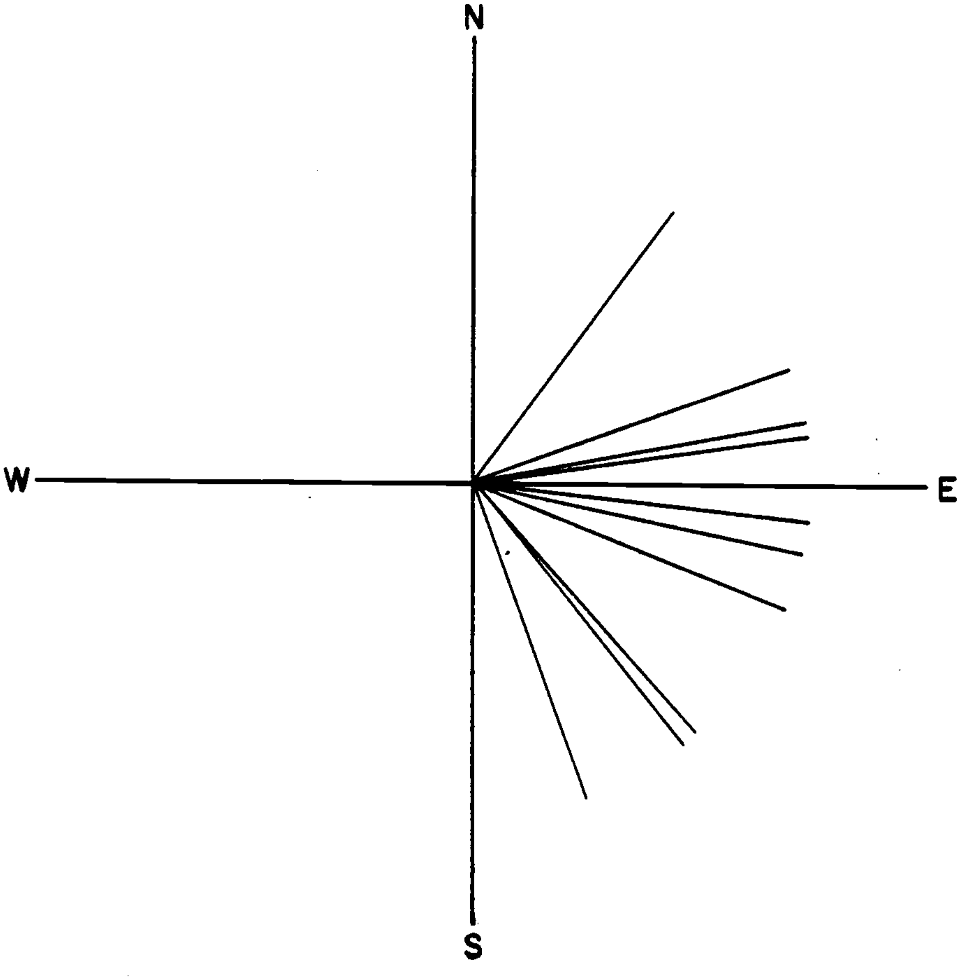


Figure 4. Aspects of Nivation Hollows

ing hillslopes. Also, the hollows are at different elevations which leads to scale differences on the photos. While this undoubtedly resulted in some inaccuracy, the differences in the sizes of the hollows are quite large (Table III), and therefore, the measurements should approximate relative sizes of the hollows.

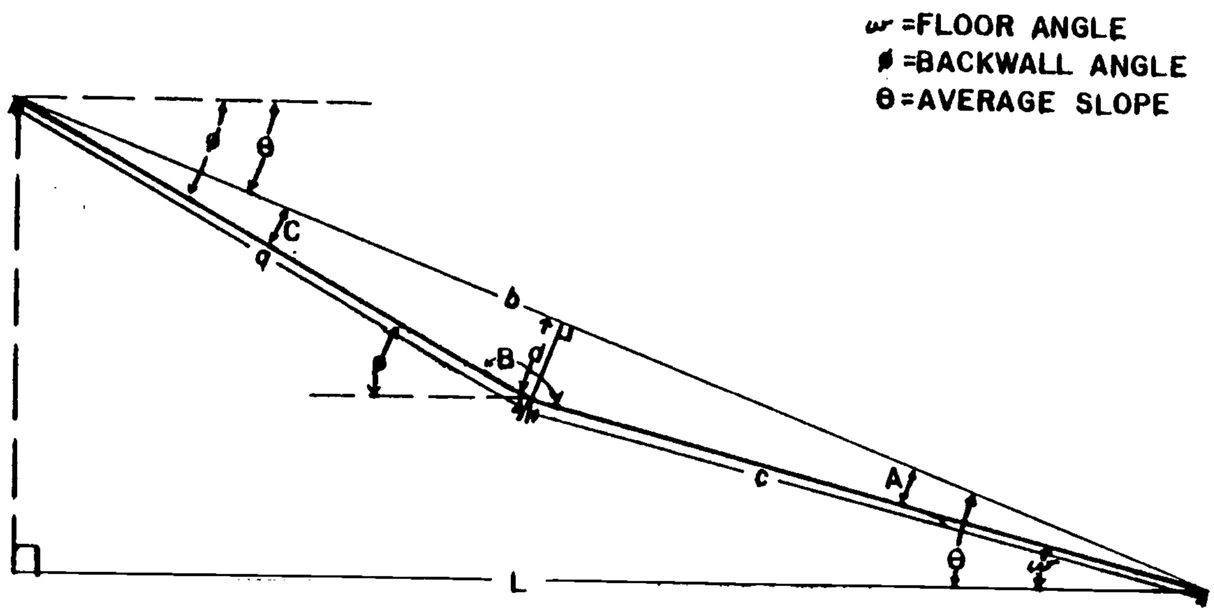
Widths refer to the distance parallel to contours and lengths are the distance along a horizontal line perpendicular to the contours rather than along a line oriented at the actual hillslope since the hollows were measured from the aerial photographs. Most of the hollows are transverse, so widths generally exceed lengths.

Depths (d) of the hollows were computed from slope, floor, and backwall angles and from the horizontal lengths measured from the air photos. Figure 5 shows the angles and formulas used to compute the depths.

Other morphometric attributes used in this study include length times width (L•W) and width divided by length(W/L). The product L•W is not a true measure of the hollow area since the hollows are irregularly shaped, but this does give a first approximation to the area, and probably a fairly accurate relative size of the hollows. The ratio W/L is a measure of the degree to which the hollows are elongate. Russell (1933) contends that hollows which retain snow for most of the year become increasingly elongate. This relationship does not hold up on Hart

TABLE III. SIZE MORPHOMETRY

	Mean	Median	St. Dev.	Range
W (m)	231	148	244	46-864
L (m)	63	54	24	46-126
L·W (m^2)	19,144	7,983	32,049	2116-108,864
d (m)	2.8	2.3	2.2	0.9-8.5



$A = \theta - \omega$

$C = \phi - \theta$

$B = 180 - (A + C)$

$b = \dfrac{L}{\cos\theta}$

$a = \dfrac{b \cdot \sin A}{\sin B}$

$c = \dfrac{a \cdot \sin C}{\sin A}$

$d = c \cdot \sin A$

Figure 5. Depth Computation

Mountain since two of the three hollows with the highest W/L did not contain snow in July, and the hollow with the third highest W/L was snow-free in June. However, snow may have remained throughout the year in these hollows during the Pleistocene, so Russell's observations may well apply on Hart Mountain.

IV. Influence of Slope on Hollow Morphometry

A. Physical Mechanisms of Slope Influence.

There are two important ways that the overall slope may affect nivation morphometry. The first involves an increase in the susceptibility to erosion of steeper slopes and the second involves an enhanced opportunity for deposition of wind blown snow on steeper slopes.

An increased slope can effect enhanced susceptibility to erosion in two ways. One results from an increase in shear stress (τ) because steeper slopes have a larger proportion of the gravitational force directed downslope. Shear stress is directly related to the slope angle (S):

$$\tau = m \cdot g \cdot \sin S \qquad (4.1)$$

where m = the mass of a soil particle; and g = acceleration due to gravity (Figure 6).

A second mechanism by which increased slope can cause an increased susceptibility to erosion is by increasing the critical shear stress (tractive force) produced by runoff on the slope. The critical shear stress (τc) represents "the downslope component of the fluid weight exerted on a bed particle" (Ritter, 1978, p. 219). This stress is also directly related to slope:

$$\tau c = \gamma \cdot R \cdot S \qquad (4.2)$$

where γ = the specific weight of the water; R = the

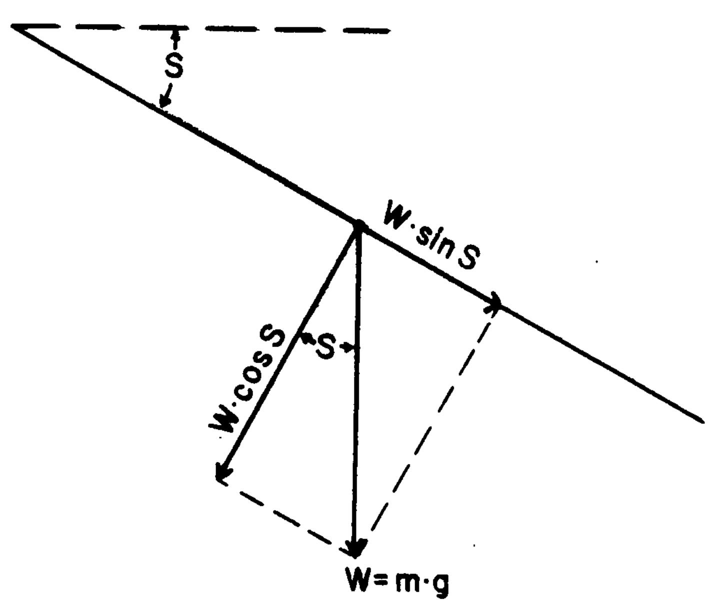


Figure 6. Affect of Slope on Shear Stress

hydraulic radius; and S = slope.

Equations 4.1 and 4.2 illustrate that slope is directly related to stresses acting to move soil particles downslope and therefore it can be expected that an increased slope angle results in hollows with longer L, W, and d attributes.

Overall hillslopes (θ) may also affect hollow morphometry by causing differences in the amount of wind blown snow deposited at a particular site. Since the hollows are located on the east side of the ridge, and the prevailing wind direction is from the west in the accumulation season (Lahey, 1979), increased deposition can be expected on steeper slopes on the east side of the ridge. Increased turbulence which occurs on the lee side of obstacles, can be expected where slopes are steeper. With increased turbulence, a decrease in the mean forward velocity and a decrease in ability to transport snow results, possibly leading to deposition. Field observations in October, 1979 confirmed increased snow depths on the lee side. Ritter (1978) indicates that turbulence may entrain particles smaller than sand, however, and actual eddy motion is extremely complex and poorly understood, so that any generalization about the effects of slope on turbulence and snow transportation or deposition is highly tentative. Determining the effects of wind flow on deposition, and on heat transfer (Chapter V), on Hart

Mountain are two very important subjects which need to be studied further in order to develop a comprehensive climatic model which accounts for hollow morphometry.

Slope also affects heat transfer in that it influences the amount of insolation received. This is not necessarily a direct relationship. Whether slope angle is directly of inversely related to insolation depends upon the orientation of the slope, the time of day, the latitude of the site, and declination of the sun. A model which includes all these factors is presented in the following chapter.

B. Slope-Size Relationships.

The morphometric attributes in the size category include W, L, L·W, W/L and d. Simple linear regressions using the least squares method between the attributes and average hillslope were computed (the specific relationships are given in Table IV. Figure 7 diagrams the strengths of the correlations, testing that $\rho \neq 0$).[4] These results show that all of the size attributes increase with increasing hillslope.

Because of the small sample size of only ten hollows, the assumption of a normal distribution of the size attributes and slope is questionable. Therefore, non-

4. Scatter diagrams of all relationships are presented in Appendix II.

TABLE IV.

SLOPE-SIZE RELATIONSHIPS

	r	t-value	significant at α=
$W = e^{1.71 + .13(SLP)}$	.7501	3.208	.01
$L = e^{2.83 + .049(SLP)}$	.7541	3.248	.01
$L \cdot W = e^{4.6 + .18(SLP)}$	.7989	3.756	.01
$W/L = -4.0 + .29(SLP)$	.6400	2.356	.05
$d = -3.67 + .26(SLP)$	.5687	1.957	.05

Critical t-values, 8 degrees of freedom:

α= .10, t = 1.397; α= .05, t = 1.860; α= .01, t = 2.869

	W	L	L•W	W/L	d
Kendall's τ	.5060	.6343	.6671	.3955	.3024
Kendall's S	+22	+26	+29	+17	+13
P1	.045	.0112	.0046	.078	.146
Theil's C	+20	+28	+22	+17	+13
P2	.045	.0065	.0295	.078	.146

P1 = probability that S is due to chance variability.

P2 = probability that the slope (β) is zero.

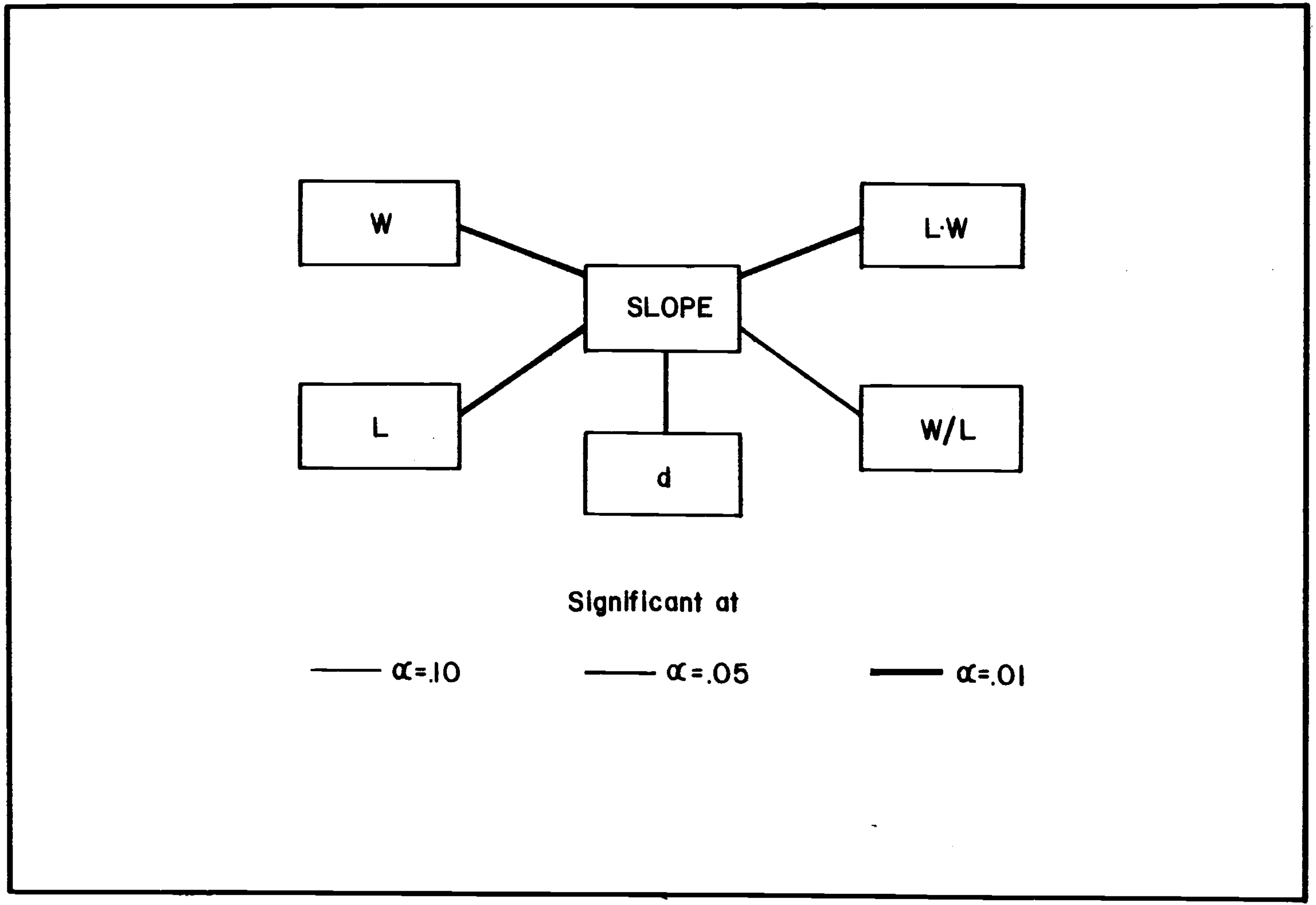


Figure 7. Parametric Test of Slope-Size Relationships

parametric tests which do not require a normal distribution are included. The tests are Kendall's tau (τ), which is a rank correlation coefficient; Kendall's S, from which the probability that this statistic is due to chance variability can be determined; and the Theil C test, which tests if the slope of the regression lines (β) calculated by the least squares method is a given number (in this case, Ho: $\beta = 0$).[5]

Figure 8 diagrams the levels of significance (α) at which the hypothesis that Kendall's S is due to chance variability is rejected (8a), and the level of significance at which the hypothesis that the slope (β) is zero is rejected (8b).

The direct relationship between W/L and slope (θ) suggests that hollows formed on steeper slopes are elongate compared to those formed on gentle slopes. The elongation with increased slope may be explained because the steeper segments of a hillslope are often confined to a relatively narrow band which follows the contours. Since steeper slopes can be exploited easier by nivation (equations 4.1 and 4.2) this elongate section of steeper slopes is more likely to develop into an erosion feature.

Depth (d) is related directly to slope as Russell

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5. Table IV gives the S, τ, and C statistics for slope vs. size attributes. The methods used to calculate these statistics are presented in Appendix III.

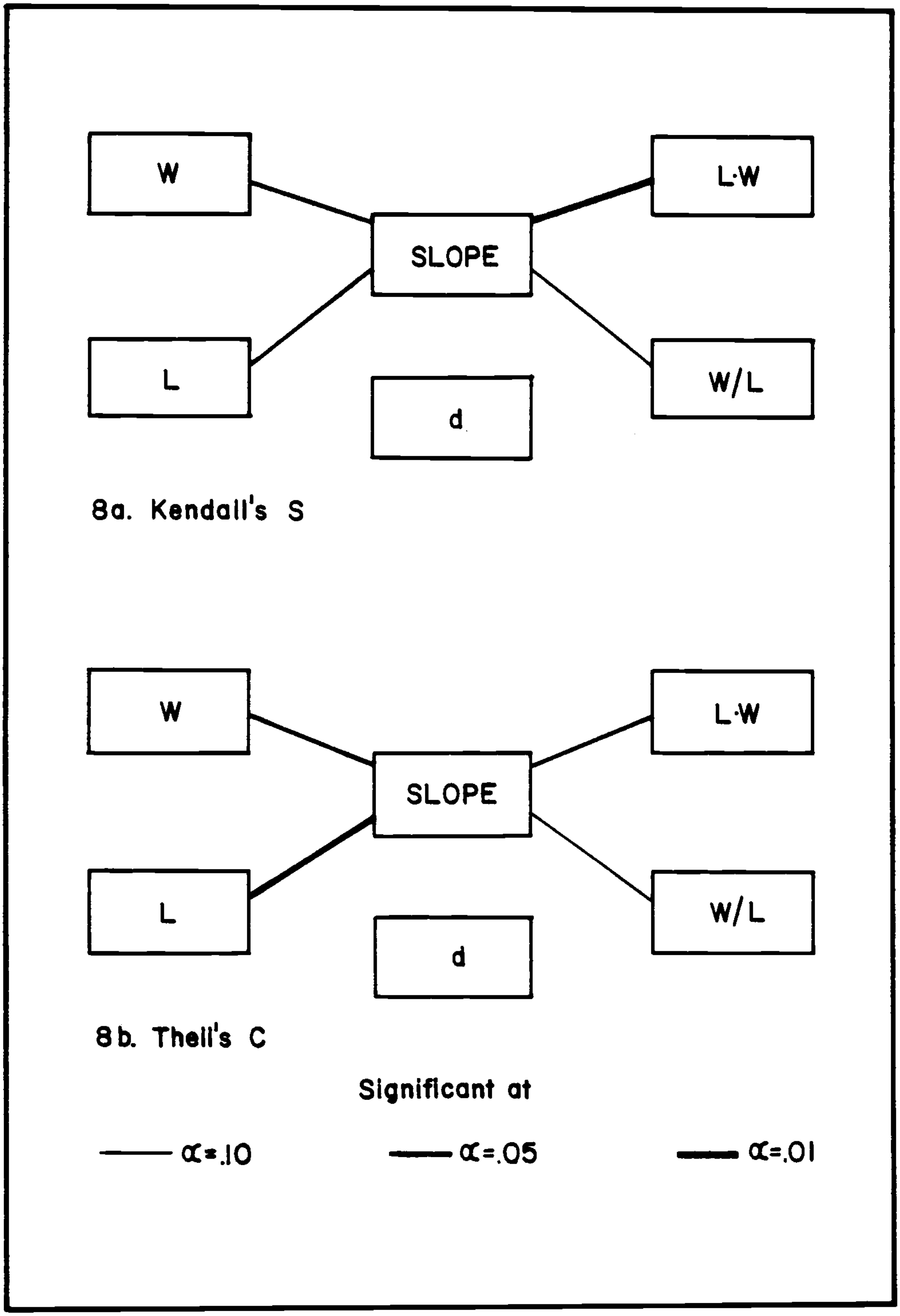

Figure 8. Non Parametric Tests of Slope-Size Relationships

(1933) suggests. However, the scatter diagram of d against slope (θ) suggests this relationship is not very strong. Removal of the largest hollow (circled on the diagram, Appendix II, p. 77) results in the correlation coefficient dropping to an insignificant level ($r = .1451$). Also, all of the nonparametric tests indicated that d and slope (θ) are not significantly related (Table IV).

C. Slope-Angle Relationships

Both floor and backwall angles are highly correlated with the overall average hillslope in both the parametric and nonparametric tests (Table V). Ninety percent of the variance in the floor angles is explained by the average hillslope ($R^2 = .8968$) and eighty percent of the variance in the backwall angles is explained by the average slope alone ($R^2 = .7957$).

TABLE V.

SLOPE-ANGLE RELATIONSHIPS

	r	t-value
Floor = -4.54 + 0.98(SLP)	.9470	8.341
Backwall = 2.39 + 1.09(SLP)	.8920	5.580

Both significant at α= .01; critical t-values at α= .01 with 8 degrees of freedom is 2.896.

	Floor	Backwall
Kendall's τ	.9072	.9072
Kendall's S	+39	+39
P1	.001	.001
Theil's C	+37	+37
P2	.001	.001

P1 = probability that S is due to chance variability.

P2 = probability that the slope (β) is zero.

V. Influence of Heat Transfer on Hollow Morphometry

A. Physical Mechanisms of Heat Transfer Influence.

There are several mechanisms by which heat transfer can affect nivation hollow morphometry. Decreasing the amount of heat transferred to the snowpatch will result in an increase in the erosive ability of most of these mechanisms. Heat transfer may affect mechanical and chemical weathering and the cohesive strength of soil particles.

Heat transfer may affect physical weathering in two ways. Firstly, rapid heating and cooling across the freezing point causes increased frost weathering. The presence of snow may cause the number of freeze-thaw cycles to increase under certain conditions (Gardner, 1969). Secondly, heat transfer provides meltwater which exploits the freeze-thaw cycles caused by larger scale climatic changes. In general, a site which retains snow for a longer period of time can be expected to undergo increased mechanical weathering.

The importance of chemical weathering in nivation is unresolved, although the presence of meltwater in lingering snowpatches is likely to increase the susceptibility of the soil minerals to chemical alteration. Therefore, an inverse relationship between heat transferred to the snow and the intensity of chemical weathering is expected.

Heat transfer may affect the susceptibility of soil particles to erosion in two ways. Firstly, the longer snow remains at a site, the less dense the vegetation covering the hollow. Less vegetative cover results in less rooting to act as a cohesive agent making the site more susceptible to erosion. Lingering snow on Hart Mountain prevents shrub vegetation which yields less surface roughness in a hollow than on the surrounding hillslope. An increase in surface roughness detains surface runoff from intense summer storms, allowing more infiltration and hence less overland flow, possibly resulting in decreased erosion. The decrease in surface roughness with lingering snowpatches makes the soil layer more susceptible to erosion. Secondly, if the snowpack over a region melts down uniformly, the runoff occurs at a time when the soil layer is still frozen and strongly cohesive due to the ice. If a snowpack ablates unevenly, snowpatches form and the meltwater from them erodes unfrozen soil which is comparatively less resistent to entrainment.

The above mechanisms all indicate that less heat transfer to a site results in snowpatch formation, which then results in hollow formation. A higher heat transfer to a site would conceivably result in a more rapid melt and less opportunity for infiltration, causing increased overland flow and erosion. However, the results of this study suggest the inverse mechanisms operate on Hart Mountain.

B. Heat Transfer Mechanisms.

In order to determine why snowpatches form in a given location, the heat transfer mechanisms which operate on a micro-scale, and therefore result in an uneven distribution of snow (i.e. snowpatch development), must be determined. The US Army Corps of Engineers (1956) and Paterson (1969) indicate seven processes by which heat can be transferred to a snowpatch:

(1) Solar radiation;

(2) Terrestrial radiation;

(3) Transfer of sensible heat by convection (eddy conduction;

(4) Transfer of latent heat by condensation;

(5) Molecular conduction from the air;

(6) Conduction from the underlying ground;

(7) Additions of heat from warm rain or loss of heat of fusion upon the rain freezing in the snowpatch.

The important transfer mechanisms which result in significant variation over relatively short distances on the ground are solar radiation and eddy conduction. Terrestrial radiation includes additions to the snowpatch by radiation from the atmosphere and clouds, but these can be expected to be relatively constant over the short distances involved in this study. Molecular conduction from the air is negligible due to the extremely low thermal inertia of still air (.00013). Conduction from the ground is a function of the temperature gradient of the ground surface according to the expression:

$$Hg = K \cdot dT/dz \qquad (5.1)$$

where Hg = heat transfer by conduction; K = thermal conductivity; and dT/dz = the thermal gradient. Since variance in heat distribution of the ground is mainly from insolation, and the ground surface lithology is fairly uniform on Hart Mountain, heat transfer to the snow from this mechanism is likely to be reflected in the analysis of solar radiation. Additions of heat by rain are generally small compared to transfers by radiation, convection, and condensation (Paterson, 1969) and since the distibution of rainfall is probably also fairly uniform over the short distances involved here, additions by rain probably do not result in significant differences in the snowpack distibution.

Solar radiation varies considerably due to slope, aspect, time of day, season, and latitude, so it is important in creating an uneven distribution of snow cover. Insolation receipts are also influenced significantly by the atmosphere, the amount of water vapor in the air, and the degree of cloud cover, but these latter three factors probably do not result in significant variations over short distances. A method for calculating the percent of possible insolation at any particular site based on latitude (L), slope (b), azimuth of the profile plane (P), declination of the sun (δ), and the hour angle (H) is presented by Brooks (1959) (Figure 9):

$$\cos i = (\cos P \sin L \sin b + \cos L \sin b) \cos\delta \cos H + \sin P \sin b \cos\delta \sin H + (\sin L \cos b - \cos P \cos L \sin b) \sin\delta \quad (5.2)$$

Cos i = percent of possible insolation at the top of the atmosphere. All angles are in degrees. The latitude is positive in the northern hemisphere and negative for locations in the southern hemisphere, the slope is positive if south facing and the site is in the northern hemisphere, the declination of the sun is positive for north declination and negative for south declination, the hour angle is determined by multiplying the number of hours from solar noon by 15^{o}/hr with morning being negative and afternoon being positive, and the azimuth of the profile plane is the number of degrees a slope is facing from a north-south line and is positive for the SW and NE quadrants and negative for the SE and NW quadrants.

A measure of the variation in insolation of the ten hollows based on differences of slope and aspect was calculated using this method, setting the seasonal declination at 23.5^{o} N and the hour angle at 0^{o}. This allows for the maximum percent of solar radiation reaching this

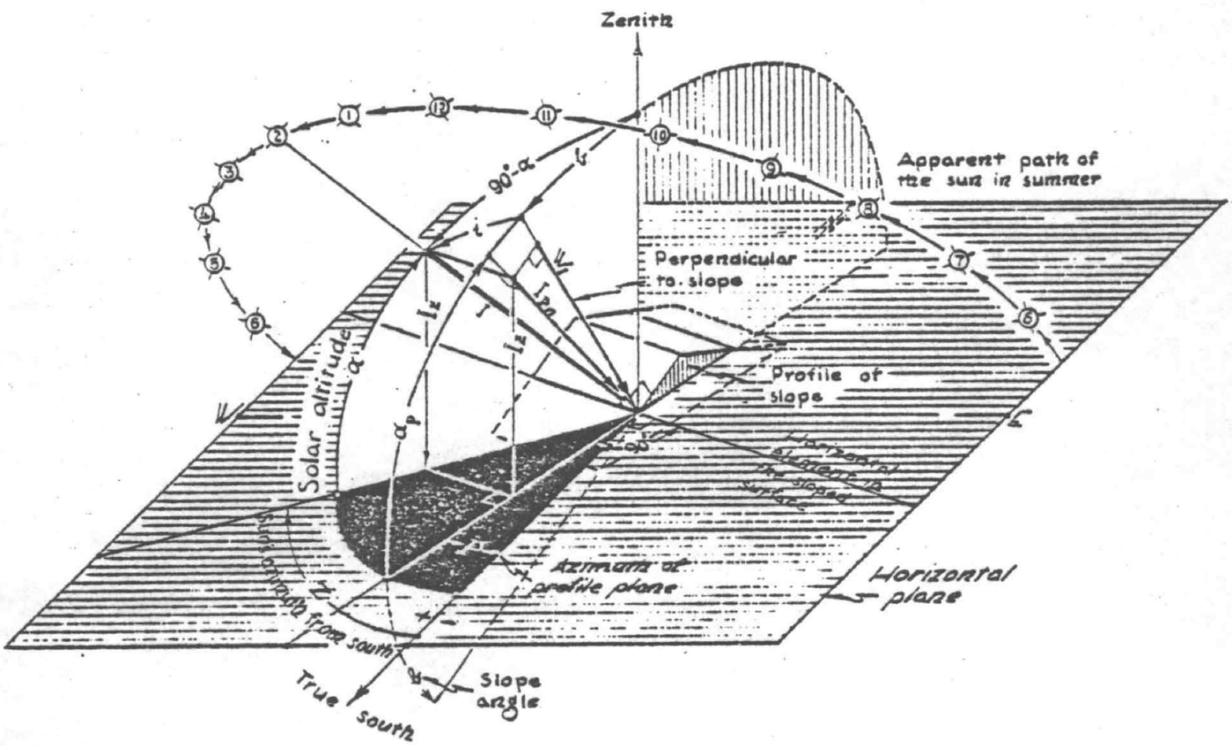

Figure 9. Diagram of Angles for Determining Solar-beam Irradiation on Sloped Surfaces. (from Brooks, 1959)

area. The latitude of all of the hollows is approximately 42.5° (The computed values for solar loading (SL) from this method, and the values of P and b of the sites are given in Table VII).

Measurement of the transfer of heat due to convection and condensation is not possible because of the lack of adequate instruments (Paterson, 1969), and therefore can be determined only by theoretical means or as the residual of the energy transfer equation (which includes the balance between all heat transfer mechanisms). The theory behind convection and condensation transfer is analogous. The basic relationship is:

$$Q = A \cdot dq/dz \qquad (5.3)$$

where Q = heat transfer, A = an exchange coefficient, and dq/dz is the vertical gradient of property q through distance z. For convective transfer, q is air temperature or wind speed and for condensation transfer q is atmospheric moisture content or wind speed. Since atmospheric moisture does not vary significantly over short distances on Hart Mountain (except in proximity to springs), transfer of heat by condensation or evaporation due to differences in moisture is probably not an important means by which an uneven snowpack distribution develops.

Differences due to air temperature and wind speed are probably quite significant because these factors vary over short distances. Since detailed information on the

TABLE VI. SL COMPUTATION FACTORS

Site #	SL	P	b
1	.8795	-78	26
2	.8733	-68	31
3	.8793	82	-19
4	.7344	36	-26
5	.9715	-39	22
6	.9936	-20	19
7	.9712	-42	20
8	.8579	-84	27
9	.8143	79	-27
10	.7323	70	-33

surface wind field on Hart Mountain is not available, an actual computation of transfer by this mechanism is not possible. Inasmuch as elevation reflects changing temperature, the elevations of the hollows are used in the following sections of this chapter as a first approximation to heat transfer by eddy conduction. Admittedly, this is a gross approximation. Establishing the surface wind field on Hart Mountain, to determine actual heat transfers and deposition of snow (Chapter IV) is probably the most important element required to develop a comprehensive climatic model for nivation hollow morphometry on Hart Mountain.

C. Heat Transfer-Size Relationships.

Both elevation (ELEV) and insolation (SL) were found to be significantly correlated with many of the morphometric attributes of the hollows. Elevations were taken from USGS 7½' topographic maps (Warner Peak and Cambell Lake quadranges). Hollow locations were plotted from field observations and with the aid of photographs so that some inaccuracy in the values undoubtedly resulted. An attempt made to locate the hollows by the intersection method, taking azimuths to prominent points with a Brunton Pocket Transit, proved unsatisfactory, possibly due to magnetic anomalies in the mafic bedrock.

1. Insolation. All size attributes are

significantly correlated with insolation (Figures 10 and 11). The parametric tests give results comparable to the nonparametric tests. All size attributes are significant at α = .01 or .05 except W/L which is significant at α= .10 (Table VII). All of these relationships are inverse, indicating that the less heat a site receives, the larger the hollow.

Since this technique for calculating SL is based only on slope, aspect, latitude, declination, and hour angle, which have not changed dramatically in recent geologic time, this calculation provides a relative comparison of insolation during the Pleistocene as well as recent time.

2. Elevation. All correlations are diredt, indicating that decreased heat transfer results in larger hollows (Table VIII gives the relationships and statistics calculated between elevation and the size attributes, Figures 12 and 13 diagram the strengths of these relationships). The scatter diagrams (Appendix II) suggest the relationships between elevation and size are not very strong, indicating that either convective transfers are not very important, or that elevation alone does not reflect convective transfer adequately.

Major differences are evident between the parametric and nonparametric tests. Depth is highly correlated with elevation using the parametric test for the correlation coefficient (significant at α= .01), but not significantly

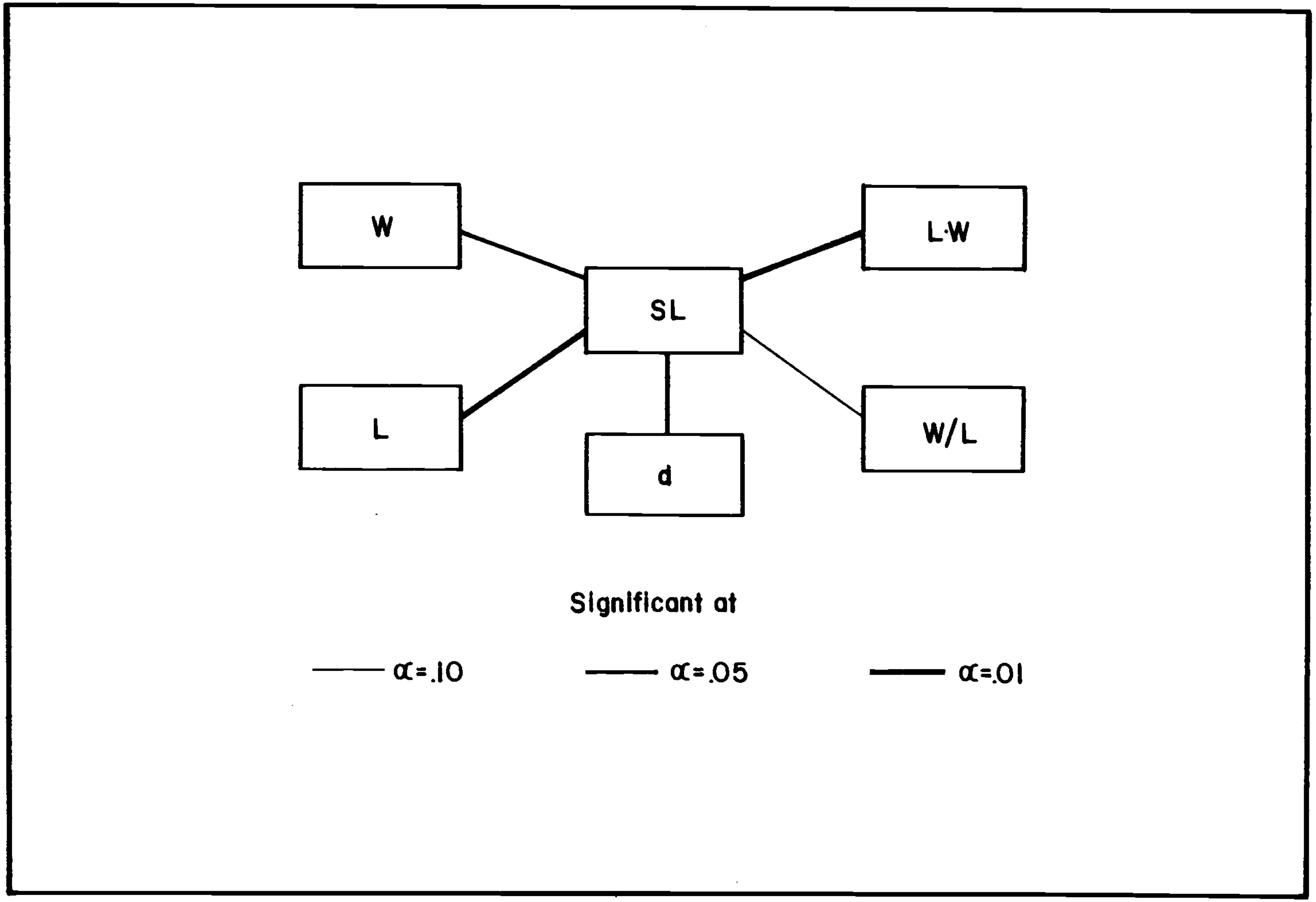

Figure 10. Parametric Test of SL-Size Relationships

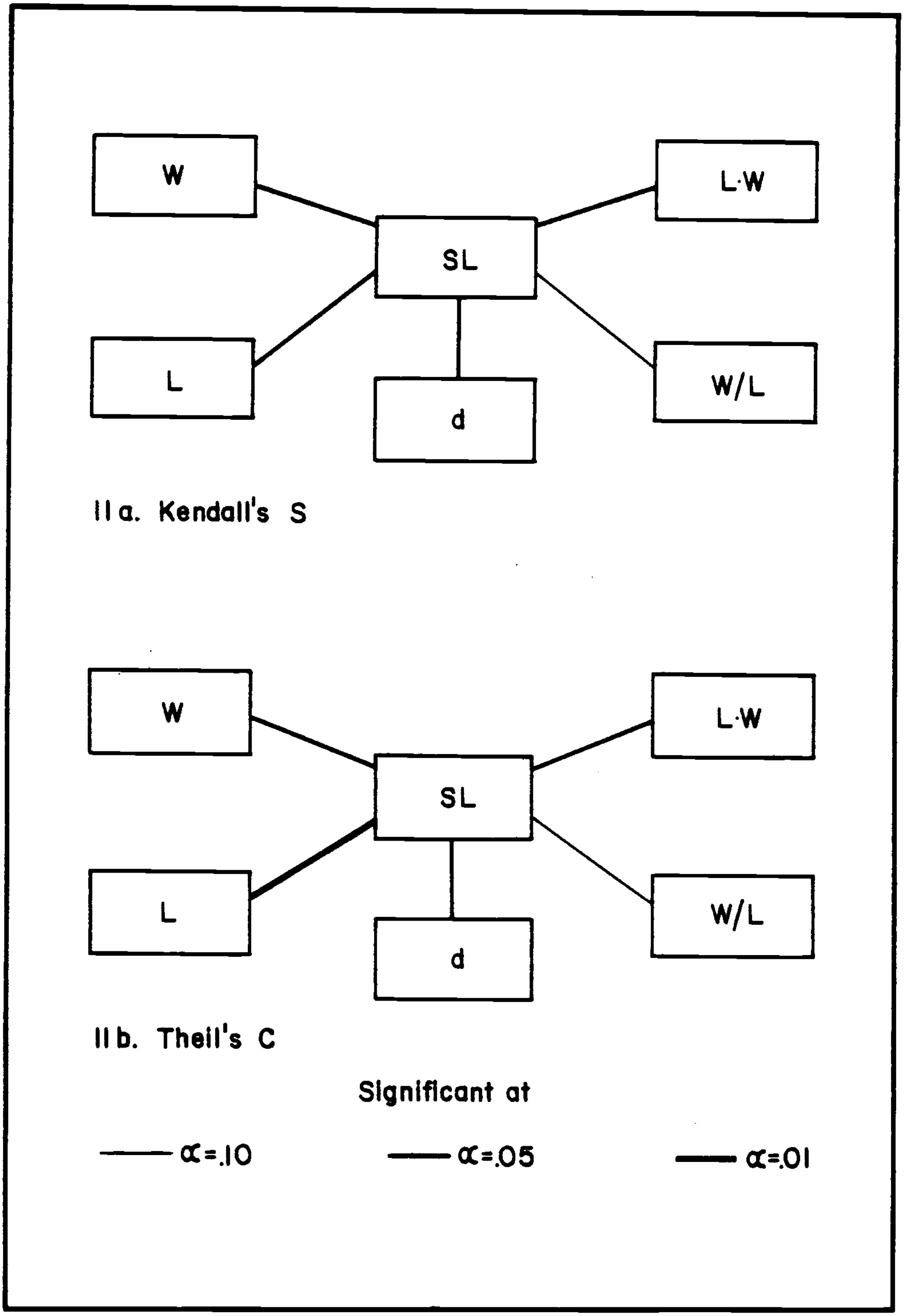

Figure II. Non Parametric Tests of SL-Size Relationships

TABLE VII. SL-SIZE RELATIONSHIPS

	r	t-values	significant at $\alpha =$
W = 1609 - 1583(SL)	-.5993	-2.1173	.05
L = 235 - 198(SL)	-.7480	-3.1881	.01
L•W = e^{17} - 9.1(SL)	-.7501	-3.2084	.01
W/L = 12.99 - 11.14(SL)	-.4532	-1.4378	.10
d = 15.7 - 14.9(SL)	-.6164	-2.2143	.05

Critical t-values, 8 degrees of freedom:

α= .10, t = 1.397; α= .05, t = 1.860; α= .01, t = 2.869

	W	L	L•W	W/L	d
Kendall's τ	-.4667	-.7542	-.4667	-.3596	-.4495
Kendall's S	-21	-32	-21	-16	-20
P1	.036	.017	.036	.093	.045
Theil's C	-21	-32	-21	-16	-20
P2	.036	.0021	.036	.093	.045

P1 = probability that S is due to chance variability.

P2 = probability that slope (β) is zero.

TABLE VIII. ELEV-SIZE RELATIONSHIPS

	r	t-value	significant at α =
W = -5121 + 2.39(ELEV)	.7162	2.9024	.01
L = -523 + .26(ELEV)	.7828	3.5581	.01
L·W = -734,953 + 337(ELEV)	.7658	3.368	.01
W/L = -27.2 + .014(ELEV)	.4442	1.4025	.10
d = -48.9 + .023 (ELEV)	.7562	3.2687	.01

Critical t-values, 8 degrees of freedom:

α= .10, t = 1.397; α= .05, t = 1.860; α= .01, t = 2.896

	W	L	L·W	W/L	d
Kendall's τ	.4091	.7045	.4652	.4052	.3371
Kendall's S	+18	+31	+20	+17	+15
P1	.066	.0023	.045	.078	.108
Theil's C	+18	+21	+18	+17	+15
P2	.066	.036	.066	.078	.108

P1 = probability that S is due to chance variability.

P2 = probability that the slope (β) is zero.

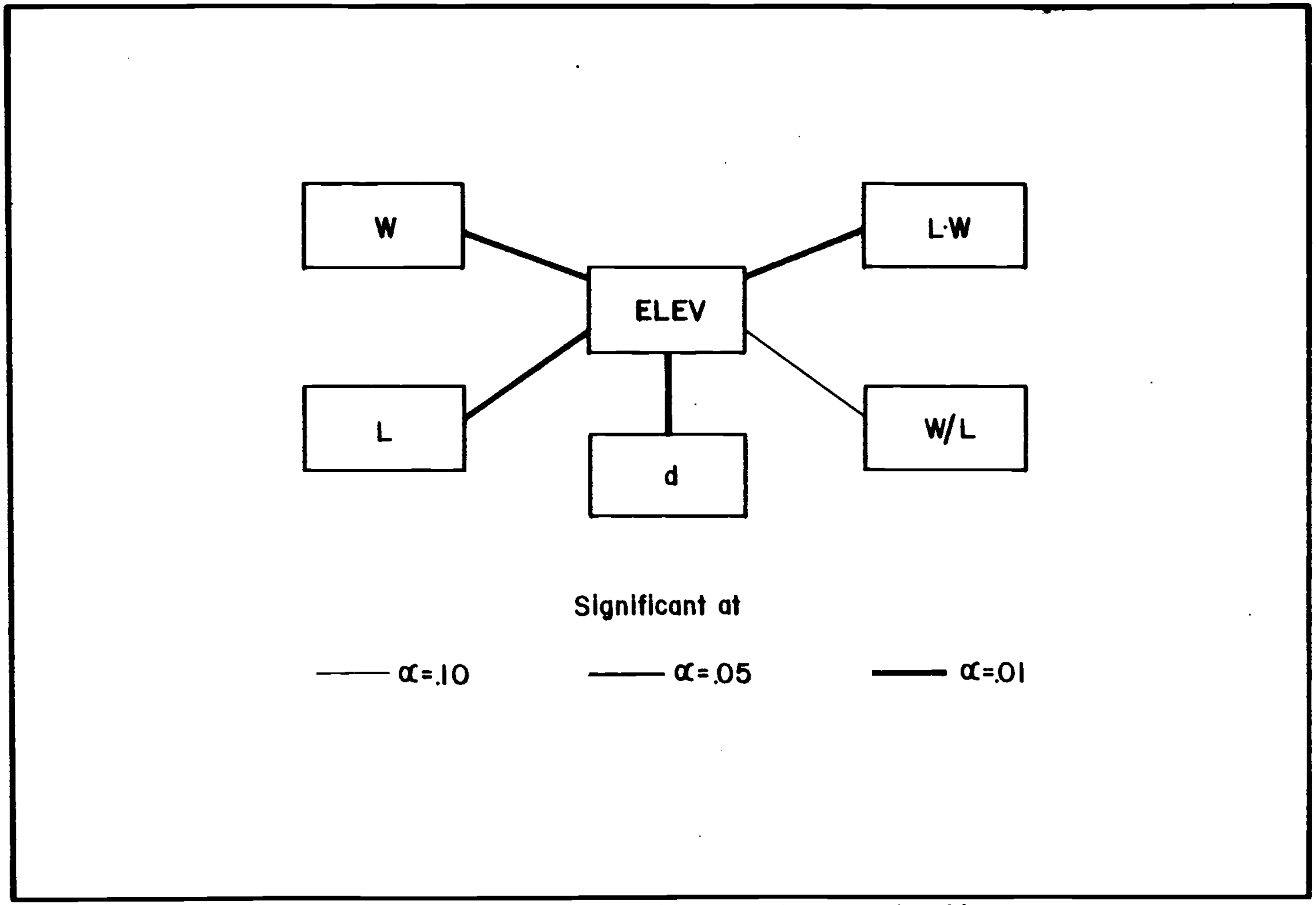

Figure 12. Parametric Test of ELEV-Size Relationships

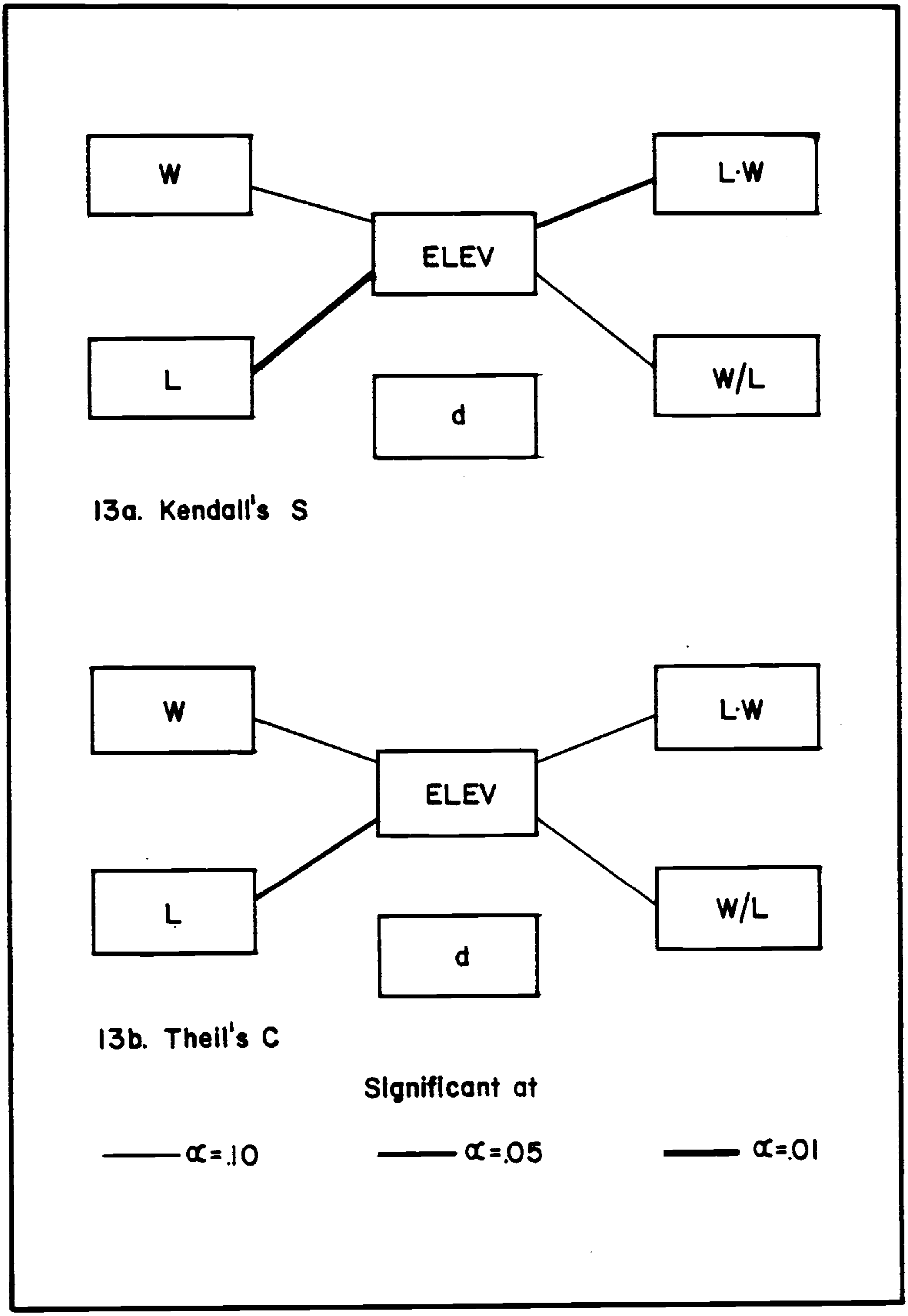

Figure 13. Non Parametric Tests of ELEV-Size Relationships

related according to both Kendall's S and the Theil C test. Also, the relationships between elevation and W and L·W are less significant according to the nonparametric tests.

D. Heat Transfer-Angle Relationships.

SL is significantly correlated (inversely) with floor and backwall angles, but elevation is not (Table IX gives the relationships and Figure 14 diagrams the strengths of the correlations).

TABLE IX. SL-ANGLE RELATIONSHIPS

	r	t-values	significant at α=
Floor = 46.7 - 30.7(SL)	-.5577	-1.901	.05
Backwall = 68.3 - 44.3(SL)	-.6808	-2.629	.05

Critical t-values, 8 degrees of freedom:

α= .10, t = 1.397; α= .05, t = 1.860; α= .01, t = 2.896

	Floor	Backwall
Kendall's τ	-.3596	-.6742
Kendall's S	-16	-30
P1	.093	.0035
Theil's C	-16	-30
P2	.093	.0035

P1 = probability that S is due to chance variability.

P2 = probability that the slope (β) is zero.

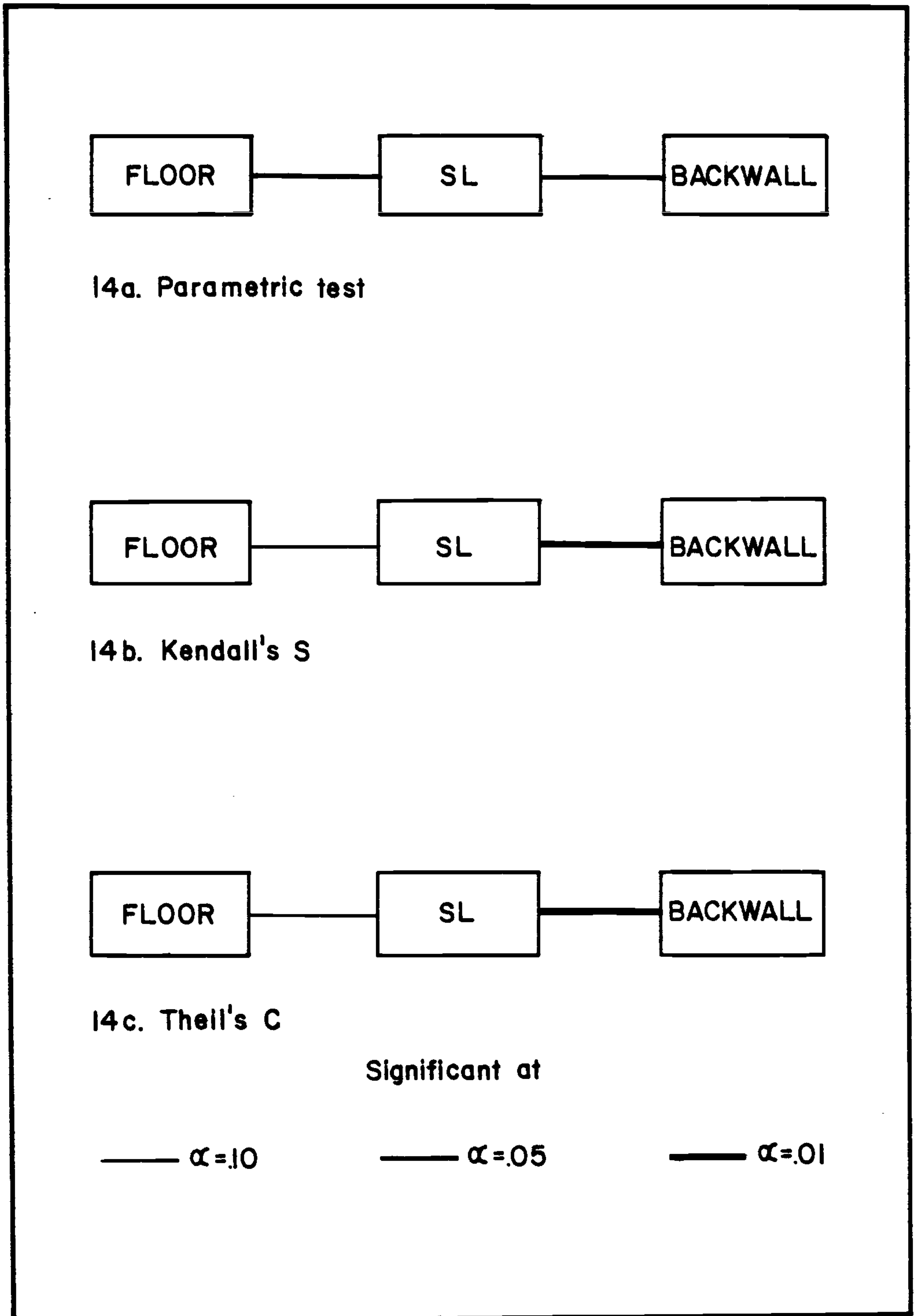

Figure 14. SL-ANGLE RELATIONSHIPS

VI. Conclusions

The presence of snow cover influences geomorphic development on much of Hart Mountain as evidenced by the presence of sub-nival channels across the western divide of the Rock Creek drainage basin.

Nivation is most effective in modifying the steeper slope segments located on the eastern side of the ridge. The effectiveness of nivation is evidenced by the development of breaks in slope of several degrees in areas where structural control is not apparent. The slope breaks thus outline nivation hollows.

The size of the hollows is directly related to the average hillslope of the site. Slope steepness influences nivation, and thus hollow size, due to its effect upon the shear stress acting to move particles downslope; thus, a steeper slope is more susceptible to erosion. Also, the steeper slopes on the east side of the ridge, which is the lee side of prevailing winds during the accumulation season, are likely to cause increased deposition of wind blown snow transported from, and across, the relatively gentle windward side of the divide. Surface topography, prevailing wind directions, and speeds therefore influence the location of erosion features which develop due to discontinuous snow cover.

Floor and backwall angles are best explained by the average hillslope of the site.

The morphometric attributes defining the hollows' sizes can be related to microclimatic factors. Relationships show that the amount of heat snowpatches receive is negatively correlated with the size of the hollow. Where snow remains for longer periods of time, weathering processes are likely to be more effective, and vegetative cover is less dense resulting in greater erosion and increased hollow size.

Nivation, while currently active on Hart Mountain, is greatly reduced in intensity since the time of hollow formation. The landforms probably developed from intensive frost action during the Pleistocene when snowpatches undoubtedly remained for longer periods of time, possibly throughout the ablation season. This conclusion is based on a review of literature dealing with nivation which suggests frost action is the dominant geomorphic process associated with snowpatches. Frost action on Hart Mountain is not significant at present, although relict periglacial landforms, such as stone stripes, polygons, and frost heaved blocks, attest to the importance of frost action during the Pleistocene.

Nivation activity continues to modify existing hollows. Currently, two nivation processes are probably operating on Hart Mountain. Firstly, snow presence is resulting in accelerated chemical alteration of the bedrock and soil in the nivation hollows. Secondly, vegetation differences caused by snowpatches is resulting in increased movement of debris within and from the hollows during intense summer storms.

Wind flow patterns influence nivation by affecting the deposition of snow, and also by affecting heat transfer between the snow and the atmosphere. Further study is required to establish wind flow patterns and to determine exactly how wind patterns influence nivation.

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APPENDIX I

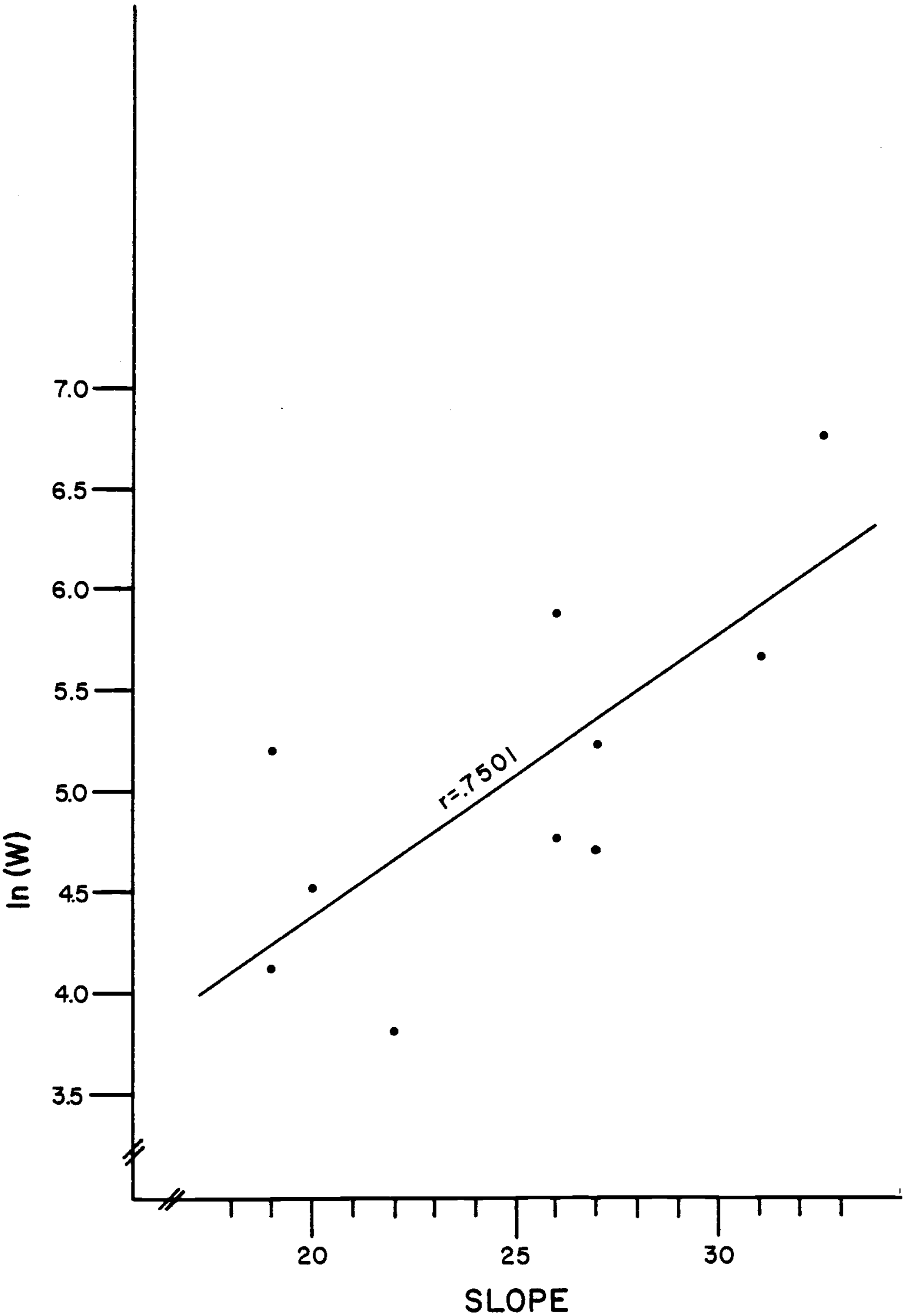
Hollow Morphometry

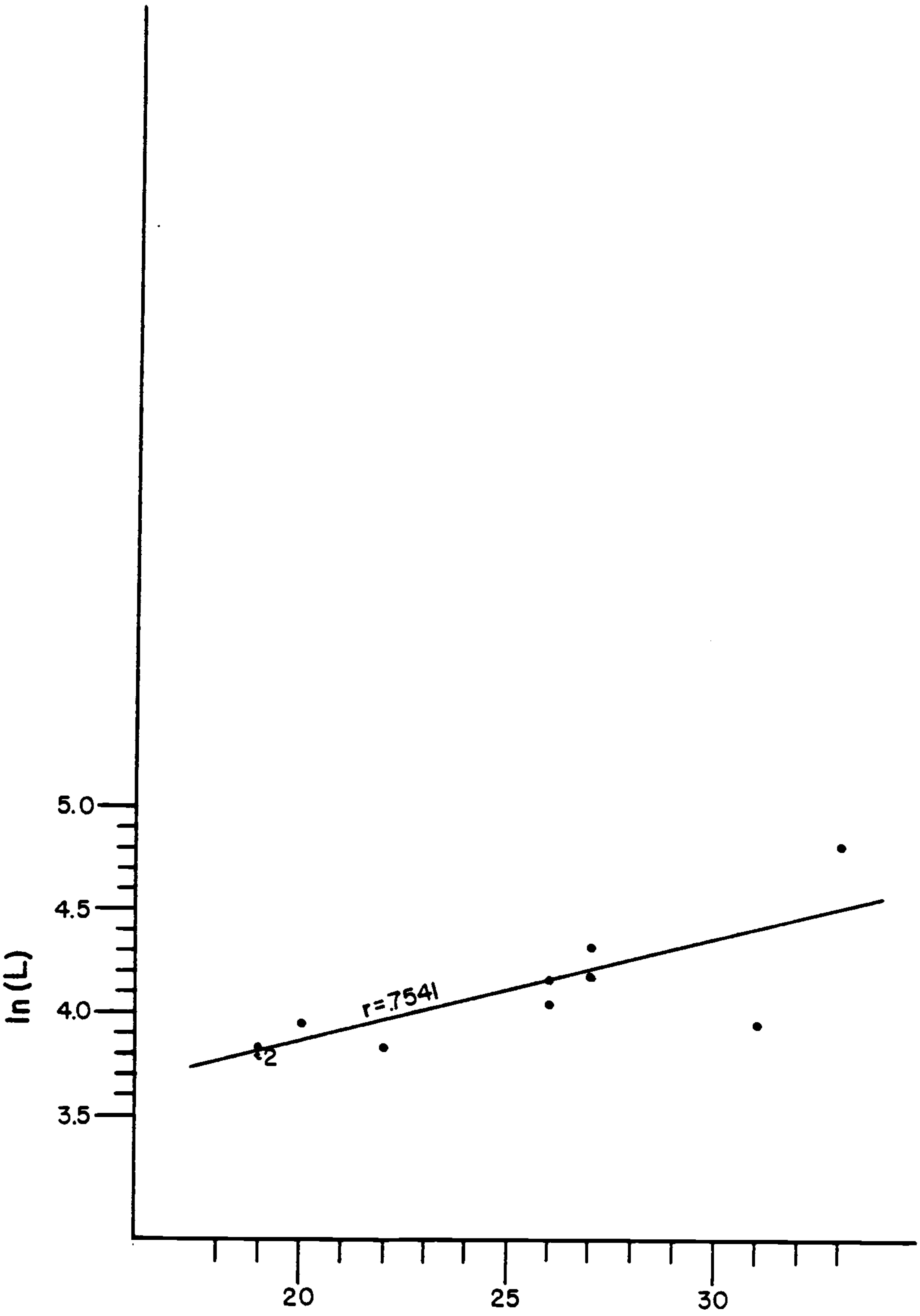
Site	ELEV(m)	Aspect	Slope	Floor	Backwall
1	2230	102	26	20	27
2	2165	112	31	28	37
3	2285	82	19	13	26
4	2310	36	26	19	28
5	2190	141	22	16	24
6	2170	160	19	16	21
7	2195	138	20	15	27
8	2200	96	27	24	32
9	2230	79	27	23	36
10	2395	70	33	26	39

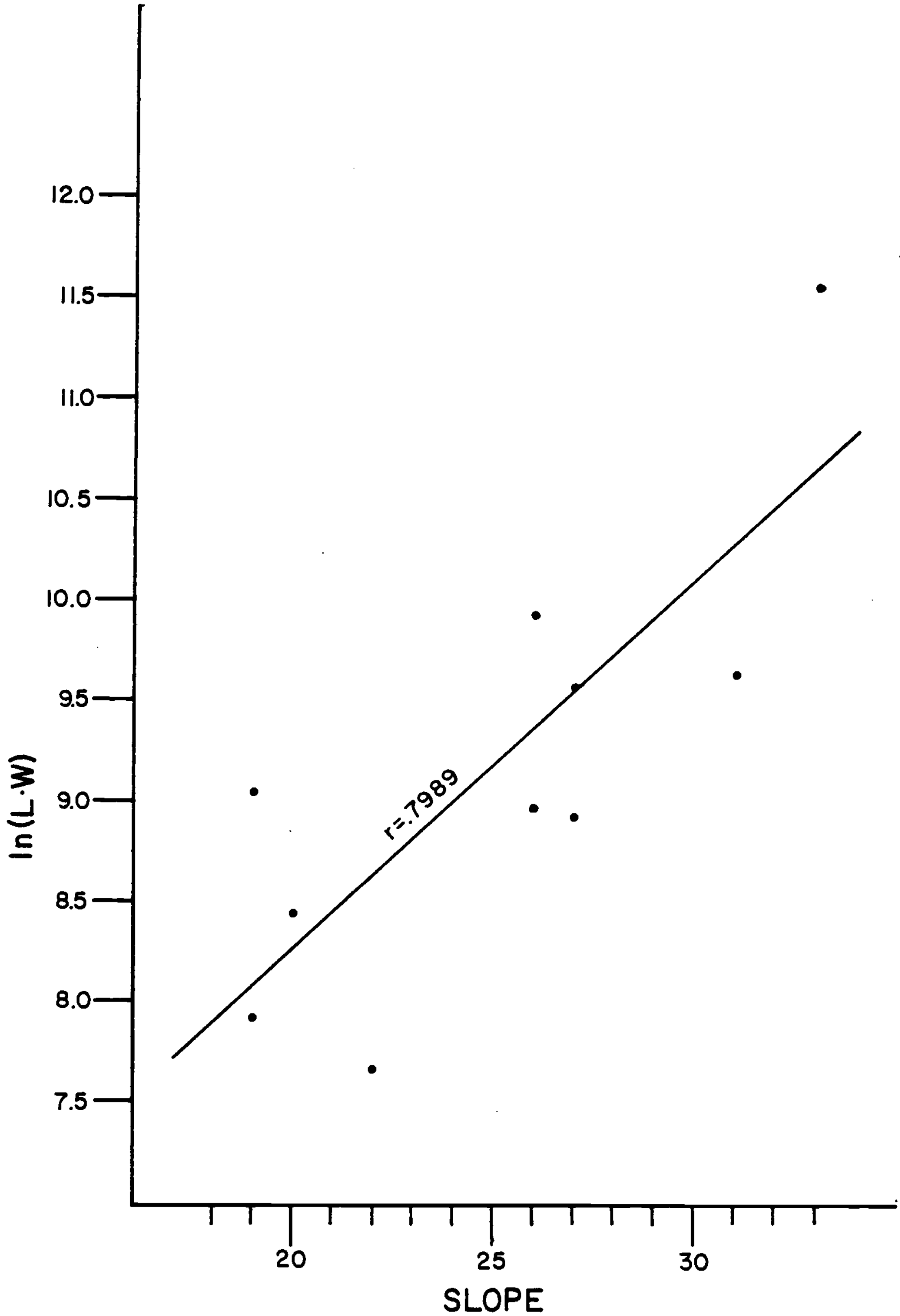
Site	W(m)	L(m)	W/L	d(m)	$L \cdot W (m^2)$
1	355	57	6.23	0.9	20,235
2	295	51	5.78	2.1	14,994
3	178	46	3.87	2.8	8,188
4	118	66	1.78	2.0	7,778
5	46	46	1.00	1.3	2.116
6	61	46	1.32	1.0	2,806
7	91	51	1.78	2.8	4,641
8	112	66	1.70	2.4	7,392
9	190	76	2.50	4.1	14,440
10	864	126	6.86	8.5	108,864

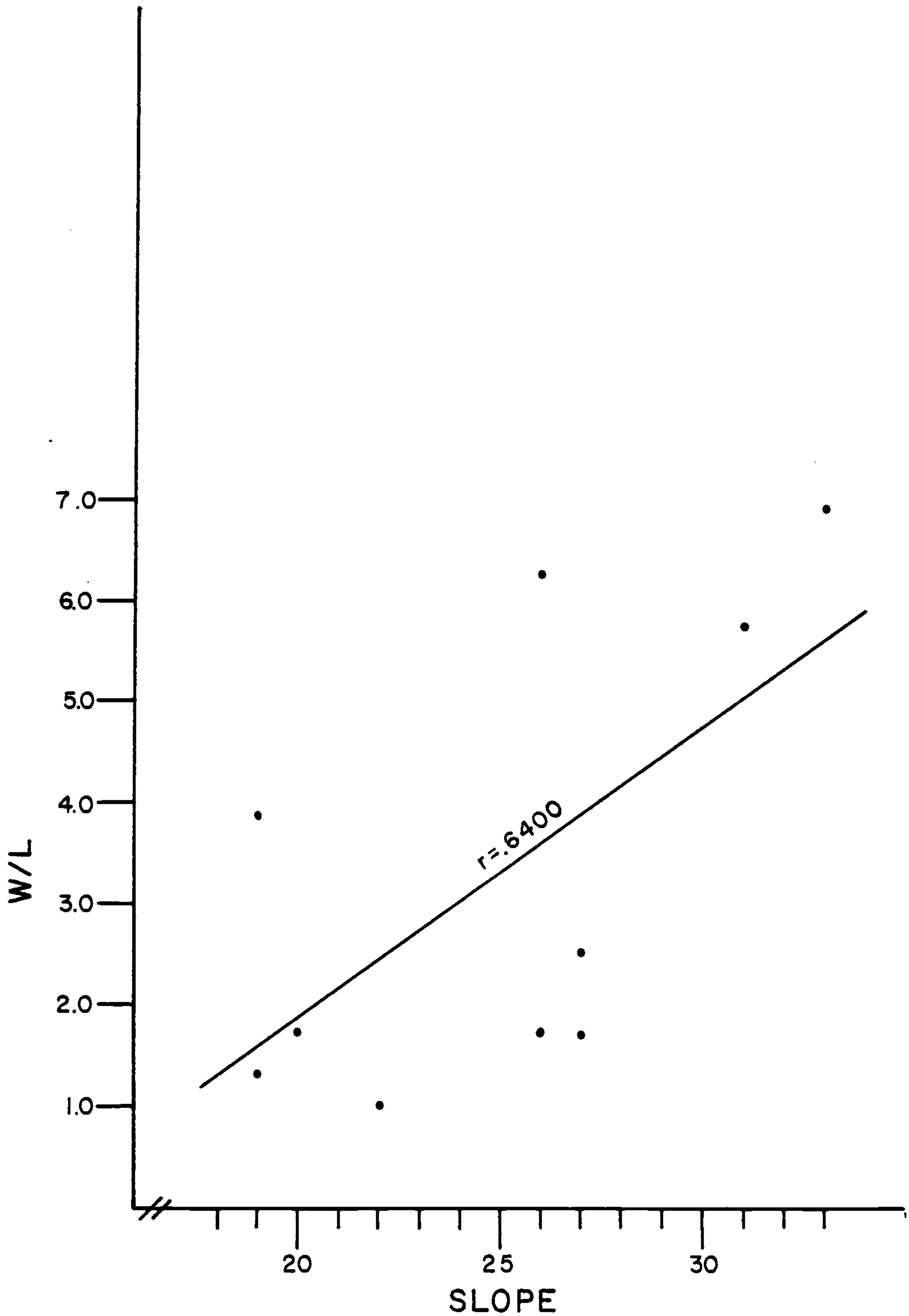
APPENDIX II

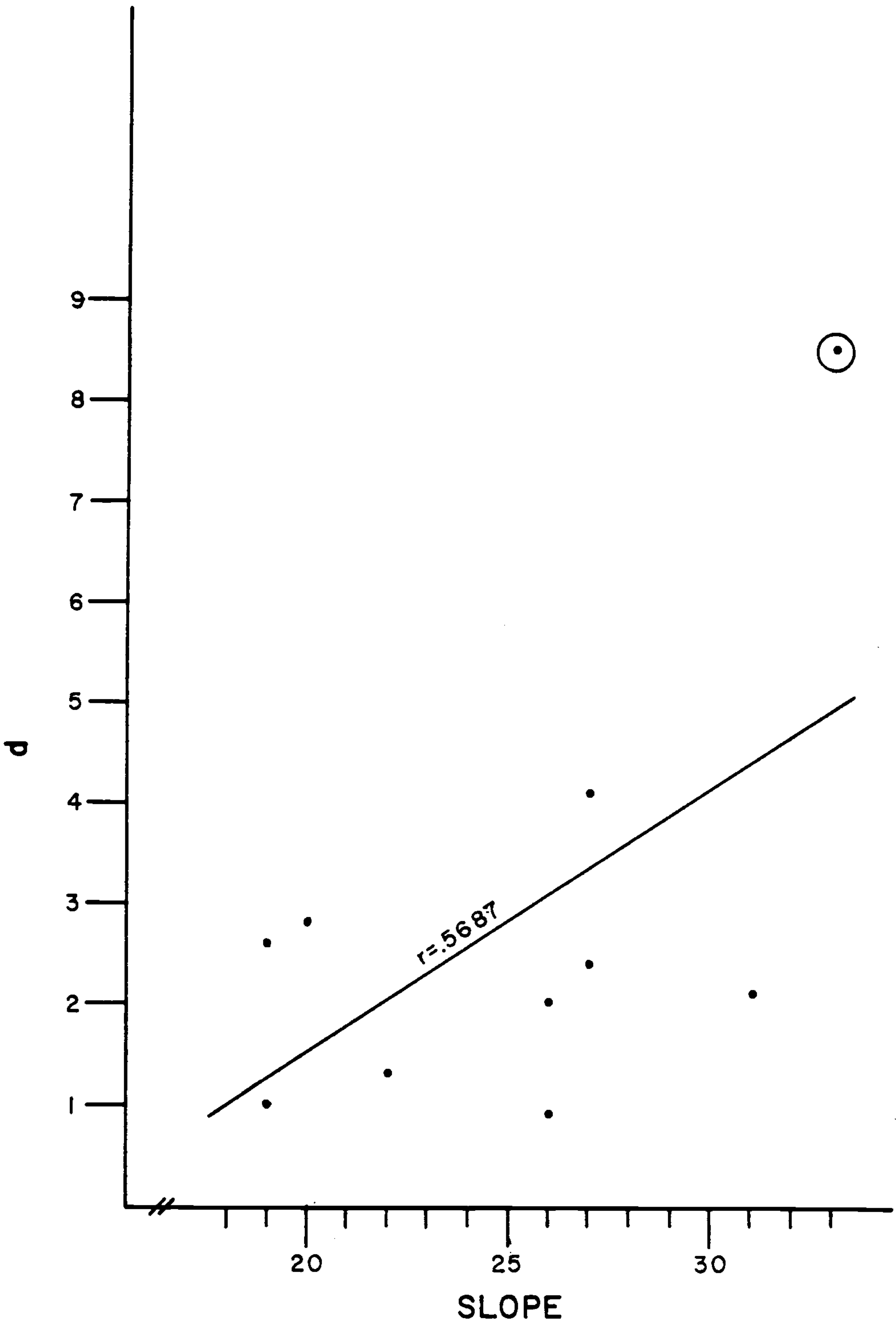
Scatter Diagrams of Significant Relationships

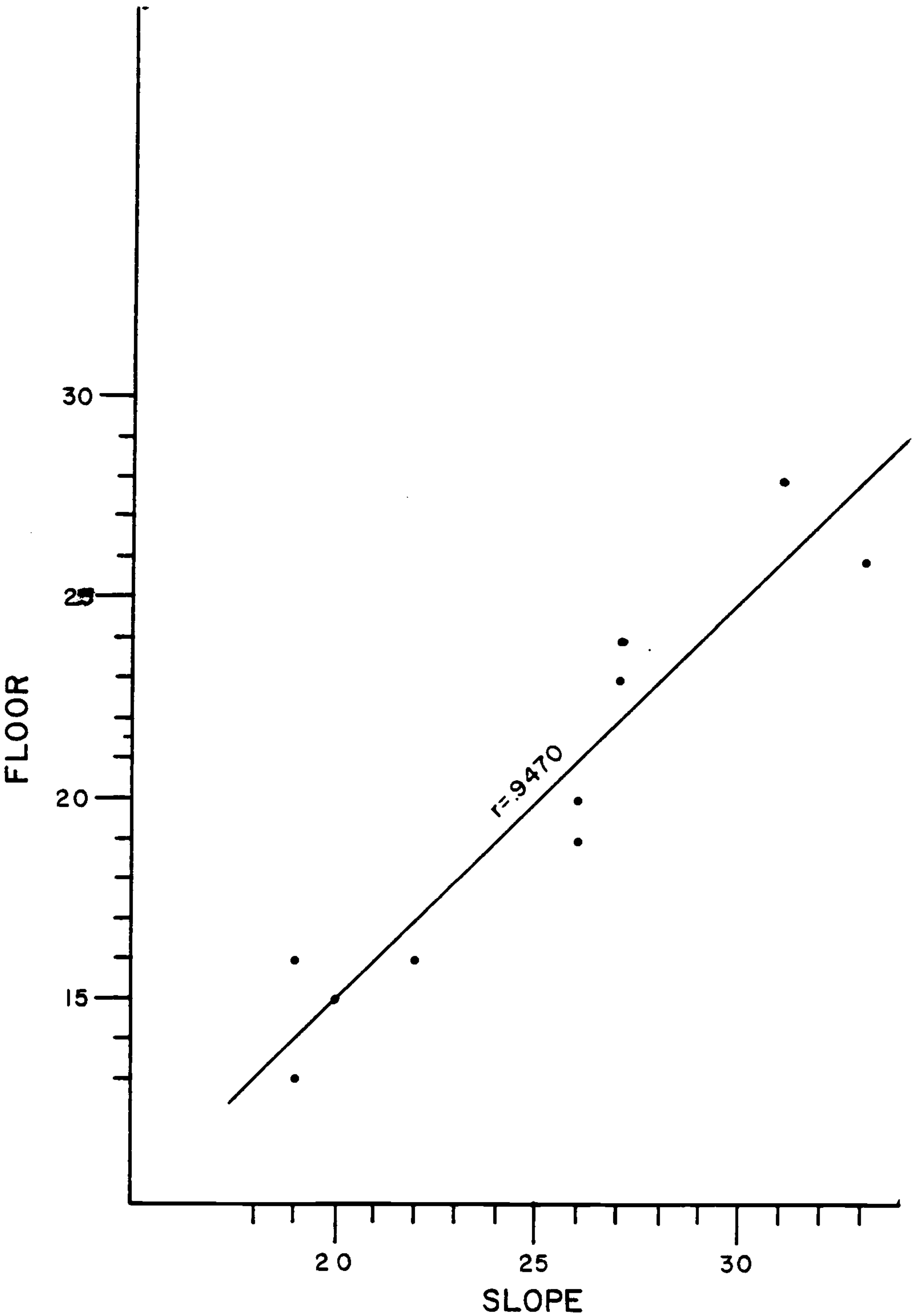

7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
ln (W)
r=.7501
20
25
30
SLOPE

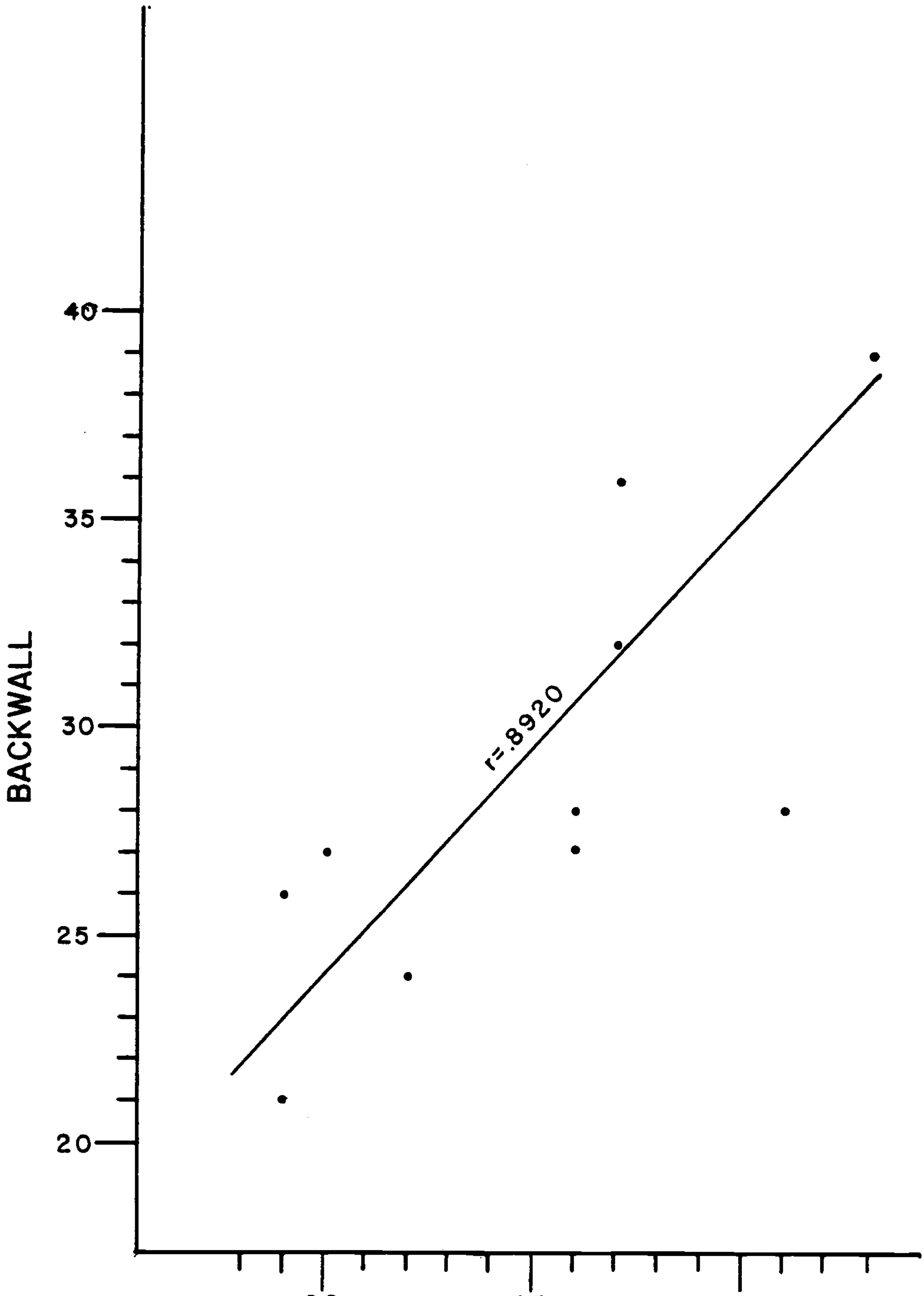

5.0
4.5
4.0
3.5
ln(L)
r=.7541
2
20
25
30
SLOPE


12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
ln(L·W)
r=.7989
20
25
30
SLOPE

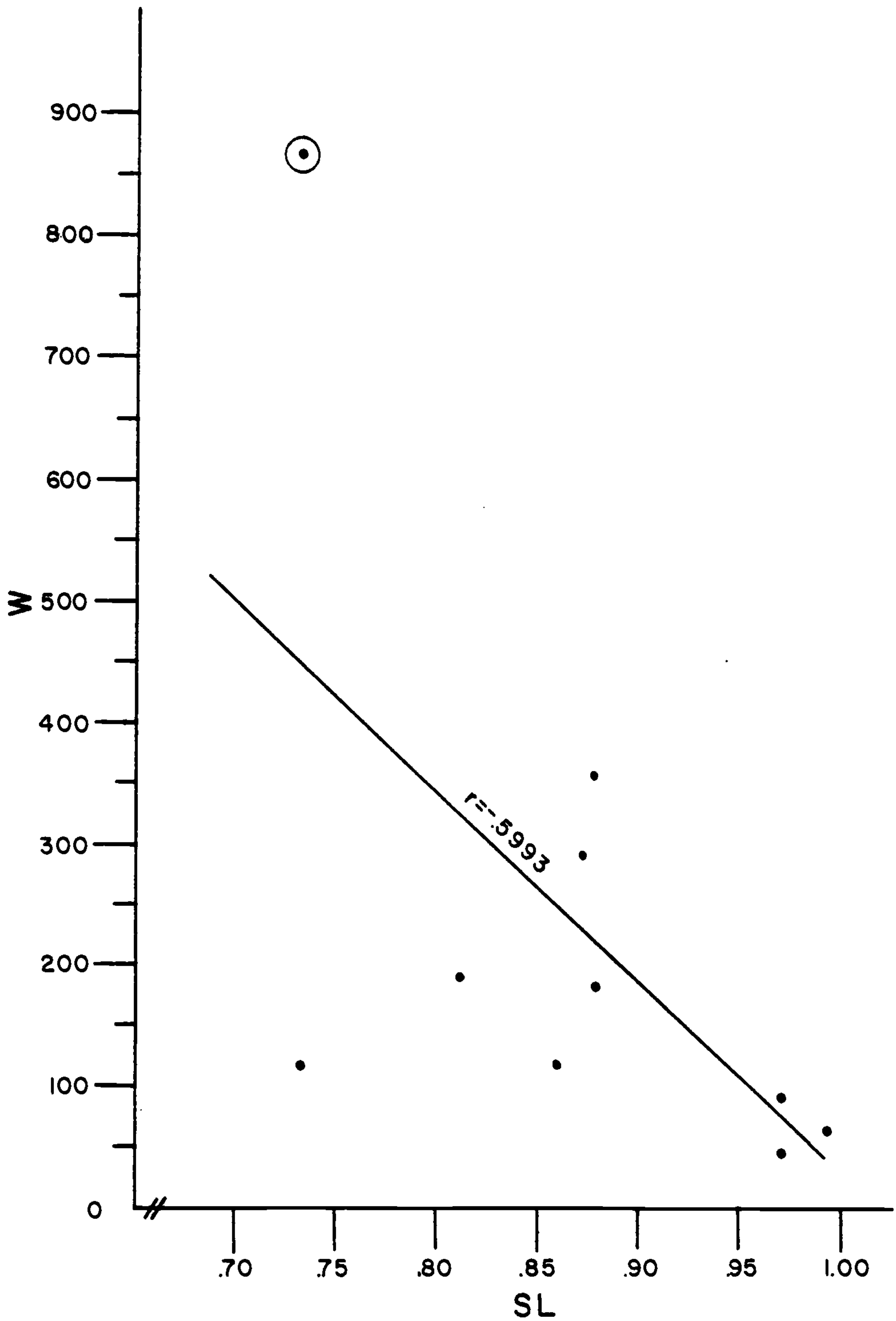

7.0
6.0
5.0
4.0
3.0
2.0
1.0
W/L
r=.6400
20
25
30
SLOPE


d
9
8
7
6
5
4
3
2
1
r=.5687
20
25
30
SLOPE

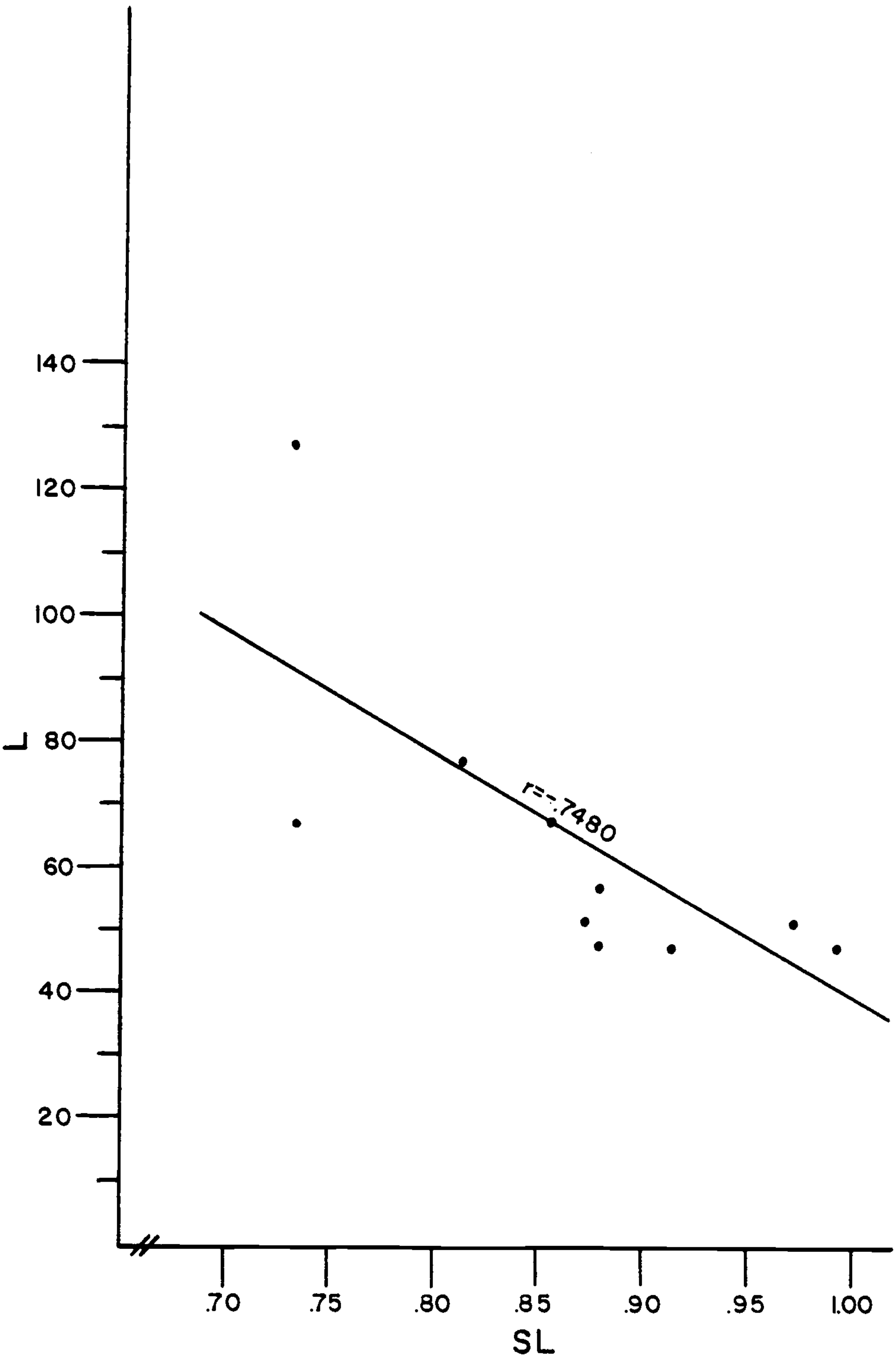

30
25
20
15
FLOOR
r=.9470
20
25
30
SLOPE

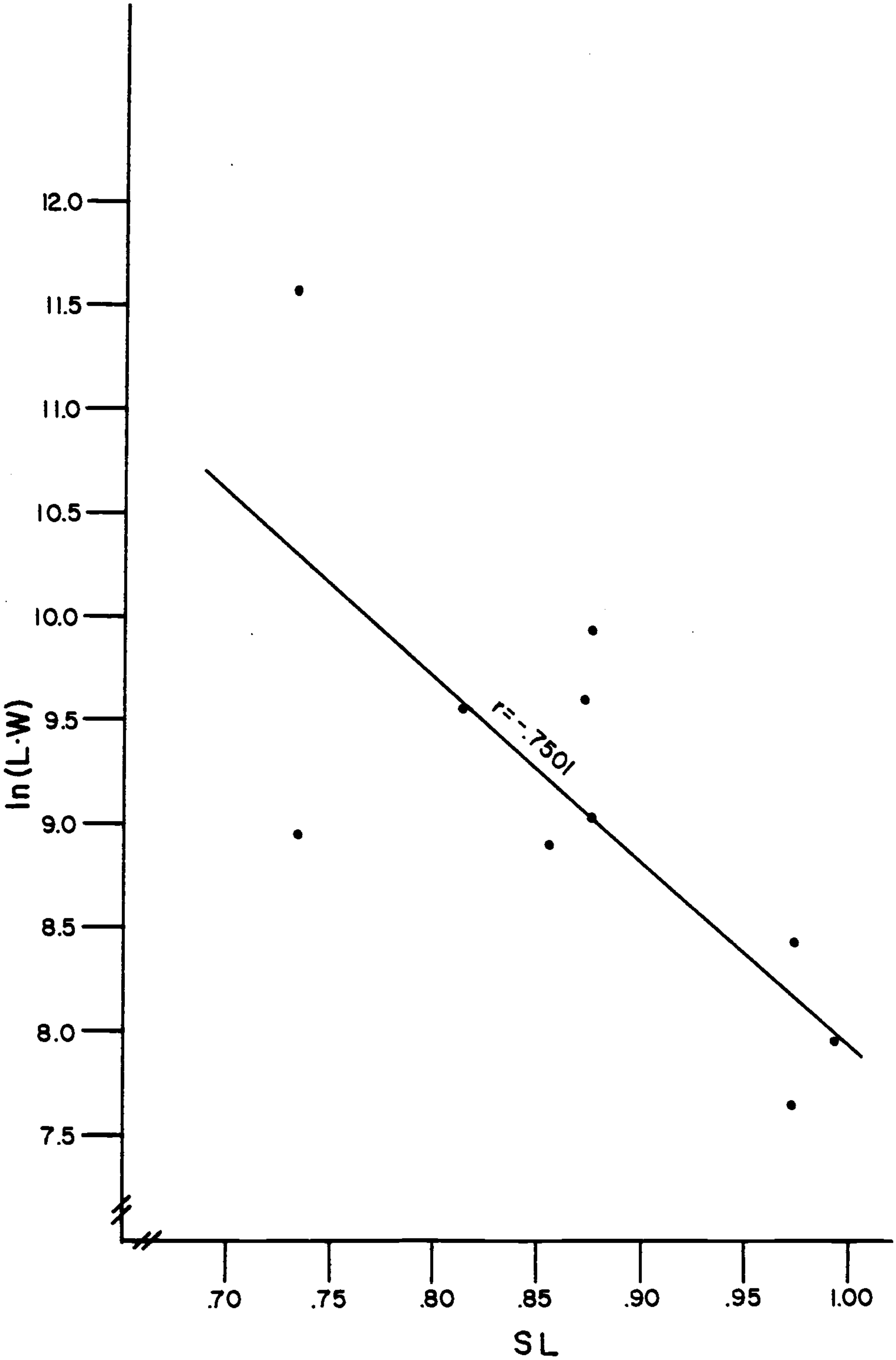


SLOPE VS. BACKWALL



900
800
700
600
W 500
400
300
200
100
0
r=-.5993
.70
.75
.80
.85
.90
.95
1.00
SL


140
120
100
80
60
40
20
L
r=-.7480
.70
.75
.80
.85
.90
.95
1.00
SL


12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
ln(L·W)
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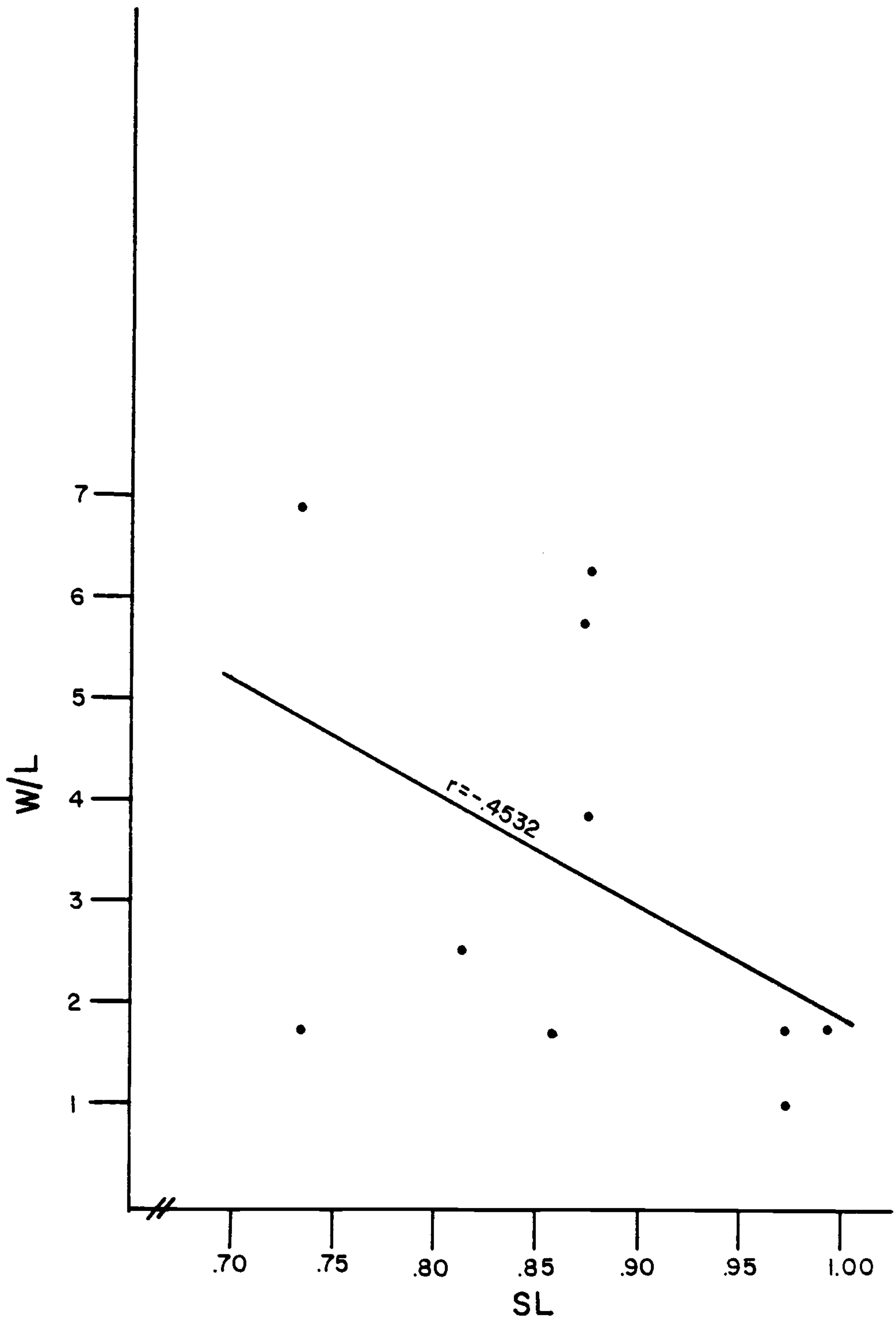
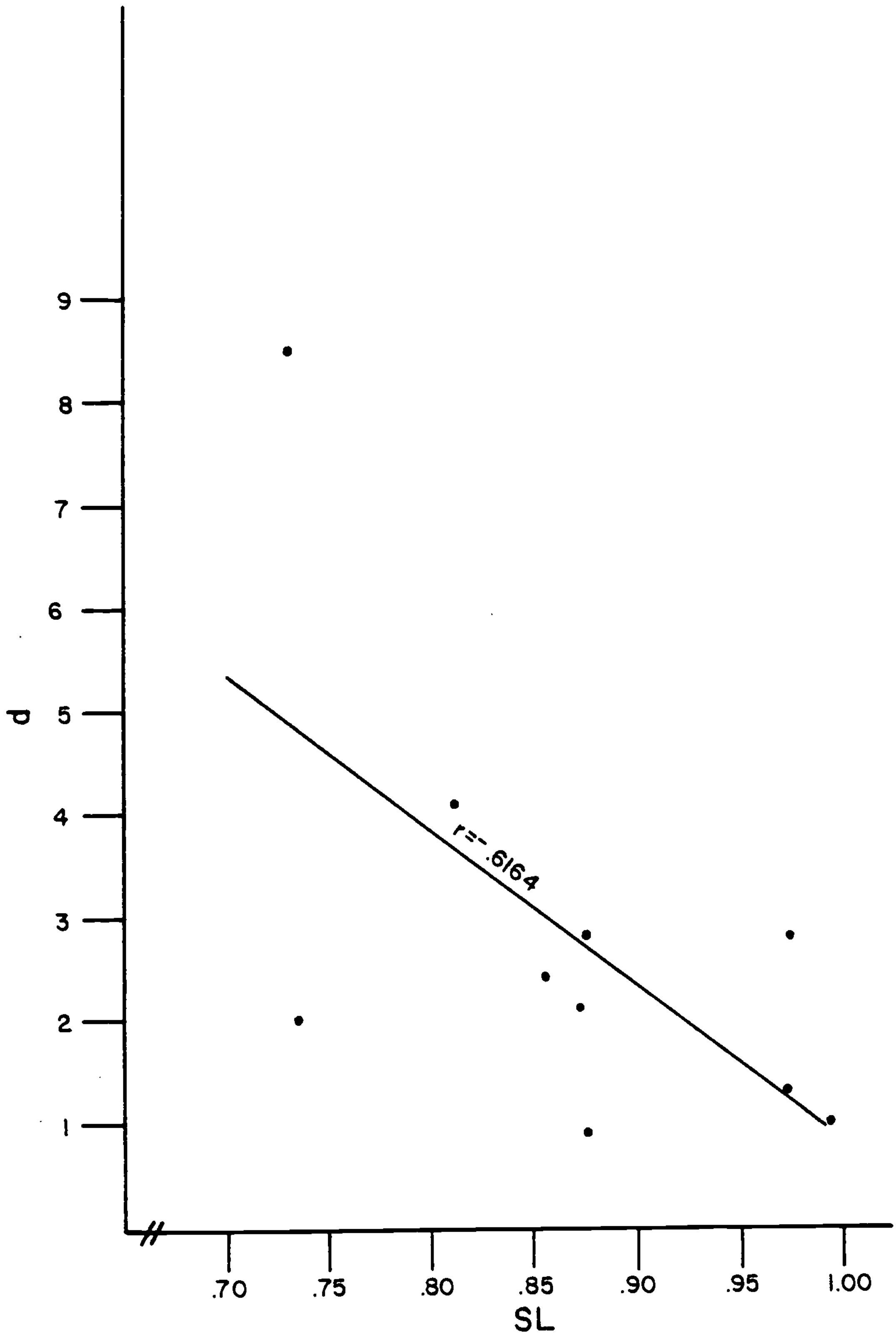
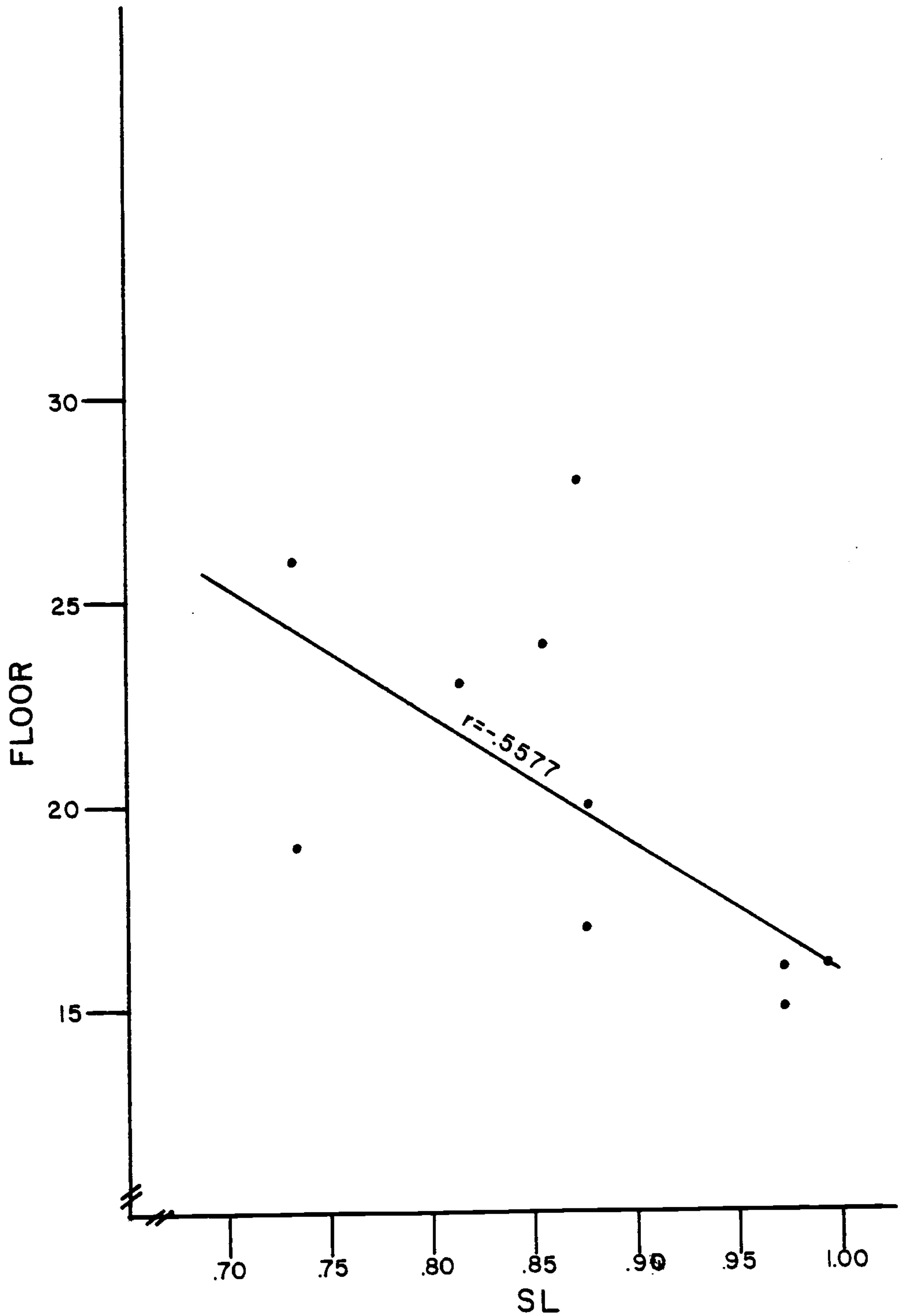
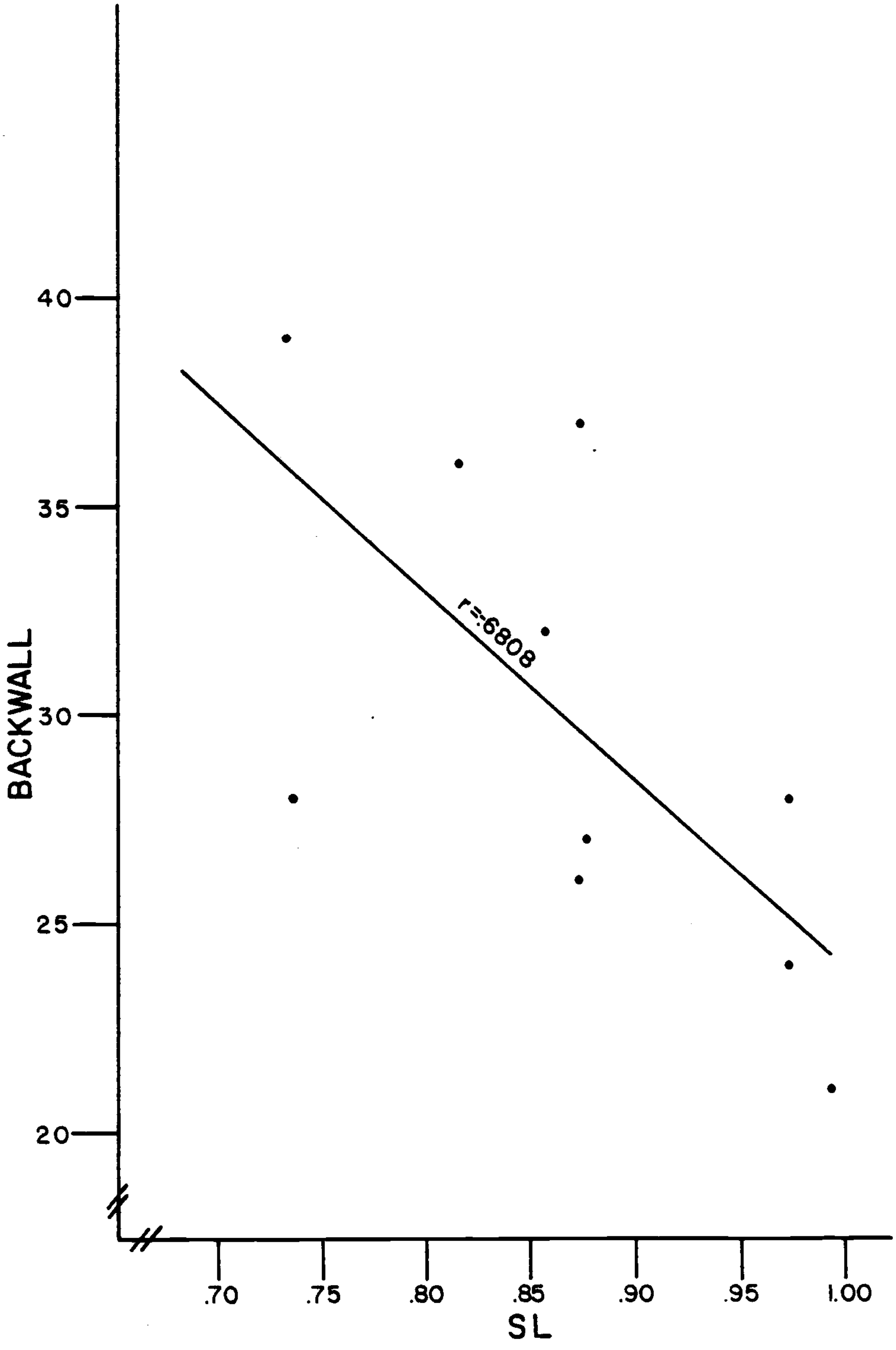
.70
.75
.80
.85
.90
.95
1.00
SL



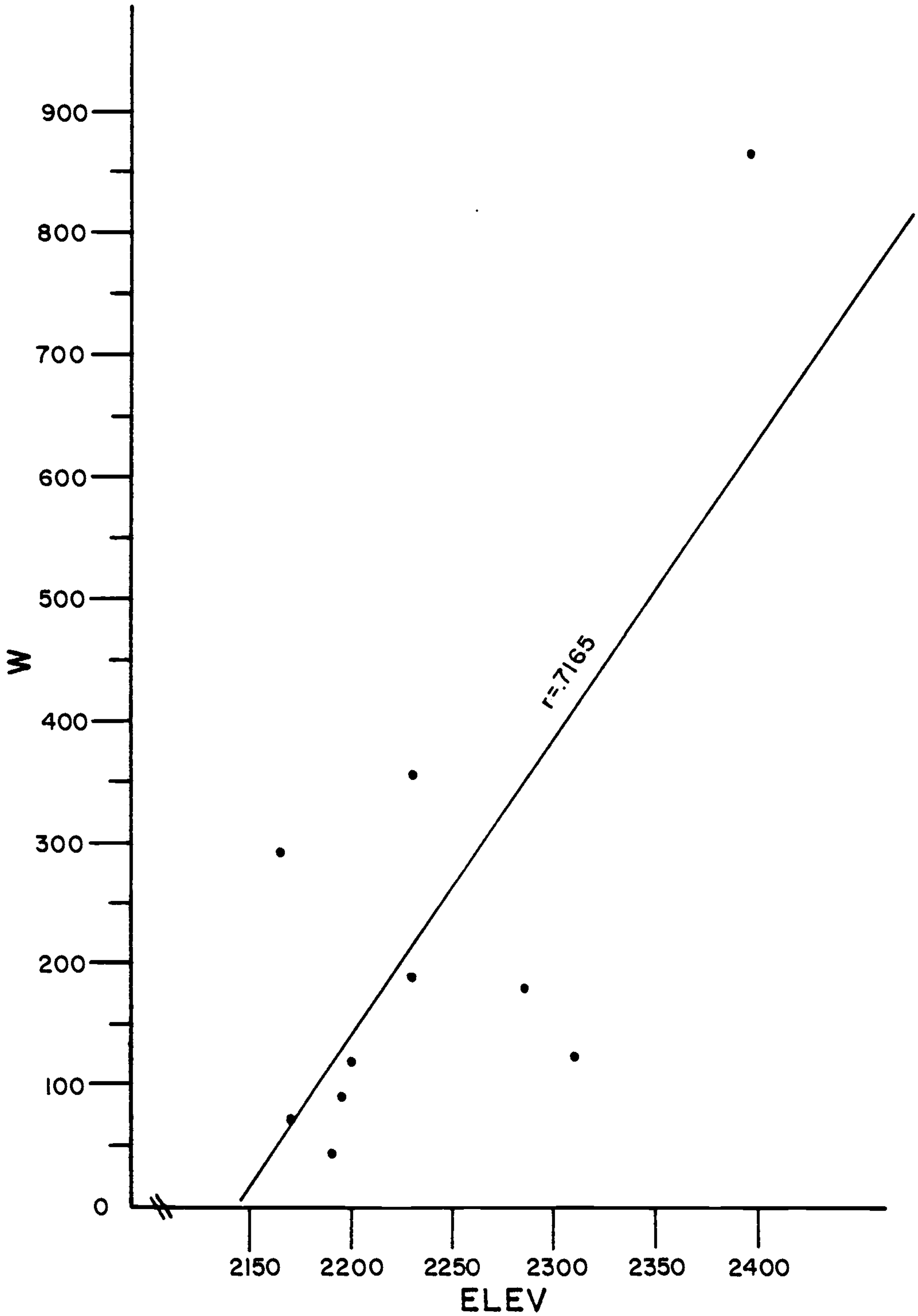
W/L
7
6
5
4
3
2
1
r=-.4532
.70
.75
.80
.85
.90
.95
1.00
SL


9
8
7
6
5
4
3
2
1
d
r=-.6164
.70
.75
.80
.85
.90
.95
1.00
SL

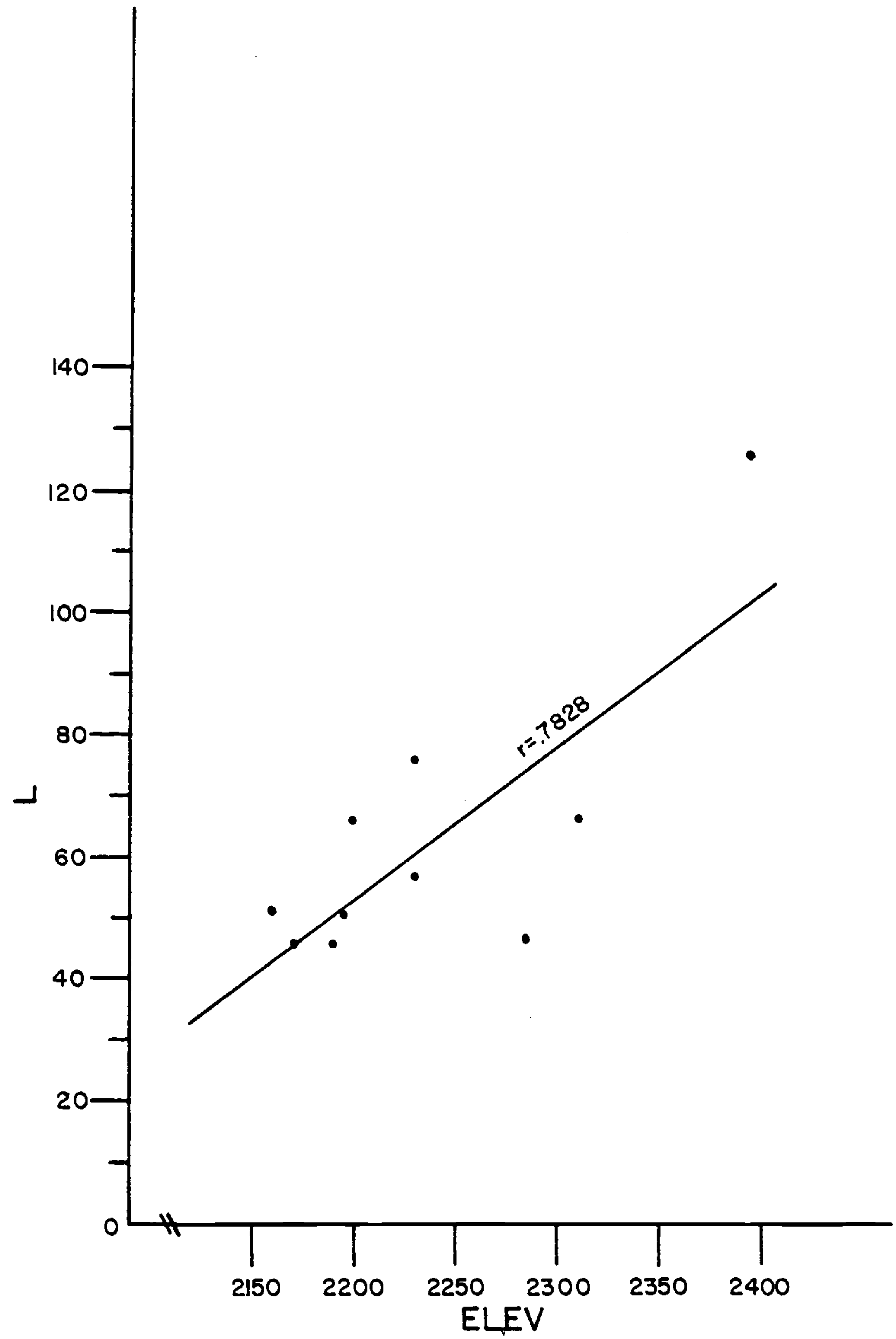

30
25
20
15
FLOOR
r=-.5577
.70
.75
.80
.85
.90
.95
1.00
SL

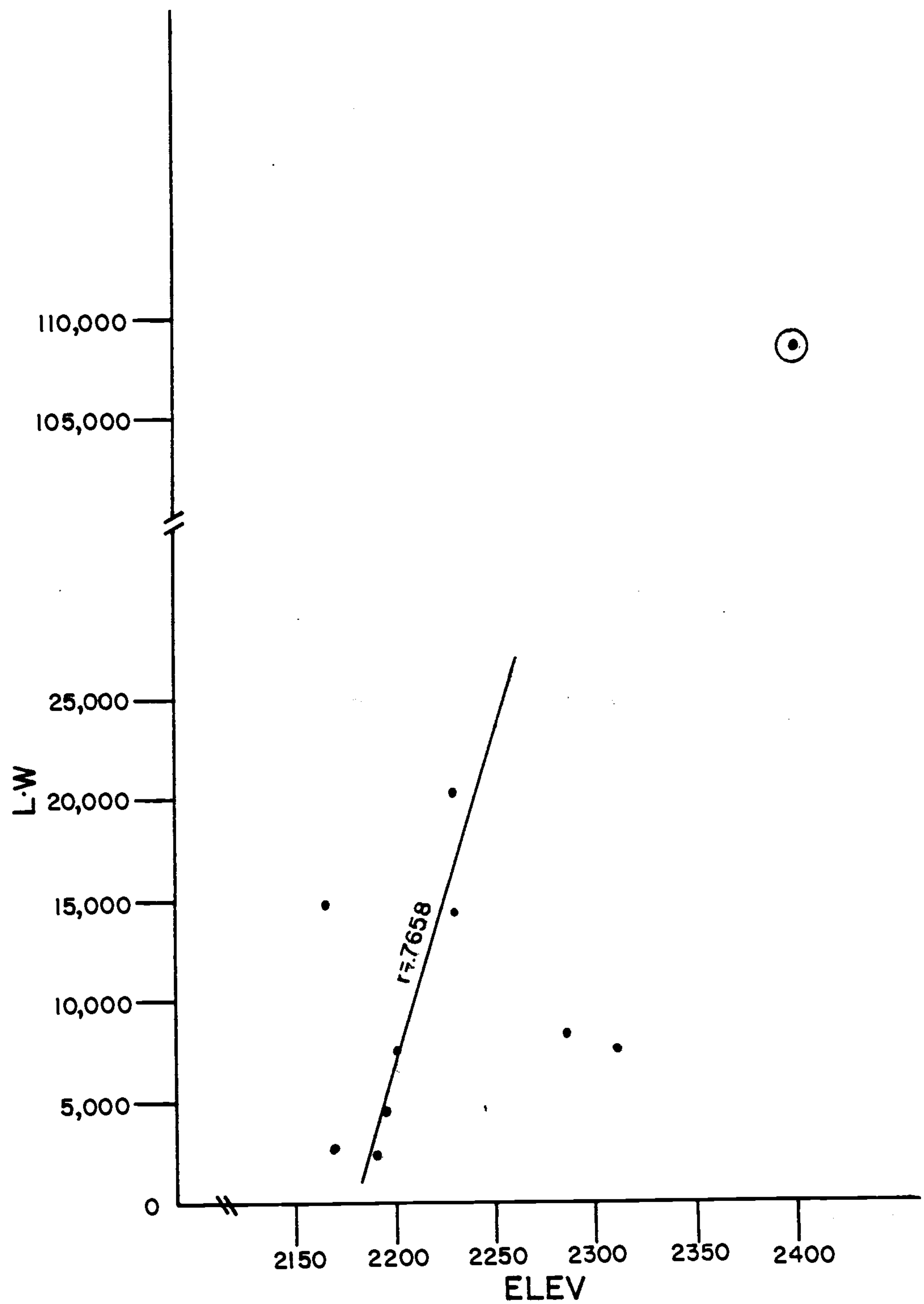


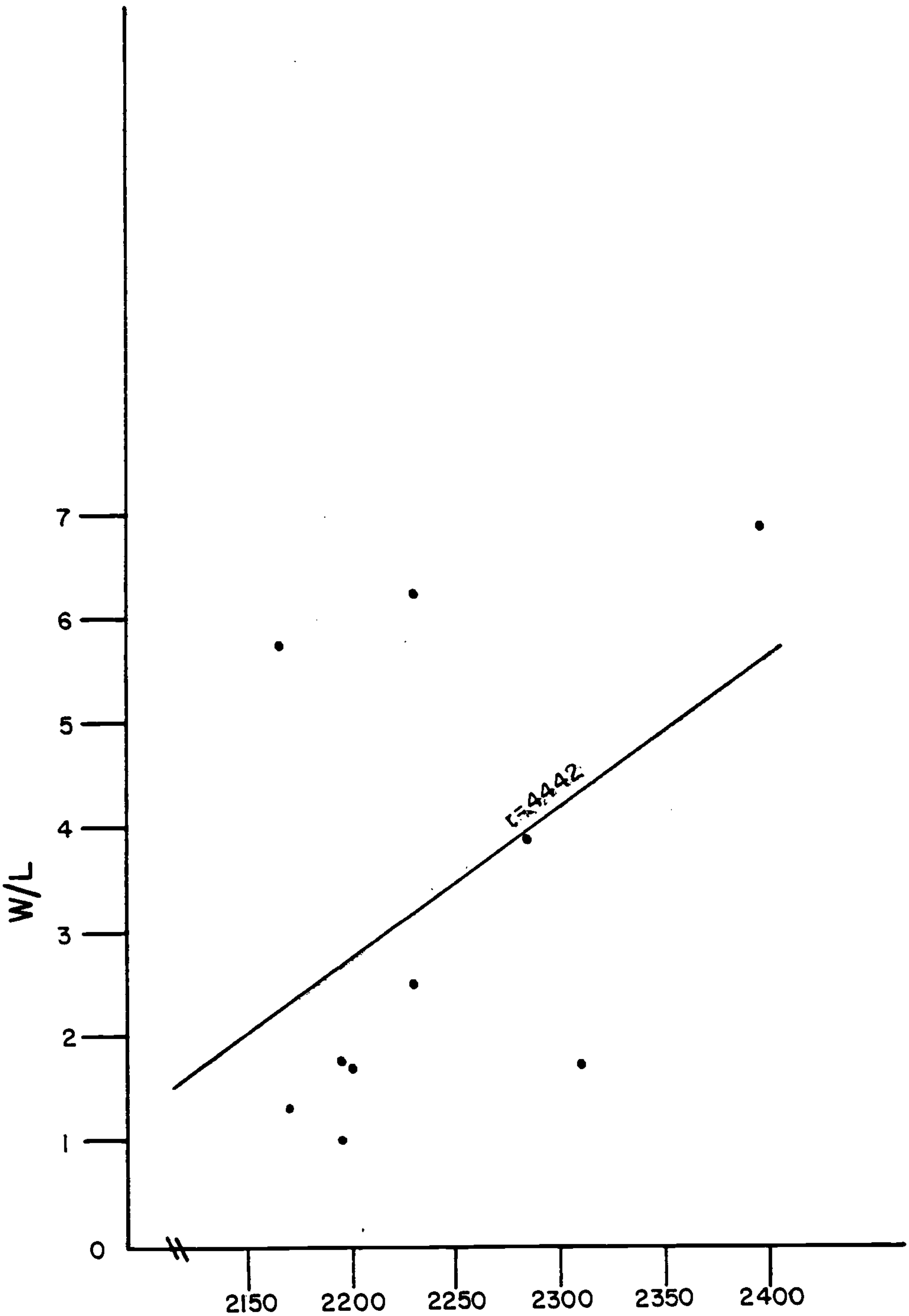
BACKWALL
40
35
30
25
20
r=-.6808
.70
.75
.80
.85
.90
.95
1.00
SL



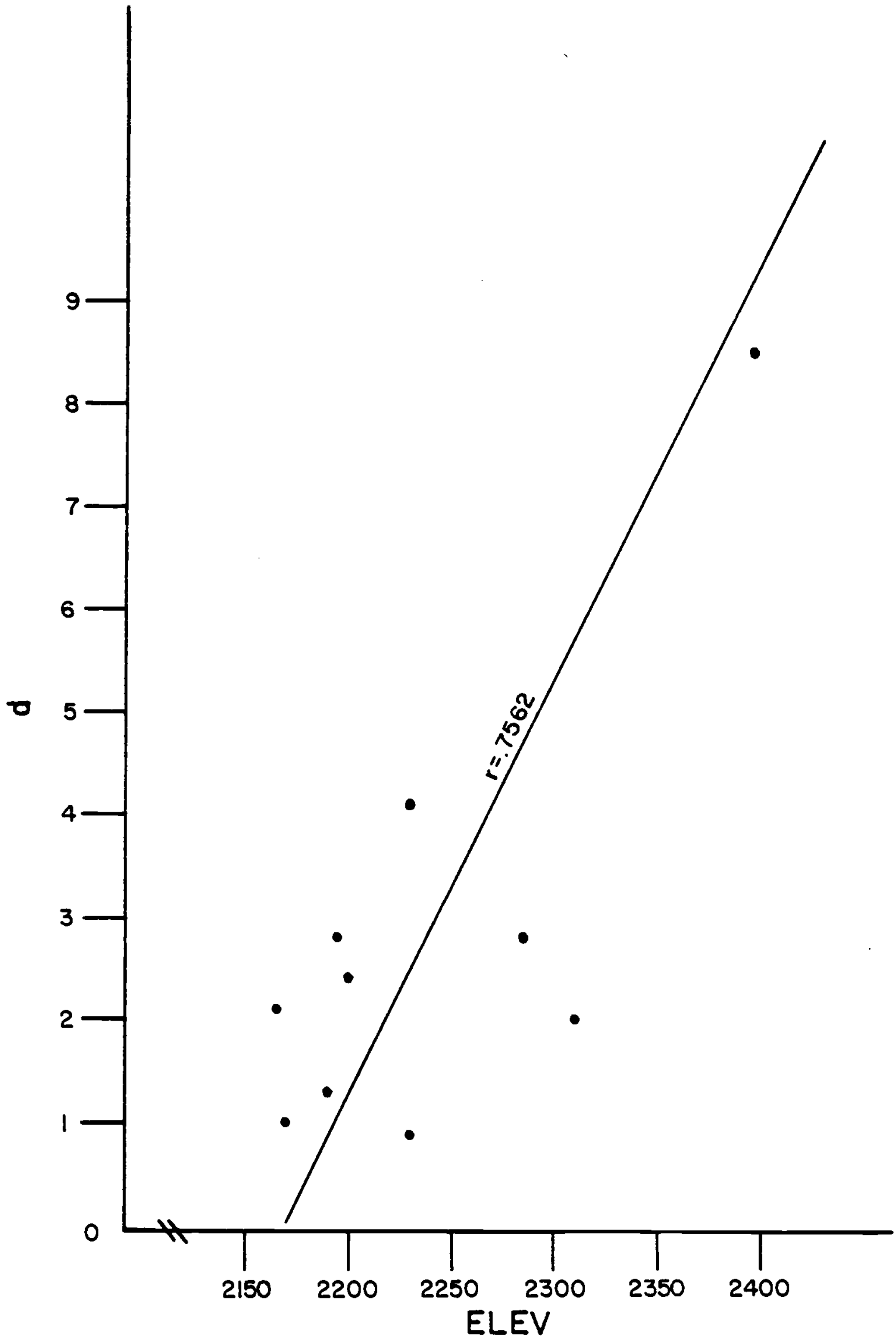
W
900
800
700
600
500
400
300
200
100
0
r=.7165
2150
2200
2250
2300
2350
2400
ELEV


140
120
100
80
60
40
20
0
L
r=.7828
2150
2200
2250
2300
2350
2400
ELEV


110,000
105,000
25,000
20,000
15,000
10,000
5,000
0
L·W
r=.7658
2150
2200
2250
2300
2350
2400
ELEV



W/L
7
6
5
4
3
2
1
0
r=.4442
2150
2200
2250
2300
2350
2400
ELEV


d
0
1
2
3
4
5
6
7
8
9
r=.7562
2150
2200
2250
2300
2350
2400
ELEV

APPENDIX III

Nonparametric Statistics

Kendall's tau and S (Hammond and McCullagh, 1974

X and Y variables are ranked. X varible is put in sequence. Starting with the first Y value, compare to subsequent Y values. If greater, assign +1, if less, assign -1, if equal, assign 0. Start with 2nd Y value and repeat. Sum these values. This sum is the S statistic.

$$\tau = S/\tfrac{1}{2}N(N-1)$$

Correction for ties:

$$\tau = s/\{\tfrac{1}{2}N(N-1) - Cx\}^{\frac{1}{2}}\{\tfrac{1}{2}N(N-1) - Cy\}^{\frac{1}{2}}$$

where $C = \frac{1}{2}\sum t(t-1)$ $\quad t = \#$ of ties

Theil's C (Hollander and Wolfe, 1973)

This tests Ho: $\beta = 0$

Compute differences: $Di = Yi - \beta oXi$ $\quad (\beta_o = 0)$

Put X's in order, $x_1\ x_2\ \ldots x_n$

$$C = \sum_{i>j}^{n} c(Dj - Di)$$

$$c(a) = \begin{cases} 1 \text{ if } a > 0 \\ 0 \text{ if } a = 0 \\ -1 \text{ if } a < 0 \end{cases}$$