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QUANTITATIVE ANALYSIS OF LONGITUDINAL STREAM PROFILES OF SMALL WATERSHEDS

Technical Report No. 18
Project NR 389-042
Contract N6 ONR 271-30
Office of Naval Research

by

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Abstract

Previous investigators used logarithmic, exponential, and power functions for equations of long stream profiles. Rational bases exist for the possible validity of all these forms.

To determine the applicability of these equations to low-order streams, six small areas were tested by map and field studies. Individual profiles in the Salt Run, Pennsylvania, area are not simple curves, but are segmented, each segment corresponding to a given order. Graphical and statistical tests show individual segments to be concave-up but not necessarily best-fitted by any one equation. A composite profile having mean properties of segments of successive orders appears to be best described by a logarithmic equation. The mean altitude change for any order segment appears to be a constant, independent of order.

In the Highlands Ranch, Colorado, area two generations of topography exist. The older, more subdued topography is characterized by a constant mean altitude difference in first- and second-order segments. The younger topography possesses steeper gradients and shows increase of altitude change with increasing order. Apparently the older topography is being destroyed by the younger. A constant mean altitude difference is considered typical of the steady state, but not of topography undergoing rapid rejuvenation. The small nick points present in the older topography may yield appreciable sediment to the drainage system. Individual segments are typically linear, with gradients decreasing at each increase in order. The Long Canyon, Colorado, area resembles the Highlands Ranch area in that segment profiles are typically almost linear, although the former area is higher, cooler in climate, and underlain by resistant rock.

The Manitou Park, Colorado area has been so seriously affected by numerous stages of pedimentation and rejuvenation that the mean altitude changes vary erratically with order. Apparently the rejuvenations have altered altitude changes without affecting segment lengths.

The Widow Woman Canyon, Colorado, area resembles the Salt Run area in that the mean altitude difference is a constant. Profiles are segmented, individual segments varying in form between a straight line and a concave-up curve.

The Chileno Canyon area is typified by a constant mean altitude difference. Profiles are segmented, individual segments being concave-up, like the Salt Run profiles. The composite profile is logarithmic.

Profile segmentation appears to be due to changes in the relationship between sediment load and discharge at a change in order. Gilbert's flume experiments indicate the general up-concavity of stream profiles results primarily from downstream increases in discharge. Linear segments may, however, be the natural stable forms of low-order stream profiles in dry climates. Horton's laws of stream length and stream slope are confirmed by the data gathered in this study.

Introduction

This paper deals with the geometric form of longitudinal profiles of streams of low order. Heretofore, little or no reference has appeared to the profiles of these small channels, which comprise the numerous branches close to the upper ends of drainage systems. Research on longitudinal profiles of large trunk streams has long been a subject of publications, whereas the small branches have been neglected. Much is known about the shapes, sizes, and valley-side slopes of small basins in relation to their order. This paper attempts to add to our knowledge and understanding of stream profiles of these small basins and thus to complete the investigation of general morphometric relationships among small drainage basins in a fluvially-eroded landmass.

The longitudinal profile, or long profile, of a stream may be defined as a line on a graph, on which the altitude of a point on the stream is plotted against the horizontal distance of that point from an arbitrary zero point, following the stream's course. A stream tends to remove initial irregularities, attaining the form of a smoothly graded up-concave profile of equilibrium which will tend to be maintained approximately, but slowly readjusted to lower slope and elevation, throughout the cycle of landmass denudation. A profile of equilibrium is considered to indicate that the stream has achieved a steady state in which, over a period of years, the stream gradient and channel characteristics are delicately adjusted to provide with available discharge just that velocity required for the transportation of load supplied to the stream by the tributary streams and slopes (Mackin, 1948).

Strahler (1950, p. 676) has advanced the idea that any small drainage basin is an open system, in which certain topographic forms, called equilibrium forms, may achieve a time-independent condition. When this condition is reached, the system is said to be in a steady state of operation. Slopes of both valley sides and stream channels are then graded. Because of the slow rates of change under geologic processes, it is difficult for an observer to determine the existence or non-existence of graded profiles, or a steady-state condition. One approach to this problem is through the study of badlands, in which erosion rates can be determined over a period of several years (Schumm, 1956). From a study of a small badland in New Jersey, Schumm concluded that parallel slope retreat was occurring there. This is one example of the steady state, wherein the slopes maintain a constant angle as material is eroded from their surfaces.

The longitudinal profile of a stream may be considered a specific type of slope within a drainage basin, probably the most gentle slope to be found in a given basin, save perhaps for small areas on the divide bounding the basin. Thus the profile is one element of the topography in an area of fluvial erosion. The properties of the stream profile investigated in this study include length as projected to a horizontal surface, altitude change, gradient, and mathematical form, and indirectly, the relation of these properties to discharge. The study deals primarily with small streams, either ephemeral (that is, carrying only storm runoff), or intermittent (that is, carrying water other than merely storm runoff, but drying up during dry seasons). Some of the streams investigated lack even a permanent channel, being marked only by a V-shaped valley cross-section, but nonetheless serve as troughs to concentrate runoff into channel flow. Because the forms investigated are small, but larger than those found in badlands, the study is, in a sense, an intermediate-scale study.

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Stream Profiles of Small Watersheds

METHODS OF INVESTIGATION

Selection of test areas

To investigate the nature of longitudinal stream profiles, the writer chose six areas on the basis of the presence of relatively homogeneous lithology and the availability of good topographic maps:

1. Salt Run, Pennsylvania
2. Highlands Ranch, Colorado
3. Long Canyon, Colorado
4. Manitou Park, Colorado
5. Widow Woman Canyon, Colorado
6. Chileno Canyon, California

Smith (1950) and Strahler (1950) have pointed out the need for using large-scale maps for such studies. All maps used by the writer were on the scale 1:24,000. Three of the areas were studied in detail in the field by the writer. Comparisons of map and field data are included for these areas. The areas investigated quantitatively were all basins of fifth order or less.

Stream orders

The assignment of order number to stream segments forms the basis for sampling profile characteristics in a drainage network. Horton (1945, p. 281) defined a first-order stream as one receiving no tributaries. A second-order stream is formed by the junction of two first-order streams, and can receive other first-order tributaries. A third-order stream is formed by the junction of two second-order streams, and can receive other second- and first-order tributaries. In short, the junction of two streams of like order forms a stream of next higher order, which can receive tributaries of any order lower than its own. Horton's system further requires that, after all streams have been classified, an investigator start at the mouth of the basin under study and reclassify part of the streams, continuing the higher order headward at a junction, following the tributary that is more nearly in line with the trunk stream. Thus, some of the unbranched tributaries have an order considerably greater than one. This relationship is illustrated diagrammatically in Figure 1a. Horton's system has two disadvantages: (1) determination of which tributary forms the headward extension of the main stream is often a subjective matter, and (2) the unbranched, or finger-tip, tributaries which are geometrically alike are not all of the same order.

These difficulties in Horton's system are eliminated by Strahler's (1952b, p. 1120) modification wherein the junction of any two stream segments of like order forms a stream segment of next higher order and all unbranched tributaries are of the first order. Strahler's system, shown in Figure 1b, was used by the writer in all studies described in this report. Stream characteristics thus always apply to specific stream segments of a given order.

Methods of map analysis

For the map study of all areas, portions of the topographic maps were enlarged photostatically to the scale 1:12,000. After basins were outlined, every channel indicated by V's in the contour lines was drawn on the enlarged map. Stream segments were classified by order, as explained above. In most cases, all segments of a given order were considered as one statistical sample. The altitude of the head and base of each segment was estimated to varying degrees of accuracy depending upon the contour interval, hence may be to the nearest 20 feet where contour interval is 40 or 50 feet, to 5 feet for large scale maps of 20 foot contour interval. The altitude difference (H) was found by subtracting one from the other. Length (L) of each stream was measured with a chartometer. Length readings were found to be generally reproducible to plus or minus one or two per cent of the mean of a set of readings. Average slope, or gradient, of each segment (H/L) was computed by slide rule. Values of H, L, and H/L for each order of stream segment for each basin were tabulated and statistically analyzed as described below.

Special methods using air photographs were applied in the Manitou Park area and to the headwaters of White and Loy Gulches (see Figures 33, 34). In this study, all streams visible stereoscopically on the air photographs at a scale of 1:20,000 were traced out on the photographs. A part of the Mount Deception map sheet was enlarged photostatically to the scale 1:12,000. This topographic map was then modified to show all of the channels visible on the photographs, and all of the streams were drawn on the large-scale map. Values of H, L, and H/L were computed as above.

Special map sampling methods were applied to the Widow Woman Canyon area because of the large number of stream segments available. The topographic map was found by field reconnaissance to be accurate in so far as one could tell without measurements and was enlarged photostatically to the scale of 1:12,000. All streams indicated by V's in the contour lines were traced out. Segment samples were selected in the following manner. The first-order sample was selected by starting at the mouth of the basin with the first first-order tributary and then, moving in a clockwise direction, numbering every sixth first-order tributary. Thus, out of 626 unbranched tributaries the sample consisted of 105 stream segments. Similarly, the second-order sample was made up of every other second-order segment, and contained 67 out of a total of 135 second-order segments in the basin. All third- and fourth-order segments were measured. Calculations of H, L, and H/L were then carried out as previously described.

For the Chileno Canyon area, California, data were gathered from a part of the Chileno Canyon topographic map photostatically enlarged to the scale of 1:12,000. The area was not visited in the field. All stream channels indicated by V's in contour lines were traced out. For the first-order sample, every third unbranched channel was measured. Length (L) data were gathered by Stanley A. Schumm (1956). Values of H and H/L were computed as before.

Reliability of map measurements

A study of accuracy of determinations of stream lengths from topographic maps was made by Morisawa (1957) for small drainage basins of low drainage density in the Allegheny section of the Appalachian Plateaus in northern Pennsylvania, a locality essentially similar to the Salt Run area of this report. Morisawa used topographic maps on the scale of 1:24,000, contour interval 20 feet, prepared by multiplex methods and published in 1950. She outlined the drainage net from contour indentations on the map, then measured the stream channels in the field in the same basins. For twelve basins less than 0.5 square miles in area and seven basins between 0.5 and 2.68 square miles, the measurements were generally in close agreement. In some basins the map-measured lengths were less than field-measured lengths; in other basins the reverse was true. A *t*-test of paired differences shows that the two classes do not differ significantly, the probabilities associated with observed values of *t* being greater than 40%.

This study is reassuring and tends to support the validity of stream length data based on modern large-scale maps in areas of very low drainage density. Disparity between map and field measurements of stream length would be expected to increase with drainage density and might reach a serious level with even intermediate drainage density values. This is shown by Coates (1958), who compared map and field data in southern Indiana. He used a modern U.S. Geological Survey topographic map on a scale of 1:24,000, contour interval 10 feet, for determination of stream length and other morphometric properties. A plane table map on a scale of 1:600 was made of a small drainage basin shown on the topographic map. For this region generally, Coates concluded that first-order channels are rarely shown on the topographic maps; second order channels are seldom shown; and most channels interpreted as first-order from contour inflections on the map are in reality third order channels, although in some instances they may be large second-order channels. Drainage densities computed from the two field maps are 26 and 83, compared with an average map-measured value of 16 for ten basins designated as third order by map methods.

These observations by Morisawa and Coates suggest that no simple correction can be applied generally to map data to yield a close approximation to field conditions, even where the maps are of a modern large-scale type prepared from air photographs under uniform procedures. These findings suggest that map studies should be accompanied by field measurements wherever possible to ascertain the degree of correspondence typical of a given region and a given map series.

Considerable attention was given by the writer, therefore, to comparison of corresponding field and map data, a subject treated in detail below.

Field methods

Field studies ranged from reconnaissance visits in which topographic features seen on the ground were compared with corresponding contour representation on the map, to detailed field surveys in which stream length and elevation were measured directly.

Field reconnaissance only was made in the Salt Run, Pennsylvania, and Widow Woman Canyon, Colorado areas. In both areas the relief is great, a factor tending to reduce the relative errors in estimating elevation differences. Morisawa's studies near the Salt Run area have shown the high degree of reliability of topographic map data in the coarse-textured topography prevailing there. No field visit was made to the Chileno Canyon, California area.

Detailed field surveying was required in the Highlands Ranch, Colorado, area, where the writer measured directly the 24 first-order and 6 second-order profiles in the headwaters of the Cheese Ranch basin and 21 first-order and 7 second-order profiles in the upper part of the Highlands Ranch Basin. One of the second-order profiles in the second basin was incomplete, so was not used in the statistical studies. Because the writer worked alone, it was necessary to stake down one end of the steel tape for every distance measurement. The stake used was a spike at the base of a light rod which supported a target fixed at the eye height of the observer. The vertical angle was read with an Abney level, calibrated in ten-minute intervals, sighted at the target. The field data thus consisted of vertical angle and slope-distance measurements. The field data were reduced to H, L, and H/L values by simple trigonometry. The writer used the same instrumental methods, determining aximuth with a Brunton compass, to prepare a large-scale contour map (Figure 22) of one of the nick points in the Cheese Ranch basin discussed elsewhere in this paper.

Field surveys in the Long Canyon area consisted of detailed measurement of 20 first-order, 8 second-order, and 3 third-order profiles using steel tape and Abney level. The writer worked alone, using the same equipment as in the Highlands Ranch area. In many cases the stream bottoms were so heavily choked with vegetation that the writer was forced to run the traverse parallel to the stream bottom, a few tens of feet to the side of the stream, occasionally making a side shot down to the valley bottom. For this reason, the profiles are not as precise as those for the Highlands Ranch area. The slope distance-vertical angle data so obtained were reduced to horizontal and vertical distances by simple trigonometry. The field work was supplemented by stereoscopic examination of air photographs, both to locate tributaries in Long Canyon basin, and to prepare the geologic map showing the general setting (Plate 1).

In the Manitou Park area the writer surveyed the altitudes of the head and the mouth of 42 first-order tributaries, using a Terra surveying altimeter, model SA2, calibrated in five-foot intervals. Before the measurements were made, the altimeter was set at a checked elevation shown on the Mount Deception topographic map. The readings were corrected by methods described by Lahee (1952, pp. 470-478). The difference between the two corrected readings for any one tributary is the altitude difference (H).

Statistical Analysis of H, L, and H/L data

The values of H, L, and H/L were tabulated and tested to determine the manner in which the sample variates are distributed. (Strahler, 1954, p. 8). This test consists of plotting the class mid-values against cumulative per cent frequencies, the latter being plotted on either a conventional probability or a logarithmic probability scale. If the points so plotted fall in a reasonably straight line on the normal probability paper, one can assume that the variates are drawn from a normally distributed population. If, however, the points are more linearly distributed on the logarithmic paper, one may assume that the variates have a logarithmic normal distribution. This graphic test is not as precise as fitting normal curves to the distributions and comparing the goodness of fit of the alternative curves, but is much faster and was deemed to be of sufficient accuracy for this investigation. H and L for any particular order were found generally in all areas studied to follow a log normal distribution, whereas H/L follows an arithmetically normal distribution. Values for the mean, variance, and standard deviation of H, L, and H/L for each order were calculated. Histograms, with tabulated data, are shown in Figures 5, 24, 25, 26, 36, 38, and 41.

Where interest centered upon the difference between observed means for any two samples, as for example the difference between map and field data for the same basin, or the difference between two adjoining basins, the statistic $\underline{t}$ was used to test the significance of the observed difference (Dixon and Massey, 1951, pp. 102-104; Strahler, 1954, p. 12-13). Following standard procedures, the null hypothesis is set up that both samples have been drawn from the same population. A critical probability value, α, is selected below which the hypothesis will be rejected. In this report, the critical probability if taken as .05. Thus if the probability associated with a given value of $\underline{t}$ is larger than .05, the hypothesis is accepted and the observed difference in means is judged not significant. In all cases the value of probability, P, is stated for all $\underline{t}$ tests so that the reader can apply his own standard for acceptance or rejection of the statistical hypothesis. Results of $\underline{t}$-tests of pairs of samples are given in Tables 3, 4, 5, and 7 and Figures 19, 20, and 21. Use of the $\underline{t}$-test is limited to cases in which only two samples are available for comparison. Should three or more means require testing, the one-way analysis of variance (single variable of classification) would be used, with the statistic $\underline{F}$. In this report, where three or four sample means were to be tested, they were associated with an ascending sequence of stream orders. Because interest centered upon the manner of change of the properties with order, regression analysis was used, rather than analysis of variance.

Regression analysis was used to relate H, L, and H/L, as dependent variables, to segment order, the independent variable. Figures 6, 27, 28, 31, 37, and 42 show the data graphically and state the essential equations and statistical parameters. In any such investigation it is desirable to select the scale of relative rates of increase on both abscissa and ordinate in such a manner that the regression is linear, i.e. that the observed points tend to fall about a straight line, without obvious and consistent tendency to concavity or convexity. Arithmetic and logarithmic scales may be used in four combinations: arithmetic scales on both ordinate and abscissa (simple linear function); logarithmic scale on the ordinate but arithmetic on the abscissa (exponential function); arithmetic scale on ordinate and logarithmic on abscissa (logarithmic function); and logarithmic on both scales (power, or log-log function).

Because tests of sample distributions for normality (Gaussian distribution) showed H and L to be characteristically logarithmic-normal in distribution, the raw data (observations) of H and L were transformed into logarithms (base 10) and grouped into equal log classes (See, for example, Figures 5 and 38) for frequency distribution analysis. This procedure dictated the use of log H and log L on the ordinate in regressions of height and length on order, because an assumption in regression analysis is that the distribution of the dependent variable is normal with respect to the theoretical value of the fitted regression line. Use of arithmetic values of L would also be undesirable because it would produce strongly up-concave plots inasmuch as ratio of increase with order is large. Tests of distribution of H/L variates within a sample showed characteristic arithmetic normality, so that H/L numbers have been used without logarithmic transformation. Plots of H/L on order, both scales arithmetic, show the simple linear regression to be appropriate in some cases, but that a marked up-concavity exists in others. The subject is treated in detail elsewhere in this report.

The statistical significance of all 18 regressions of H, L, and H/L on order was determined. Order, the independent variable, is designated as "X" in the regression. The dependent variable, designated "Y", is log H, log L, or H/L. (In Salt Run only, log H/L was used, because this treatment gave a much more nearly linear fit). The regression coefficient, b, and the numerical constant, a, were computed by a least squares method. The scatter, $S_{y.x}$, was calculated for each regression.

A _t_-test of significance of the slope of the regression was applied (Dixon and Massey, 1951, p. 160). This "Test for Independence" tests the hypothesis that in regression analysis a variable Y is independent of a variable **X**. If independence exists, the mean Y is the same for each value of **X**, which means that B = 0, where B is the slope of the population regression. Our statistical hypothesis is therefore: B = 0. After selection of the level of significance, α, the statistic _t_ is computed, where

$$t = \frac{(b-0)\,S_x\sqrt{N-1}}{S_{y.x}} \qquad (1)$$

In this equation, the estimated standard deviation of the x-variates,

$$S_x = \sqrt{\frac{\Sigma x^2 - (\Sigma x)^2/N}{N-1}} \qquad (2)$$

Three significance levels have been used: .10, .05, and .01. The results are given on Figures 6, 28, 37, and 42 as _Sig._ (means "significant") or _N.S._ (means "not significant") for all three levels of significance. In general, use of the .10 level has the advantage of reducing the β-error; that is, the possibility of accepting the statistical hypothesis, B = 0, when it is actually false. We are looking for an expected relationship between H, L, and H/L and order, so we will want to decrease the possibility of the β-error. In surveying the results of the analyses, it is seen that quite a number are significant regressions at $\alpha = .10$, but not significant for the smaller values of α. To limit the test by $\alpha = .05$ or smaller would cover up many relationships that probably do exist but which are shown poorly because of the small number of pairs in the regression.

Regression of log H on order (Figures 6, 28, 37 and 42) was exceptionally varied from area to area. In Salt Run (Figure 6) and Chileno Canyon (Figure 42) areas large scatter and low value of regression coefficient yielded a non-significant relation of log H to order. The geological reason for this independence of variables is considered in a later section of this report.

If for a given order one includes by summation the mean values of H for all lesser orders, a different relief statistic, the _cumulative relief_, H', is obtained:

$$H' = \sum_{u=1}^{n} \overline{H}_u \qquad (3)$$

where u is order and $\overline{H}_u$ is the mean observed H for segments of order u, and n is the order under investigation. The relationship of H' to order shown in Figures 6 and 42 is very nearly linear, but the linearity is not apparent here because log H', rather than H' is shown plotted against order. This cumulative method of plotting is comparable in effect to using Horton's classification system in that the mean characteristics of a relatively high-order stream include characteristics of numerous lower order stream segments.

If one plots the logarithms of the mean values of L against order, L can be seen to increase generally with the logarithm of order (Figure 6 and 42). If, however, one plots the logarithms of cumulative mean length L', or

$$L' = \sum_{u=1}^{n} \bar{L}_u \tag{4}$$

where n and u are defined as above, and $\bar{L}_u$ is the observed mean value of L for order u, the regression of log L' on order is more nearly linear, the curve appearing as a straight line.

Regressions of log L on order and log L' on order, if either proved linear, could be generalized into exponential functions

$$L = Ke^{k_1 u} \tag{5}$$

and

$$L' = Ke^{k_1 u} \tag{5a}$$

where K and k_1 are constants, and e the base of natural logarithms. Both are equivalent expressions of Horton's Law of Stream Lengths (Horton, 1945, p. 291) which states that "the average lengths of streams of each of the different orders in a drainage basin tend closely to approximate a direct geometrical series in which the first term is the average length of streams of the first order." The law may be written

$$L_u = L_1 R_L^{(u-1)} \tag{6}$$

or

$$L_u = L_1 R_L^{u} R_L^{-1} \tag{6a}$$

in which L_u is the mean length of segments of order u; L_1 the mean length of first order streams; and R_L is the length ratio. The exponential functions (5, 5a) can readily be transformed into Horton's Law by (1) substituting L_1 for K and R_L^{-1} for e^{k_1}, and (2) defining the function only for integer values u = 1, 2, 3, ... s. where s is the order of the trunk stream.

As Horton stated the law, the expression "the average length of streams of each of the different orders" was intended to conform with his system of defining stream orders. As explained above, Horton's order system carries every stream of order greater than one headward to include a single finger-tip tributary (Figure 1), whereas Strahler's system limits the order designation to a stream segment between junctions. Horton's system therefore yields fewer numbers of streams of each order lower than the trunk stream, but the average lengths are correspondingly longer for each order greater than one and the discrepancy increases as order increases. Therefore, the validity of Horton's law may depend upon the manner of defining order. Equation (5) uses Strahler's definition of stream order; the length L being the mean length of segments of a given order. Equation (5a) using cumulative stream lengths, has an effect in the same direction that would be achieved by using Horton's definition of stream order, namely to increase the length parameter of streams of successively higher orders.

Strahler (1952a, p. 1137) plotted log of mean length of stream segments (identical with L as defined above) against stream order for six localities differing widely in lithologic, climatic, and tectonic controls. All six plots show a nonlinearity characterized by up-concavity of a fitted curve. Subsequently, on the basis of similar results in other localities, Strahler (personal communication) has questioned the validity of Horton's law of stream lengths when order is defined by his method. As a substitute, Strahler (1957, p. 915) proposes a power function in which log of total stream length in each order is a function of log of order.

The writer's regressions of L on order (Figures 6, 27, 28, 31 and 42) show a marked up-concavity in all areas except Salt Run, bearing out the observation that Horton's law of stream lengths is not followed when the Strahler numbering system is used. On the other hand, the regression of L' on order (Figures 6 and 42) show reasonable linearity and form the basis of a tentative conclusion that Horton's Law holds for cumulative lengths.

Method of single-channel profile plotting

In the Salt Run and Chileno Canyon areas single-channel profiles were plotted from topographic maps from the heads of selected first-order channels down to the lower ends of higher order channels. In the Salt Run area, four profiles were plotted down to the lower ends of the third-order channel segments; in the Chileno Canyon area a single profile down to the end of a fifth order channel segment (Figures 8 and 43).

In order to determine the general nature of any stream profile plotting may take one of four forms: (1) Simple linear form in which both altitude and distance are plotted on arithmetic scales. A straight line on such a plot is represented by the regression equation of the basic form Y = a − bX, where Y is elevation and X is horizontal distance. Although useful in providing a visual impression of the longitudinal profile the arithmetic linear plot yields a strong up-concavity for profiles including several orders and is therefore not used in curve fitting. (2) Exponential form in which altitude is on a logarithmic scale while horizontal distance is on an arithmetic scale. A straight line on such a plot is represented by the basic regression equation log Y = a − bX. (3) Logarithmic form in which altitude is plotted on an arithmetic scale on the ordinate against distance scaled logarithmically on the abscissa. A straight line on such a plot is represented by the regression equation of the basic form $Y = a - b (\log X)$. (4) Power form (log-log form), represented by the basic regression equation $\log Y = \log a - b \log X$. With appropriate definition of X and Y, the exponential, logarithmic, and power functions are capable of making the up-concave profiles more nearly linear.

Reference points in profile plotting

Of particular concern in the plotting of stream profiles in exponential, logarithmic, and power forms is the selection of meaningful reference points from which the arbitrary constants of these equations are derived. In the simple linear (arithmetic) plot the problem is trivial, because the assignment of arbitrary constants does not affect the geometry of the plotted profile. In the case of the logarithmic regression function, $Y = a - b \log X$, where X is distance downstream from the head of the profile, the equation cannot be solved for $X = 0$ because when $X = 0$ $\log X$ is not defined (approaches minus infinity). Adding to X an arbitrary constant, C, allows the head point to be plotted, for then when $X = 0$, $Y = a - b \log C$. Thus an element of horizontal distance must be added to the stream head to serve as the origin, or reference point, for the measurement of downstream distance. The degree of curvature of a given plotted logarithmic profile will, however, depend upon the values assigned to the constant. If the constant is treated as a third variable, the equation can be closely adjusted to fit a given profile, but in so doing the application of the function as a general case is seriously impaired. The problem, then, is to find a meaningful constant.

A reasonable reference point lies on the drainage divide of the watershed where intersected by the profile line projected in the upstream direction. The horizontal distance lying between the stream head and the divide is essentially equivalent to Horton's (1945, p. 284) length of overland flow, L_g. During the evolution of the drainage system L_g is adjusted to a magnitude appropriate to the scale of the first-order drainage basins and is approximately equal to one-half the reciprocal of the drainage density, D.

Because L_g may be difficult to select by headward projection of a curving or irregular stream channel, L_g is here defined unambiguously as the longest path of overland flow leading to the head of the channel (Figure 2). The divide point at which this path starts is taken as the reference point of the profile (point R in Figure 2). Correspondingly, H_g is defined as the vertical distance between reference point, R, and head of stream channel, O. The variable, Y, is defined as vertical drop from O to any point P on the stream. The variable, X, is defined as the horizontal distance in the downstream direction from O to any point P. In regression equations, the origin of numerical values shifts from point O to point R; the dependent variable becomes $(Y + H_g)$, the independent variable $(X + L_g)$.

Using the above system of definitions, the simple linear regression equation becomes

$$(Y + H_g) = a + b\,(X + L_g). \tag{7}$$

Figure 3A shows the manner of plotting this equation. If the stream maintained a constant slope, this linear equation would fit the stream profile. Although the constants H_g and L_g are superfluous in this equation they are used for purposes of consistent data treatment, keeping in mind that the two raw data columns will consist of $(Y + H_g)$ and $(X + L_g)$.

The logarithmic equation then becomes

$$(Y + H_g) = a + b \log (X + L_g) \tag{8}$$

which is shown in Figure 3B. The constant H_g is of not essential in this form of regression equation.

Turning to the exponential function, a difficulty again arises concerning arbitrary constants. The curve must be asymptotic with respect to the X-axis, because the stream slope must diminish downstream. Otherwise the function would not apply to the up-concave stream profiles, which are the almost-universal type. To achieve the desired form, the dependent variable of elevation must diminish with increasing downstream distance. That is to say, the first derivative of the function must decrease downstream. The term $(Y_o - Y)$, where Y_o is vertical distance between stream head, O, and end point, M, represents such a diminishing quantity, but is equal to zero at M. Therefore the logarithm of $(Y_o - Y)$ approaches minus infinity as the curve approaches the lower end of the stream segment and the point M cannot be plotted. Here, again, an arbitrary constant is needed. In most exponential river plotting to date (Krumbein, 1937; Shulits, 1936, 1941; Yatsu, 1955) sea level has been taken as the arbitrary reference base. Although this is a natural geological feature and can be unambiguously defined, there is good reason to think that it does not relate dynamically to the control of stream slope in the upper reaches of the stream and that its use will only create confusion and misrepresentation. Rubey (1952, p. 134) has amply stated as follows the reasons for concluding that the base level (level of water body into which a stream empties) controls only the vertical position of the profile, not its slope:

"...the graded slope at any point along a stream's course depends upon the volume of water and the amount and kind of load being carried there. None of these factors is influenced by the distance from or the elevation above the stream's base level, and the graded slope at that point is therefore determined, not by the conditions downstream but by duties imposed from upstream. And, inasmuch as the longitudinal profile of a stream is simply a continuous series of all the slopes at different points, the shape of the entire profile is likewise determined not by the distance from or elevation above base level but by these imposed duties, discharge and load. Here the objection may quite properly be raised that a stream is necessarily graded with respect to its actual base level. This is of course correct but only in the sense that the altitude rather than the shape of the curve or in mathematical terms the constant of integration, is fixed by the altitude of the local base level. The slopes at different points and the shape of the profile are controlled by duties imposed from upstream, but the elevations at each point and the actual position of the profile are determined by the base level downstream. This distinction may seem academic but its importance lies in the corollary that the profile of a graded stream may intersect the base level at an appreciable angle. In fact, it would rarely happen that the profile graded to fit the imposed duties, discharge and load, would also happen to approach the base level asymptotically."

As noted in connection with the logarithmic equation, the selection of different values of arbitrary constants results in different profile curves. Consequently the use of mean sea level as the arbitrary base of reference will be meaningless. The solution, discussed below, is to study the relation of slope, S, to distance downstream, where S is defined as dY/dX. This has the effect of removing the constant of integration, mentioned by Rubey above, from consideration. Nevertheless, should the exponential regression equation be plotted, it might take the form

$$(Y_c + Y_o - Y) = e^{-b(X+Lg)} \quad (9)$$

or

$$\text{Log } (Y_c + Y_o - Y) = -b\ (X + Lg) \quad (9a)$$

as shown in Figure 3C. The constant Y_c is the elevation of the end point M above sea level.

For the power function the problem related to added constants must be dealt with in both variables. Again, the curvature of the plotted profile can be varied by changing the constants. It has been shown that the constant Lg has some dynamical significance as a control in form development, so that the variable $(X + L_g)$ provides a justifiable means of expressing horizontal distance downstream. As with the exponential function, the problem of arbitrary base level can be avoided by plotting the slope, S, as a function of distance downstream. The power function for terms as defined above is as follows (Figure 3D):

$$(Y_c + Y_o - Y) = a\ (X + L_g)^{-b} \quad (10)$$

or

$$\log\ (Y_c + Y_o - Y) = \log a - b \log\ (X + L_g) \quad (10a)$$

In summary, the plotting of regressions of elevation on distance is useful only for the linear and logarithmic forms. Such plots are shown in Figures 7, 8, and 43 for the Salt Run and Chileno Canyon areas.

Regressions of channel slope on distance

Attempts to evaluate the goodness of fit of linear, logarithmic, exponential, and power functions to observed stream profiles have been based upon regressions of slope, S, and $\log_{10}$ S, to downstream distance (X + Lg) and $\log_{10}$ (X + Lg). Slope S, is here defined as ratio of vertical drop to horizontal distance within a very short element of stream channel. In practice, the vertical distance is taken as one or two contour intervals; the horizontal distance is the map distance between contour crossings. The distance downstream, X, is measured on the map following the channel line from the stream head to the midpoint of the particular short element of channel on which the slope has been determined.

Under this system, our new regression equations, derived by differentiation of equations 7, 8, 9, and 10, take the forms:

Linear: $S = b$ (11)

Logarithmic: $S = b/(X + L_g)$ (12)

Exponential: $\text{Log}_{10} S = b - b(X + L_g)$ (13)

Power: $\text{Log}_{10} S = \log ab - (b + 1) \log_{10} (X + L_g)$ (14)

or

$\text{Log}_{10} S = a' - b' \log_{10} (X + L_g)$ (14a)

Plots of log S on distance are shown in Figures 9, 10, and 11, for individual segments of four third-order streams in the Salt Run area. To determine if concavity exists, exponential and power equations were fitted by least squares method and the scatter calculated. Tests of goodness of fit, carried out as previously explained, are considered in the discussions of the Salt Run locality.

Method of plotting composite profiles

Composite profiles were prepared for the Salt Run and Chileno Canyon areas by the following method. Using the data of H and L in Figures 5 and 41, the mean values of H and L for a given order were used as the vertical and horizontal legs, respectively, of a right triangle, whose hypotenuse represents the mean profile of all segments of that order. Figures 12 and 44 show the two composite profiles. Triangles for each order are arranged in sequence to produce a composite profile composed of segments of successive orders.

As for the single-channel profiles, the slope S (equal to H/L) for each segment was plotted against distance ($X + L_g$) measured to the midpoint of each segment. Figures 13 and 45 show the arithmetic, logarithmic, exponential, and power regressions of slope on distance. These data are evaluated in a later section of this report.

THEORETICAL CONSIDERATIONS OF PROFILE FORM

Causes of up-concavity in stream profiles

That most graded streams display a longitudinal profile which is up-concave, if a relatively large element of the stream's length is plotted, is an observation so widespread in the published works on geomorphology that this must be regarded as the normal, or universal, form. The earlier literature on stream profiles is reviewed by A. O. Woodford (1951, p. 826) who mentions up-concave profiles of various forms proposed by Galileo, Tylor, Sternberg, Dunkelberg, I. C. Russell, Lake, and Exner (references are cited by Woodford). English geomorphologists, among them O. T. Jones (1924), J. F. N. Green (1936), A. A. Miller (1939), W. V. Lewis (1945, 1946), E. H. Brown (1952), and W. E. H. Culling (1956, 1957a, 1957b) have represented stream profiles as up-concave in form. American students of stream profiles, among them Gilbert (1877), Rubey (1931, 1952), Krumbein (1937), Mackin (1937, 1948), Shulits (1936, 1941) Woodford (1951), and Hack (1957) confirm the up-concavity of most stream profiles. Yatsu (1955) shows up-concavity of profile for several Japanese Rivers.

One instance of linear long profiles is reported by Maxson (1950) in the lower reaches of two fairly large streams draining the east flank of the Panamint Range, in eastern California. He considered the lower reaches to act essentially as chutes. These receive a heavy discharge of water and sediment from the higher parts of the basins, which receive rainfall in the form of occasional cloudbursts. Because of the limited area affected by any one storm, the discharge from this area would not be increased gradually by numerous small tributaries, as in more humid regions, but would maintain a constant flow until depleted by evaporation and percolation into the fan at the mouth of the canyon. This is obviously a special case, requiring special conditions for the formation of a stable linear profile.

Causes of up-concavity can be considered qualitatively as a step preliminary to proposing mathematical functions that will best describe the profile forms in detail. First, it will be assumed that the stream systems under discussion are essentially graded, that is, have through long-continued activity adjusted their slopes and channel characteristics with available discharge characteristics so as to transport through the system just that quantity of load supplied from the watershed slopes (Gilbert, 1877, p. 108; Mackin, 1948, p. 471). This means that the stream profiles, although constantly adjusted by minor episodes of aggradation and deposition, represent in the long-term sense the stable forms of an open system in a steady state of operation (Strahler, 1950, 1952a). The down-stream decrease in slope is therefore basically an expression of the stream's greater efficiency in the downstream direction in transporting its load. Slope is a major and primary factor controlling both capacity and competence, as shown by Gilbert's (1914) flume experiments. This is because slope acts as a prime determinant of stream velocity, which in turn determines the intensity of shear near the bed and the intensity of turbulence within the stream. The observed downstream decrease of slope is a clear indication that the load can be moved effectively on a lessening grade. The stream has, through time, developed a decreasing slope in order to compensate for some change or changes in other controlling factors, and thus has counterbalanced what would otherwise be a tendency toward a downstream increase in capacity. These principles were lucidly stated by Gilbert (1877) and are well known.

The primary controls imposed upon a stream, and to which it must adjust its channel and profile characteristics are discharge and load. Load may be divided into two controls: quantity per unit time, and particle size. In the discussion to follow, discharge, Q, is defined as volume rate of flow (L^3T^{-1}), load will refer only to mass rate of flow (MT^{-1}), whereas the size or caliber of the particles will be described as diameter (L) or fineness (L^{-1}). Discharge and load are dimensionally quite alike, inasmuch as volume can easily be related to mass. Both describe the rate of movement of matter through the stream's cross section. One might also introduce water viscosity as a variable with temperature, but this will be disregarded in the present discussion.

Those factors in the stream regimen that the stream itself can control are slope (dimensionless quantity) and channel form. The latter includes form ratio (depth/width), those aspects of roughness related to bed forms such as ripples and bars, and straightness of channel. Thus, if the stream has a permanent change in discharge, load, or fineness imposed upon it, the stream can restore its steady state and graded profile only by changing the slope or channel-form characteristics. These changes are readily made by aggradation or degradation, and by redistribution of bed materials. In the following discussion we assume that any such adjustments have been completed.

If discharge should increase downstream, without any changes in load or fineness, the bed load capacity of the stream would tend to increase, as Gilbert (1914) has amply demonstrated by observations that capacity for bed load increases with discharge. Therefore, the stream would have decreased its slope in the downstream direction in compensation for the increased discharge. This case can be considered unrealistic, inasmuch as downstream increases in discharge will also be accompanied by increases in load, since runoff from adjacent slopes and from entering tributaries will normally also add debris eroded from the watershed area. (An exception might be a system of tributaries fed largely from base flow in a limestone terrain.)

If load should decrease downstream without changes in discharge or fineness, the stream could operate on a lessening slope, and would therefore produce an up-concave profile of equilibrium. This case, too is unreal, because the load cannot be permaently disposed of in a natural way without aggradation, and this is precluded by the requirements of maintaining grade.

We are therefore forced to deal with downstream increases of both discharge and load as the normal state in most watersheds. This leaves open the possibility of a downstream change in the ratio of load to discharge (L/Q). Decrease in this ratio downstream would require a compensating decrease in slope. There is reason to think that the ratio L/Q will decrease downstream in a large drainage basin (Mackin, 1948, p. 480). Near the principal drainage divide, where first-order streams head, the greatest local relief and steepness of slopes can be expected. Here, overland flow entrains a greater proportion of load than it does in the slopes of tributary basins located in the middle and lower parts of the stream system where local relief is less and slopes are lower. Thus we might expect that the successive contributions of small tributaries will consist of less load in proportion to discharge and the overall effect will be a downstream decrease in the ratio L/Q along the trunk stream.

Aside from consideration of changes in the L/Q ratio, there is the possibility that even if the ratio remained constant, the absolute increase in discharge would itself cause an increase in stream efficiency. To examine this possibility we turn to considering slope discontinuities at stream junctions.

In all real stream systems load and discharge do not increase steadily downstream, but take the form of sudden increments where junction of two channels takes place. The sudden drop in slope which occurs at the point of junction is well known. Mackin (1948, p. 491-492) emphasizes the segmented nature of profiles and recommends that they be studied as such. Single channel profiles plotted by the writer (Figures 8 and 43) of streams in Salt Run and Chileno Canyon show some degree of segmentation. In general, the foregoing discussion of causes of up-concavity can be applied equally well to segmented profiles, assuming only that the changes in the ratio L/Q and in fineness occur abruptly, rather than uniformly.

In plotting composite profiles, elements of the profile are defined according to stream order. The abrupt drop in slope in passing from one order to another shows that the joining of two channels of equal order produces a change in stream slope. Yet, we have no reason to postulate a change in the ratio L/Q at this junction. The reason is as follows. On the average, all streams of a given order will be expected to have the same watershed area, basin relief, and slope properties. Individual differences will follow some chance function only. Therefore, when two streams, of, say, the third order join to form a fourth-order channel segment, there is no reason to suppose that the ratio L/Q of the fourth order segment will be consistently different from that of either third-order segment. Neither will there be any consistent change in the fineness of the debris. Yet the slope discontinuity is real and must be explained. An explanation lies in the effect of increasing discharge upon capacity following principles stated by Gilbert (1877, p. 103), who reasoned that if the channel form of a stream remained constant, but that discharge increased, the relative amount of energy expended in boundary friction would diminish. "Hence increase in quantity (discharge) of water favors transportation in a degree that is greater than its simple ratio." Further on he states (p. 104) that there must be an increase in slope in the upstream direction otherwise "the tributaries of a river will fail to supply it with the full load it is able to carry". Still further on (p. 107-108) he explains the concept of gradation of the stream and concludes that "when an equilibrium of action is reached, the declivity of the main stream will be less than the declivities of its branches. ...In any river system which traverse and corrades rock of equal resistance throughout, and which has reached a condition of equal action, the declivity of the smaller streams is greater than that of the larger. ... in general, we may say that, ceteris paribus, declivity bears an inverse relation to quantity of water."

Many years later Gilbert was able to quantify these relationships by flume experiments. He found that in any given flume experiment with debris of a given grade, there is a competent discharge, below which the debris is not moved (Gilbert, 1914, p. 149). At greater discharges, the capacity increases as a power function of the difference between the observed discharge and the competent discharge. The rate of variation of capacity with respect to discharge called by Gilbert the index of relative variation, which is the derivative of logarithm of capacity with respect to logarithm of discharge where log C = f (log Q), was computed for a variety of conditions. The equation relating capacity to discharge is given by Gilbert (1914, p. 144) as follows:

$$C = VQ^{i} \tag{15}$$

where C = capacity (MT^{-1}).
Q = discharge (L^3T^{-1})
i = index of relative variation
V = variable coefficient.

Plotted on log-log paper, the capacity-discharge data are not linear, but form a line convex-upward. Thus the exponent, *i*, is variable. The coefficient V, which is the capacity at the intercept (log Q = O) is also variable. The index of relative variation is itself a function of discharge being less as the discharge is greater. Values of *i* were found to average 1.42; with the ordinary range from 1.00 to 2.00. In other words, capacity for bed load transport increases at a greater rate than a direct proportion, and may, in fact, increase as the square of the discharge under certain conditions. It is of further interest that i increases with decreasing fineness. Table 35 (Gilbert, 1914, p. 144) shows that for a given discharge and flume width *i* has a value of 1.17 for debris of Grade A (medium sand), but increases to 2.04 for Grade G (gravel), and to 3.46 for Grade H (coarse gravel or pebbles).

Applying these findings to the problem of slope change at the junction of two streams of the same order, it is evident that the doubling of discharge will more than double the capacity. Thus the larger stream can transmit the combined load on a lower slope than can either segment separately above the junction. Abrupt decreases in gradient can be expected through abrupt discharge increases at any point where a tributary enters, regardless of its order in relation to the main stream, but they may not be apparent if the discharge increment is small. In reaches of a segment where no tributary enters, the discharge will be augmented in time of high surface runoff generally by discharge and load brought directly into the channel from the adjacent valley side slopes. Here the increasing discharge should cause a uniform, although small decrease in slope, but the departure from linearity may not be detectable.

Turning next to caliber of load, assume that the ratio L/Q remains constant, but that the fineness increases downstream. Gilbert (1914, p. 150-154) demonstrated the increase of tractive capacity with increasing fineness. Capacity was found to vary approximately as the square root of fineness in excess of the competent fineness. Furthermore, with increasing fineness, a greater proportion of the load can be transported in suspension, a mechanism requiring relatively little dissipation of energy (if not actually increasing the stream's efficiency by reducing turbulent intensity). Thus, if fineness increases downstream, the stream will have a lessening slope to compensate for the greater ease of load movement.

There are two possible causes of downstream increase in fineness. First is comminution of bed load particles to progressively finer grains by abrasion. This was considered an effective process by Sternberg (1875) whose "Abrasion Law", stating that the weight of a particle decreases exponentially with downstream distance, has been used by Shulits (1941) in development of a rational stream profile equation. Yatsu (1955) lends support to the effectiveness of abrasion in increasing fineness by his finding that the median diameter of fluvial deposits in several Japanese rivers shows an abrupt downstream change from about 20 mm (gravel) to 2 mm (sand). This size discontinuity is attributed to the shattering of the gravel particles to produce much smaller sand grains, intermediate sizes produced by gradual wear being few.

A second possible cause of downstream increase in fineness is that the load contributions from successive tributaries and from direct runoff of valley side slopes may become finer in the downstream direction (Mackin, 1948, p. 480). This tends to reduce the median (or mean) particle diameter downstream, even as the load and discharge both increase. The reason for downstream increase in fineness of tributary contributions is the same as offered for relative decrease in load contributions, namely, that small-order watersheds situated in the interior of the large basin, or nearer the mouth, will probably have lesser local relief and gentler slopes than small watersheds near the main divide. If so, not only will less debris be carried into channels by overland flow, but the particles will tend to be finer. The coarser particles are not entrained because they exceed the competent fineness under the given conditions of slope.

The possibility exists that downstream increase in fineness may be due to sorting, rather than to abrasion. It is difficult to distinguish between the effects of sorting and abrasion in the study of the size distribution of particles found in a stream bed. The consensus seems to be that abrasion is effective, at least in particle sizes coarser than sand.

Whatever may be the cause of increasing fineness downstream, several investigators who have sampled deposits of bed materials have found a downstream increase in fineness. Krumbein (1937), Eckis (1928), Blissenbach (1954) and Yatsu (1955) found that the maximum diameters of grains on alluvial fans decrease with distance from fan apex.

Woodford (1951, p. 818-819) sampled bed material from the dry channels of Arroyo Larguito, California, and found that median diameter showed no strong trend toward decrease or increase. The sediment was fine (.2 to .5 mm) as bed deposits go. The maximum diameter of grain, however, showed an increase from about 2-5 mm near the stream head to 20-40 mm at the lower end, a distance of 8000 feet. Hack (1957, p. 58) plotted median diameter against stream length and stream slope, but found the relations highly inconsistent. In some streams the median diameter of bed material remained constant with decreasing slope, in others slope and median diameter increased together, while in one stream the median diameter increased greatly with decreasing slope. When stream slope was plotted against drainage area for the same basins there was a general decline of slope with increasing area, but the regressions were not highly consistent. Then, by combining the median diameter, M, with drainage area, A, in the ratio M/A, he obtained a consistent regression of slope upon this ratio (Hack, 1957, p. 58). The points were fitted with a power function

$$S = 18\,(M/A)^{0.6} \qquad (16)$$

This suggests that fineness is a contributing factor in stream slope. In all cases cited above the material sampled represents bed deposits left behind by the stream (i.e. greater than competent fineness), so that the data may not even be relevant to the question of the change in median particle size of bed load in movement during stream flow in the same reach of stream. The question of downstream increase in fineness would need to be answered through an extensive program of sampling of bed load actually moving, not only at one observing station, but at several points distributed throughout the length of the profile. Moreover, the regression of fineness on distance would be meaningful only for corresponding relative discharges, and perhaps only for individual flood waves.

The possible causes of downstream decrease in slope, (changes in fineness, ratio L/Q, and discharge) are not mutually exclusive. They may work together to the same end. Rubey (1952, p. 132) by transformation of Gilbert's flume data has combined discharge, load, and particle size in a single product, which is equated to the product of slope and form ratio:

$$S^a \rho = k\,\frac{L^b D^c}{Q^e} \qquad (17)$$

where S = graded slope of stream or water surface
ρ = depth-width ratio (form ratio) = d/w
a, b, c, e, and k are constants
L = sediment load
D = average diameter of particles of load = 1/F
Q = discharge

The equation is largely empirical and is not dimensionally homogeneous. Nevertheless, stripped of the exponents, the equation states that if form ratio remains constant, slope increases directly as some power of load, some power of particle diameter, and inversely as some power of discharge. The introduction of form ratio (depth-width ratio) deserves additional discussion. This is a quantity that the stream can control, making its channel relatively deep or relatively shallow by accretion and scour of bed materials in an appropriate manner. Lane (1937, p. 138) explains that a broad, shallow channel is typical of a stream carrying a heavy bed load. Presumably this means not only a high proportion of bed load in relation to discharge, but a load of generally coarse particles as well. Streams carrying largely fine sediment in suspension, and forming their channels in fine-grained, cohesive alluvium, tend to have deeper but narrower channels. One reason for this correlation is that channels in coarse materials have banks of like material, non-cohesive and readily subject to bank caving. Hence the channel is easily broadened. By contrast, the highly cohesive banks of slit and clay resist shear stress and do not cave readily. A more important fundamental reason is that a broad-shallow channel presents a greater bed surface over which the coarse particles can be dragged and is therefore a more effective form for transport of relatively large bed loads. Of course, slope must be steepened to compensate for the shallower depth. In the stream carrying most of the load in suspension, a greater depth of water can be effective on a much lower slope, since turbulent intensity is the determining factor in suspended load transport. Consequently such streams develop deep, narrow channels with high form ratio, but with low slope.

Following these principles, it would seem that in the downstream direction, if fineness increases, the proportion of suspended load to bed load will increase, and slope will then decrease in compensation. Considerable evidence is brought to bear on this problem by Leopold and Maddock (1953) who have assembled the data on downstream changes in depth, width, and discharge for many streams. They state (Leopold and Maddock, 1953, p. 14) "As a rough generalization, it may be stated that in a downstream direction, the rates of increase in width, depth, and velocity relative to discharge are of the same order of magnitude for rivers of different sized drainage basins and of widely different physiographic settings". Average values of the exponents of power functions relating width and depth to discharge (increasing downstream and therefore a function of distance) are 0.5 for width; 0.4 for depth. This means that on the average, width increases at a slightly greater rate than depth, causing a downstream reduction in form ratio, but the change is small. The change in form ratio varies among the cases cited, in one decreasing markedly downstream, in another (Missouri-Mississippi) increasing downstream, in others showing little change. One must conclude from these data that downstream change in form ratio, where it exists, is slight and in any case does not provide an important variable in explaining the up-concavity. In Rubey's equation, then form ratio can be regarded as another constant within a single stream.

In conclusion, there are sufficient reasons, verified by experimental evidence and field data, that the widely observed downstream decrease in stream slope can be brought about by increase in fineness of load, by reduction in the load-to-discharge ratio, and by the absolute increase in discharge. All three may tend to produce up-concavity. Where fineness remains constant or decreases, the effect of discharge increase alone may more than compensate for any tendency to require a steeper slope.

Mathematical equations of longitudinal stream profiles

From the conclusions as to causes of up-concavity of stream profiles it may be useful to derive rational equations for the longitudinal stream profiles in terms of elevation, $\underline{y}$, as some function of distance, $\underline{x}$, in the downstream direction. These equations are based upon certain initial assumptions as to the downstream changes in the load, L, the discharge, Q, the ratio L/Q and the fineness, F.

The effect of increasing fineness in the downstream direction has already been discussed by Shulits (1936, 1941) who assumes the validity of Sternberg's abrasion law

$$P = P_o e^{-ax} \tag{18}$$

where P = weight of particle at distance x
P_o = initial weight of particle at $x = 0$
x = horizontal distance in the downstream direction from the head
a = coefficient of abrasion.

Shulits introduces the additional assumption that slope of the stream bed is proportional to the particle weight, giving

$$S = kP_o e^{-ax} \tag{19}$$

where S = slope, defined as dy/dx, y being elevation.

k = a constant of proportionality.

At the starting point, where $x = 0$, and $S = S_o$, $kP_o = S_o$ and $S = S_o e^{-ax}$. Substituting dy/dx for S, and integrating, the exponential function for a stream profile is derived by Shulits as

$$y_o - y = S_o/a\ (1 - e^{-ax}) \tag{20}$$

where y_o = elevation at the head, when $x = 0$.

Generalizing, the stream profile can be derived from two assumptions: (a) an assumed relationship of particle magnitude (whether weight, volume, diameter, or fineness) to downstream distance, and (b) an assumed relationship of stream slope to particle magnitude. An exponential equation results if size decrease is postulated to be exponential with respect to distance and slope is proportional to particle size. By means of assumptions different from Shulits' a stream profile function of power form may be derived.

Consider the second assumption first. Gilbert's (1914, p. 150-154) experimental data yielded the conclusion that the index of relative variation of capacity with respect to fineness ranges from .5 or .6 in fine grades to about 1.0, or more for coarse grades. For mixtures Gilbert (1914, p. 182) concludes that "on the average, the capacity of streams for natural grades of debris varies with the 0.60 to 0.75 power of linear fineness." These data suggest that we may be permitted to assume that capacity for bedload is roughly directly proportional to fineness. If so, we can use the observed relations between capacity and slope as equivalent to the relations between fineness and slope. Gilbert (1914, p. 115) gives values of from 1.5 to 2.0 generally as the index of relative variation of capacity with respect to slope for mixtures of grades. This might suggest a power function of the form

$$S = a_1 F^{-b_1} \text{ or } S = a_1 D^{b_1} \tag{21}$$

where b_1 is a constant substantially greater than one.

The next step is to assume a power function to relate fineness to downstream distance:

$$F = a_2 x^{b_2} \tag{22}$$

The exponent b_2 might be positive or negative, or might be assumed to be unity, depending on whether fineness increases, decreases, or remains constant in the downstream direction. In any case, a substitution of distance for fineness would yield another power function of the form

$$S = a_3 x^{b_3} \tag{23}$$

Substituting dy/dx for slope and integrating there results still another power function relating elevation y, to distance, x.

$$y = a_4 x^{b_4} + C \tag{24}$$

where $b_4 = b_3 + 1$

$$a_4 = \frac{a_3}{b_3 + 1}$$

and C is a constant of integration.

The third alternative, that of a logarithmic equation of elevation as a function of distance, of the form $y = a \pm b \log x$, could be derived from an assumption that slope varies inversely with distance downstream

$$S = b/x \tag{25}$$

This is a special case of the power function $S = a_3 x^{b_3}$ where $b_3 = -1$ and has been used by Hack (1957, p. 70-71). This in turn might derive from the assumption that particle size varies inversely with distance downstream and that slope is proportional to particle size. There does not appear to be any compelling reason to invoke the inverse relationship and it does not seem to have been discussed by other writers. Observational data on slope and particle size presented by such writers as Gilbert, Hack, Krumbein, and Yatsu, have not been fitted to an inverse function. Nevertheless, if we assume $S = b/x$ and substitute dy/dx for S, the function integrates to

$$y = b \ln x + C \tag{26}$$

Summarizing, by means of various assumed functions relating particle size to downstream distance, and slope to particle size, one can predict exponential, power, and logarithmic functions for the longitudinal stream profile. These assume that the controlling variable is particle size and that load and discharge are not variable factors.

Consider next load and discharge, but assume no change in particle size. Although both load and discharge increase downstream, we cannot postulate (for reasons previously discussed) any change in the ratio L/Q. Therefore, the stream profile form will be determined solely by the effect of absolute increase in discharge in the downstream direction.

Data on a large number of drainage basins, collected by Langbein (1947) and Hack (1957) show a close relation between stream length and drainage area, described by a power function

$$L = 1.4A^{0.6} \tag{27}$$

where L is stream length in miles and A is basin area in square miles. Because basins tend to become more elongate in outline with increasing size, the exponent is somewhat higher than the value of 0.5 which would be expected if geometrical similarity were preserved. The relation of stream discharge to the single factor of area is not easy to estimate, since area is only one of several factors contributing to rate of runoff. We shall assume that discharge increases as some power of area, hence that the relation of stream length to discharge is a power function. If so, the relation of discharge to downstream distance x, may be written

$$Q = ax^b \tag{28}$$

The increase of capacity with discharge has already been discussed. Gilbert (1914, p. 144) found the relationship to be described by a power function with an index of relative variation of from 1.00 to 2.00. It has been noted also that Gilbert applied a power function relating capacity to slope. Substituting capacity for discharge, then slope for capacity, the relationships remain power functions, but with different constants. Then by substitution of dy/dx for S, and integration, we obtain still another power function. In this case y must be defined as vertical drop in elevation from stream head. Thus considerations of discharge alone suggest the applicability of a power function to the longitudinal stream profile.

In searching for some deductive means to introduce an exponential function relating slope to discharge, there arises the basic difficulty in finding a related variable that decreases at a rate proportional to the quantity itself. Instead, one is limited merely to making the assumption that the rate of increase of discharge in the downstream direction falls off exponentially; that the slope is directly proportional to the discharge; hence that the slope must decrease exponentially downstream.

Hack (1957, pp. 69-74) has attempted to derive mathematical expressions for several stream profiles, using empirical methods and taking into account both particle size and, indirectly, discharge. As already noted, Hack found that the streams which he studied were fitted by the power function

$$S = 18\left(\frac{M}{A}\right)^{0.6} \tag{29}$$

where M is median diameter of bed material and A is drainage area in square miles. He also observed that

$$X = 1.5A^{0.6} \tag{30}$$

where X is distance downstream in miles. Substituting X into Equation 29 he obtained

$$S = 25 \frac{M^{0.6}}{X} \qquad (31)$$

which relates slope to particle size and distance from head. Discharge is presumed to be an increasing function of area, hence distance is also some increasing function of discharge. Next, Hack notes that median diameter, M, appears systematically related to distance, X, by a power function of the form

$$M = jX^{m} \qquad (32)$$

The exponent m would be negative where diameter decreases downstream; positive where it increases downstream, and equal to zero where diameter remains constant. All three cases were observed among the several streams which Hack studied.

Substituting the value of M of Equation 32 into Equation 31, Hack obtains

$$S = 25\, j^{0.6} X^{0.6m-1} \qquad (33)$$

Then, to obtain the mathematical form of the stream profile in terms of y (drop in elevation from stream head) and X, Equation 33 is integrated, assuming that slope, S, is here defined as dy/dx. This gives

$$y = 25j^{0.6} \ln X + C, \quad \text{where } m = 0 \qquad (34)$$

$$\text{and } y = \frac{25j^{0.6} X^{0.6m}}{0.6m} + C \quad \text{where m does not equal 0.} \qquad (34a)$$

Hack had obtained data on the median diameter of bed materials for four streams. He could therefore compute the stream profile equation using only the data of particle size and distance. These computed profiles could then be compared to the true profiles where the elevation drop, y, was measured from the maps. The agreement is not close, but it is difficult to evaluate the difference in terms of goodness of fit. The important point is that a power function was considered to be the best means of relating drop in elevation to downstream distance, taking into account observational data on particle size. Where particle size remains constant with distance, the function is logarithmic, and this may be regarded as a special case.

It is concluded that various lines of inquiry both rational and empirical can favor different profile equations. Beyond the certainty that most stream profiles have an up-concavity (although some appear linear in shorter reaches), it would be unwarranted to predict a better fit by an exponential function than, say a power or logarithmic function. Inasmuch as the present study deals with stream segments of low orders, it would seem profitable to plot the profiles of individual order segments and determine the goodness of fit to exponential, logarithmic and power functions. This is perhaps better handled through study of the relationship of slope (dy/dx) to downstream distance than of elevation to distance, first, because slope is dimensionless and is free of arbitrary reference elevations and second, because the data on the H/L ratios of first-, second, and third-order segments are closely related to slope as a function of downstream distance, inasmuch as order increases downstream.

SALT RUN AREA

Description of the area

The basin of Salt Run is about two miles northeast of the town of Emporium, Pennsylvania, and occupies parts of Portage, Lumber, and Shippen townships in Cameron County, and a part of Portage township in Potter County (Figure 4). The basin is within the Emporium topographic map quadrangle, mapped by the U. S. Geological Survey in 1950 on a scale of 1:24,000, contour interval 20 feet, using multiplex methods. Salt Run is a tributary of Sinnemahoning Portage Creek, a part of the drainage system of the west branch of the Susquehanna River. The altitude ranges from 1,040 feet to 2,380 feet above sea level. Prior to settlement, the entire area was heavily forested. The forest cover now consists of second growth 40 to 60 years old. Salt Run is near the transition zone between a red-oak (Quercus borealis) forest to the north and a white-oak (Q. alba) and chestnut-oak (Q. montana) forest to the south. Both forest types contain numerous deciduous species, including: beech (Fagus grandifolia), sugar maple (Acer saccharum), yellow birch (Betula lutea), black cherry (Prunus lutea), white ash (Fraxinus americana), basswood (Tilia americana), black birch (Betula lenta), and red maple (Acer rubrum). Hemlock (Tsuga canadensis) is common. Prior to extensive cutting, stands of large white pine (Pinus strobus) were widespread (Denny, 1956). Climate data gathered at a station in Emporium are summarized in Table 1 (U. S. Weather Bureau, 1955). Precipitation is distributed evenly throughout the year. Thunderstorms occur on from 30 to 40 days per year (Visher, 1945).

The basin of Salt Run is in the Kanawha section of the Appalachian Plateaus (Fenneman, 1938). The area is underlain by nearly flat-lying sedimentary rock. The stratigraphy of the area is summarized in Table 2, based mainly on a similar summary by Denny (1956). Geologic structure in this general area consists of broad, open folds, which strike northeasterly. Maximum dips are about five degrees. Salt Run is on the north flank of the Sabinsville anticline, which plunges gently to the northeast. The long axis of the basin is roughly parallel to the axis of the anticline. The soil in the area is stony and highly permeable (Denny, 1956), so that most streams gather their discharge from subsurface flow rather than direct runoff. This combination of dense forest cover, permeable soil, and coarse-grained bedrock, together with a general lack of intense storms (Visher, 1945), is highly favorable to a coarse texture of topography. It is not surprising, then, that Smith (1950) chose an area just south of Emporium as a type locality for coarsely textured topography.

Relation of H, L, and H/L to order

Data of H, L, and H/L are shown in histogram form in Figure 5. Log H, log H', log L, and log H/L are shown in regressions on order in Figure 6. The mean values of H appear to have no significant trend with respect to order. The mean values of log L vary directly with order; log H/L inversely with order; both regressions being significant at α = .01. The lack of significant slope in regression of H on order suggests that, in a given region of relatively homogeneous lithology and simple geomorphic history, the mean value of H for successive orders of stream segments may tend to be a constant. Of course, the absolute value of mean H would vary from one region to another. This possibility remains to be verified by data of other localities.

The mean value of H/L starts with a finite value for the first order and decreases with order. In a homogeneous region, as order increases to values greater than those investigated by the writer, the gradient will tend to approach zero asymptotically. This must be true since, if for any order the gradient should reach zero, the stream would be ponded to form a lake. When the logarithm of the gradient is plotted against order (Figure 6), the points are distributed linearly, which suggests that gradient is an inverse exponential function, or

$$(\overline{H/L}) = K_2 e^{-k_3 u} \tag{35}$$

where K_2 and K_3 are constants, and e and u are used as above. This agrees with Horton's law of stream slopes (Horton, 1945, p. 295). Schumm's (1956, p. 205) findings tend also to confirm Horton's work on this law. If the cumulative values of H and L are used to compute the gradients, or

$$H'/L' = \sum_{u=1}^{n} \overline{H}u / \sum_{u=1}^{n} \overline{L}u \tag{36}$$

the relationship between gradient and order is more accurately described by an exponential curve. It would appear, then, that the relationship between order and mean values of H, L, and H/L is more regular when the cumulative system is used than when Strahler's order system, unmodified, is used.

Single-channel stream profiles

To investigate the properties of profiles in detail, the writer measured from the topographic map four profiles, each consisting of a first-, second-, and third-order segment. (Because Salt Run has only three third-order streams, Lucore Hollow, a small third-order basin adjacent to Salt Run to the northwest, was used also). These profiles were first plotted arithmetically on both ordinate and abscissa in order to give direct visual appraisal of the profile. Figure 7 A, B, C shows separate plots of each order, with a different degree of vertical exaggeration for each. The scales were selected to produce a graph line of strong slope, so as to bring out departures from linearity. It is evident that all profiles except the first-order segment of Russell Hollow have up-concave form.

Next, the profiles were plotted in the logarithmic form (Equation 8) in which drop in elevation plus a constant ($Y + H_g$) is scaled arithmetically on the ordinate; the logarithm of distance plus a constant ($X + L_g$) on the abscissa (Figure 8). This largely removes the gross curvature in the profiles. In addition, distinct breaks in slope of the logarithmic plots for Salt Run and Wheat field Hollow (Figure 8 A, B) between first and second order segments are apparent. This appears to reflect the segmentation described by Mackin.

Then, the slope, S, was computed for each element of the profiles and plotted against distance according to equations 12, 13, and 14 (Figures 9, 10, 11). It was assumed that the slope was not constant with distance for most of the profile segments; that in any case the occurrence of a horizontal line on the regression of log S on distance would reveal a constant slope. Regression equations were fitted by means of least squares and the scatter computed.

Regression data are given in Table 10. A noteworthy feature of the exponential regression (log slope on distance) is the extremely low value of the regression coefficient, b. This means that the regression line, although sloping toward the right (in downstream direction) is close to being a horizontal line. This would lead to suspicion that there is no significant decrease in slope in the downstream direction, hence that the profile of each channel segment is virtually a straight line. Heightening this suspicion is the large scatter ($S_{y.x}$) and small number of pairs of variates (N). On the other hand, the very large values of scatter of distance (s_x) will tend to make the slope a significant one. To test the hypothesis that the population value of the regression coefficient of which b is an estimate is actually equal to zero, a test for independence was carried out, using the statistic t (Dixon and Massey, 1951, p. 160). The results are given in Part A of Table 10. Three significance levels are used, 10%, 5%, and 1%. At both 10% and 5%, 10 of the 12 coefficients are judged significantly different from zero. This supports the hypothesis that the profiles tend to be concave-up. Two segments, Russell Hollow first order and second order, yielded not-significant results at all three levels of significance. For these we have no reason to doubt that the profile segments are straight lines.

Next, the regressions of log slope on log distance were calculated and tested. Data are given in part B. of Table 10. Scatter seems not to have been appreciably changed, in some cases being larger, in others smaller than in the exponential regressions. Fewer of the regression coeffcients are significantly different from zero, but the overall picture is quite similar in both types of treatment.

Composite profile

A composite profile for the entire Salt Run area was constructed from statistical data on H, L, and H/L given in Figure 6. For each order, the mean values of H and L were used as the vertical and horizontal legs respectively of a triangle whose hypotenuse represents the mean segment of a given order (Figure 12). Triangles are fitted together for successive orders in the downstream direction. The last triangle is formed by a single value of H and L, there being only one trunk segment of the fourth order. From inspection of Figure 12 it is obvious that the slope of the segments decreases rapidly downstream, but that the vertical drop varies little. This matter is treated elsewhere in the discussion of change of H with order.

Next, the slope, S, of each segment was plotted against downstream distance, X, plus an added constant, L_g. To obtain L_g the four values of L_g used in the single profile plots were averaged. The average was within a few feet of 1000, so that the value of L_g = 1000 feet was accepted. The distance X is measured from stream head horizontally to the mid-point of each order segment.

Figure 13 A, B, C, and D shows arithmetic, logarithmic, exponential, and power functions tested by means of the first-derivative functions, Equations 11-14a. Slope or log slope is plotted against distance $(X + L_g)$, inverse of $(X + L_g)$, or log distance, as required. The arithmetic plot (A) is a very poor description of the data. The logarithmic plot (B), S against $1000/(X + L_g)$, produces a nearly linear distribution of points, with only a faint up-concavity. The power plot (D) is nearly as good, with only slight up-convexity. However, the presence of the additional constant in Equation 14 provides an inherently better fit for the power function (Equation 14) than for the logarithmic curve (Equation 12). Therefore the logarithmic form is judged superior. This differs from the conclusions of Hack and Rubey that the power function best describes stream profiles.

HIGHLANDS RANCH AREA

Description of the area

The Highlands Ranch test area is in sections 2, 3, and 9 through 15, T. 6 S., R. 68 W., and sections 6, 7, and 18, T. 6 S., R. 67 W., Douglas County, Colorado (Figure 14). Three small fourth-order basins were investigated: (1) Cheese Ranch basin, tributary to Big Dry Creek; (2) Highlands Ranch basin, tributary to Dad Clark Gulch; and (3) Dad Clark Gulch basin, at the headwaters of Dad Clark Gulch (Figure 15). The names Highlands Ranch basin and Cheese Ranch basin are given by the writer for convenience in discussion. The Highlands Ranch area is named from a large ranch within whose limits lie all three basins. Both Big Dry Creek and Dad Clark Gulch are tributaries of the South Platte River. All small streams in the area are ephemeral; a few of the larger ones are intermittent. A small part of the Dad Clark Gulch basin is in the Littleton topographic map quadrangle, but most of that basin and all of the other two basins are in the Highland Ranch topographic map quadrangle. Both of these maps have a scale of 1:24,000, with a contour interval of 10 feet. Both quadrangles were mapped in 1939 by plane-table methods. Altitude in the area ranges from 5,530 feet to 6,050 feet. Vegetative cover is primarily grama grass (Bouteloua gracilis), with abundant soapweed (Yucca glauca), and some mountain mahogany (Cercocarpus ledifolius intricatus) on the north-facing slopes. A few large cottonwoods (Populus sargentii) grow along the larger stream channels.

Fairly near the area are two weather stations: one at Parker, about 10 miles to the east-southeast; the other at Kassler, about 7 miles to the west-southwest. Table 1 summarizes the climate data for the two stations (U. S. Weather Bureau, 1955). The altitude range of the Highlands Ranch area is between the altitudes of the weather stations, so the mean precipitation and temperatures there probably fall within the ranges given in the table. Most of the precipitation falls during the late spring and summer, commonly as local thundershowers. Thundershowers occur in the area from 40 to 50 days per year (Visher, 1945).

The Highlands Ranch area is in the Colorado Piedmont section of the Great Plains physiographic province (Fenneman, 1931). The topography is gently rolling, with low relief. Reichert (1956) reported the area to be underlain by the Paleocene Denver and Dawson formations. The Denver formation, the older of the two, consists of a sandstone containing debris from andesitic rocks. The Dawson formation is a light-colored, arkosic conglomerate, sandstone and sandy shale. In the basins studied, the bedrock is exposed only in scattered stream cuts and borrow pits. The exposed material varies from a light-gray, sandy clay to a very light-gray, fine-grained, quartz sandstone containing thin layers of clay chips, to a light-gray, coarse-grained, conglomeratic sandstone. The coarser units are commonly cross-laminated, and contain small iron oxide concretions. The pebbles in the sandstone, ranging up to one and one-half inches in diameter, are of quartz, feldspar, and granitic rock fragments. All of the units are poorly consolidated. The sediments in the area are nearly flat-lying.

The Denver and Dawson formations are overlain by a well-developed soil. Most of the stream channels whose profiles were measured by the writer are entirely floored by this soil. A few streams in the Highlands Ranch basin have cut through the soil into the poorly consolidated sediments below. A typical soil profile measured in the Cheese Ranch basin is shown in Figure 16.

Profiles and nick points

The field-measured profiles for the Cheese Ranch basin (Figure 17) have two marked characteristics. First, on an over-all basis, they are linear rather than concave-up. Second, the profiles are marked by numerous nick points. When examined in detail, some of the segments between nick points are concave-up. This complex relationship is commonly found in large rivers that cross alternate belts of soft and resistant rock, the resistant rock forming the nick points. Comparable profiles for the Highlands Ranch basin (Figure 18) are similar in that they are generally linear and are interrupted by numerous nick points. The two sets of profiles differ in that the gradients of the Highlands Ranch profiles are notably steeper than those of the Cheese Ranch profiles and that the nick points in the Highlands Ranch basin are in part much higher.

The lower halves of Figures 19, 20, and 21, showing the field data for the first-order segments, were compiled in the same way as were the map data described in a previous paragraph (upper halves of the same figures), and tested by t-test in the same way. Figure 19 shows the mean values of H for the two basins. The difference between means for the two basins is small and not statistically significant. Figure 20 shows the comparison of values of L. In this case the mean value of L is considerably longer in the Cheese Ranch basin, but the difference is not significant. Finally, the mean value of H/L (Figure 21) is much steeper in the Highlands Ranch basin, and the difference is clearly significant. Because the samples for the second-order streams are so small, the results of tests comparable to those for the first-order segments are shown in Table 3 rather than by histograms. Again, only the observed difference between mean values of H/L is significant, the gradients for the Highlands Ranch profiles being much steeper. The two basins are within a mile of each other, and are in comparable altitude zones.

To explain this puzzling difference in gradients, it is necessary to compare the nick points from the two basins. The nick point shown in Figure 22 is typical of those in the Cheese ranch basin. It consists of a generally crescentic scarp, vertical to slightly overhanging, with the crescent open downstream. The scarp is highest in the center and diminishes gradually downstream, until the scarp is replaced by a slight increase in slope. No rock is exposed in the scarp. The cap layer is turf, with the soil bound by a mat of roots. In some nick points the cap layer is overhanging, and there is a small closed basin just below the scarp, somewhat comparable to a plunge pool. Similar scarps have been described by Rubey (1928) in a similar geologic setting: gently rolling, grass-covered hills underlain by arenaceous sediments. Rubey attributed these scarps to localized removal of fine particles from beneath the sod by subsurface discharge of water. This would leave the sod unsupported, so it would settle, leaving not only the scarps but also elliptical basins and long crescentic fractures. The latter two features were not observed in the Highlands Ranch area. Because of the absence of fractures and basins in the Cheese Ranch basin, and the presence of overhanging turf cap layers and small-scale plunge pools, the writer believes the scarps are due to the upstream migration of small waterfalls, present only at times of heavey rainfall. Because turf floors the entire valley bottom, the falls would continue to migrate to the head of the stream. The advancement of the falls is probably aided by grazing animals trampling down the overhanging rim. The scarps may originate at the head of small wallows, where the sod might be destroyed by trampling by grazing animals when the soil is saturated. Once started, the scarp would tend to be self-perpetuating. Hadley and Rolfe (1955) described low scarps, which they called seepage steps, somewhat similar to the scarps studied by the writer. Unlike the features under discussion, the seepage steps are roughly parallel to the stream channels, tending to follow the contour lines. The seepage steps are much longer than the nick point scarps in the Cheese Ranch basin. Hadley and Rolfe considered the seepage steps to be due to sapping of the soil by water seeping parallel to the slope above an impermeable surface of weathered bedrock. It is entirely possible that some seepage does exist here, perhaps contributing to the undermining of the scarp. According to this description, the nick points are of local origin, and reflect a minor instability of the topography under present climatic conditions.

Some of the smaller nick points in the Highlands Ranch basin may originate like those described above, but others are much larger (see Figure 18, profiles M_2, Q_2, S_2). Profile S_2 is particularly important, as it consists of two markedly different sections. The section above the series of nick points has a gradient comparable to the upper reaches of the second-order profiles measured in Cheese Ranch basin (Figure 17). First-order segments S and T, which join to form segment S_2, have gradients comparable to those of the first-order segments of Cheese Ranch basin. The topography of the upper part of the small basin drained by segment S_2 is very much like the topography in the Cheese Ranch basin. The lower part of profile S_2 is marked by six nick points in a distance of 190 feet. The lower five nick points are not crescentic, but mark the abrupt heads of trenches cut into the valley floor. The uppermost nick point is like those in the Cheese Ranch basin. The valley sides of the lower reach of the small basin are generally much steeper than those in the headward reach. It is the writer's impression that the older, gentler, topography is undergoing destruction through trenching by the streams of the basin. The cause for the marked contrast in conditions in the two basins is probably some downstream rejuvenation of Dad Clark Gulch, which has progressed headward to modify the topography of Highlands Ranch basin almost in its entirety. This rejuvenation could be due to a downcutting of the South Platte River, in which case the rejuvenation has not yet reached the upper part of Cheese Ranch basin.

Three pieces of bone were collected from one of the larger nick points of profile S_2. These were identified by Mr. Larry Frankel as either immature cow or immature Bison bison. Such an identification is not sufficiently precise to aid in establishing erosion rates, other than to say that the small valley has been filled and partly re-excavated in recent time (Schultz and Stout, 1948).

Comparison of map and field data

For comparison with the field data, the map data for the identical parts of the basins studied in the field were compiled as separate samples. The map data from the Cheese Ranch area contained 32 first-order and 6 second-order segments. The same data for the Highlands Ranch basin contained 21 first-order and 6 second-order segments. The Highlands Ranch map data correspond in number to the field data, but the Cheese Ranch map data contain one-third again more first-order segments than the field data. The reason for this difference is not readily apparent. The Cheese Ranch basin contains several man-made drainage terraces, suggesting that the additional channels may have been gullies that have healed in the sixteen years between the date of mapping and the date of the writer's field work. The map-measured values of H, L, and H/L for the first-order segments are shown above the field data in Figures 19, 20, and 21. An investigator working from map data alone would conclude that the difference between mean H's for the two basins is not significant, but that the differences between L's and H/L's for the two basins are significant. These results do not differ radically from those of the field data. However, when the mean values of field and map data are compared, the results are disappointing. Because the two samples were drawn from the same areas, there is no chance that the differences are due to sampling errors. In both basins, the map values of both H and L are larger than the field values. Hence, any map study of values of first-order H and L must be considered with a certain amount of reserve. The map and field values of H/L within each basin are comparable. The explanation for the observed differences may be that the topographer carried the V's in the contour lines too far toward the divides, or that gullies at the heads of the present valleys have healed since the maps were made. The writer regards the second explanation as unlikely. It should be noted here that the head of a first-order segment is difficult to locate accurately in this area. There is no clear-cut channel in the center of each small valley, but rather a sod-covered valley floor with a cross-section in the form of a very broad V. The change from the broad V to the broadly rounded hopper at the valley head (Strahler, 1950, p. 803) is difficult to locate precisely.

The mean values of H, L, and H/L for the second-order map-measured data are listed in Table 4. A comparison of this table with Table 3 yields more information on the reliability of map samples, this time of second-order stream segments. First, within Table 4, the differences between means for H and L are not significant, but for H/L the difference is significant. Clearly, the map and field data have the same relative relationship. However, when one compares absolute values of H, L, and H/L for the two sets of data for the Cheese Ranch basin, the map values of H and L can be seen to be much larger than the field values. The gradients are comparable. The Highlands Ranch basin results indicate that here the map values are comparable to the field values for H, L, and H/L. Hence, if one should make an extensive map study, the results for the Cheese Ranch basin should be regarded with a certain skepticism, whereas the results of such a study in the Highlands Ranch basin, with the exception of the first-order values of H and L, should be fairly accurate.

One more item of information can be gained by comparing the field- and map-measured values of H, L, and H/L for first and second orders. The results of t-tests of the differences between means of the two orders are shown in Table 5. Part a applies to the Cheese Ranch basin. The results for the field and map data are directly comparable. The difference between mean values of H for first and second orders is not significant. Part b, for Highland Ranch, shows quite different results. The difference between mean H's for both sources of data are significant. The differences between mean values of H/L for the two sources of data are not significant. Finally, the field data show the difference between mean L's to be clearly significant, but the map data do not. This suggests that map data from the Cheese Ranch basin will indicate the relative values of H, L, and H/L for the various orders. With the exception of L values, the same is true of the Highland Ranch basin. The geometry of the two basins can be expected to be quite different.

Relation of H, L, and H/L to order

With the above reservations stated, it is now appropriate to discuss the results of the more extensive map study in the three basins. These results are shown diagrammatically in Figures 24, 25, 26, and 27. Considering the mean values of H for Highlands Ranch basin first (Figure 27), one can see that the first- and second-order values are almost equal, but that the mean values for orders greater than one appear to increase systematically with order. The field-map comparative study can be used to explain this apparently irregular behavior. Since the first-order field-determined mean H is slightly more than one-half the map value (Table 5b), and the second-order values are comparable, one may conclude that here the apparent equality between first- and second-order mean H's is due to the method of obtaining data, and that the mean value of H actually increases systematically with order. In relative measure, then, the values of H as related to order are comparable for the Highlands Ranch and Dad Clark Gulch basins. However, the Cheese Ranch basin values of mean H's for first- and second-order streams are equal, and this equality is probably valid (Table 5a), although the absolute values are probably too high. The values of H appear to increase systematically with order for orders greater than one. The statistical significance of these relationships has been tested by regression analysis, the results of which are shown in Figure 28. In the case of the H data for all three basins, the slope of the regression line is significant at least at the .10 level, and in Dad Clark Gulch basin, at the .05 level. This would seem to confirm the idea that mean values of H increase systematically with order in this test area. It is interesting to note that the histograms for first-order H values for the Dad Clark Gulch and Cheese Ranch basins are bimodal, the former markedly so. This is also true of the second-order H's for Highlands Ranch and Cheese Ranch basins. This may be the result of the partial destruction of the older, very gently rolling topography as discussed above. In this case, the modes representing lower values of H are probably due to the older topography, and the modes representing higher values of H are due to the newer or rejuvenated topography. Since the third-order mean H's for all basins are almost identical, the rejuvenation is considered to have affected all of the third-order segments, as well as some of the first- and second-order segments. The fourth-order samples are too small to be of any statistical value. Furthermore, it is noteworthy that in the Cheese Ranch basin, where the older topography is best preserved, the mean H's for first- and second-order segments are equal. This behavior is here interpreted to indicate that in the older topography the mean H was constant, independent of order, and that the rejuvenation has upset this relationship.

The theory is offered here that when the rejuvenation has run its course, the mean value of H will again approach a constant, although not necessarily of the same value as in the older topography. This theory offers a possible quantitative criterion for determination of the existence or non-existence in a basin of a steady state condition (Strahler, 1950, p. 676), the steady state existing when the mean value of H is a constant, independent of order. The theory needs testing, perhaps by a study in a badlands where an actual change in form could be observed over a period of a few years.

The mean value of L (Figure 27) may be treated in a similar fashion. Referring again to Table 5b, one can see that in the Highlands Ranch basin the mean value of L for the first order is probably too high, but for the second order is probably reasonably accurate. In the relationship between length and order the Dad Clark Gulch and Highlands Ranch basins are comparable, although the absolute values of the mean lengths for the first and second orders are not comparable. This may reflect the effect of slightly different stages of rejuvenation in the two basins, the rejuvenation modifying the values of L as well as H. The differences between the first-order mean lengths of the Cheese Ranch basin and for the other two basins may be more apparent than real, since the field values for the Cheese Ranch basin (Table 5a) are much less than the map values as found in the comparative study. The statistical significance of the relationships between mean values of L and order was tested (Figure 28). Slopes in two out of the three samples are significantly different from zero at the .10 level. These results are not as definite as those for the Salt Run area, but there seems to be a regular increase in L with increase in order. All three second-order histograms are bimodal, which may be interpreted, as for the H values, to mean that some of the second-order segments probably have been produced by formation of new first-order tributaries during the rejuvenation now in progress.

Rejuvenation explains also the apparent differences between mean gradients for the Cheese Ranch basin and the other two basins (Figure 27). The gradients of the Cheese Ranch basin are consistently lower than, and differ significantly from, those of the other two basins, expectable because more of the older, flatter topography is preserved in this basin. The comparative study (Table 5) indicates that the differences are probably stronger than the map data show, as the map values for the Highlands Ranch basin are slightly too low, and the map values for the Cheese Ranch basin are probably slightly too high. Unlike the other basins studied by the writer, the mean gradients tend to decrease with increase in order in a rather irregular manner. Despite the irregular distribution of the points in Figure 28, the slope of the fitted line is significant at the .10 level in all three cases. This irregularity is probably due to the incomplete rejuvenation affecting the area.

Figure 22, as described previously, shows a typical nick point from the older topography of the Cheese Ranch basin. Figure 23 shows the same area, with the pre-nick point slopes projected to form an approximation to the pre-nick point topography.

In that part of the Cheese Ranch basin studied in detail in the field, the writer observed 67 nick points. The area involved is about 0.32 square miles, hence the number of nick points per square mile may be estimated at 208. Strahler (1952b) described in detail a means of studying the area-altitude, or hypsometric relationships of drainage basins. That technique was used in a slightly modified form to estimate the difference in volume below the hypothetical pre-nick point topography (Figure 23) and below the present topography (Figure 22). The difference in volume is 135 cubic feet, which means that 135 cubic feet of material has been removed from the nick point, assuming the reconstructed topography to be reasonably correct. If this nick point is assumed to represent an average for the area under discussion, the total estimated sediment yield from the area due to nick point formation and growth alone would be about .64 acre-feet per square mile. Such a figure seems within reason as an order of magnitude, considering that the average sediment yield in the plains of Colorado has been estimated at .38 acre-feet per square mile per year (Missouri River Basin, 1952). At least two problems concerning this form of nick point remain to be solved. First, it is not known if all the material eroded from a nick point is removed from the basin, or whether the material from the nick point face is strewn in a thin veneer over the flat-bottomed valley floor. The second possibility is quite similar to the discontinuous erosion and sedimentation described by Schumm and Hadley (1957). Second, the rate of headward migration of the nick points is not known. Both of these problems could be approached by the placing and observation over a period of years of a number of stakes along several representative nick points. The results of such a study might be useful in estimating sediment rates and, therefore, life-expectancies of reservoirs in areas where such nick points are common. Because the Highlands Ranch area contains a two-cycle topography, the results of the study are not useable for a study of the general characteristics of long stream profiles. However, as far as one can tell, the older topography is similar in its geometry to the Salt Run area, although certainly not similar in scale. The Highlands Ranch area study does serve to show that rejuvenation tends to disturb the relations between H, L, H/L, and stream-segment order.

LONG CANYON AREA

Description and geology of area

The Long Canyon basin is in sections 1, 2, 11, and 12, T. 1 S., R. 71 W., Boulder County, Colorado (see Figure 14 and Plate 1). The basin is within the Eldorado Springs topographic quadrangle, mapped in 1942 on a scale of 1:24,000, contour interval 50 feet. Long Canyon joins Gregory Canyon, which in turn is tributary to Boulder Creek, a part of the South Platte River system. The altitude of the basin ranges from 6,650 to 8,000 feet. The smallest streams are ephemeral, whereas the largest is intermittent. The area is covered by a forest of western yellow pine (Pinus ponderosa), Douglas fir (Pseudotsuga taxifolia), and aspen (Populus tremuloides). Generally, north-facing slopes are thickly covered by smaller fir and aspen, whereas south-facing slopes have open stands of pine, with some grass cover. Table 1 contains a summary of climate data for two stations near the area (U. S. Weather Bureau, 1955). Both stations are lower in altitude than Long Canyon. Boulder is about two miles to the northeast, and the Hawthorne station is about four miles to the southeast, near the town of Eldorado Springs. Records from both stations show that most precipitation falls in the spring and summer months. Thunderstorms are common, occurring on 40 to 50 days per year (Visher, 1945). In 1955, Boulder recieved a total of 15.25 inches of precipitation, Hawthorne 18.08, and Silver Lake, west of Boulder at an altitude of 10,200 feet, an estimated 25.24 inches (U. S. Weather Bureau, 1955). From this information one may conclude that the climate of Long Canyon is wetter and cooler than Table 1 would indicate, but probably not drastically so.

Long Canyon basin is entirely within the southern Rocky Mountain province of the Rocky Mountain system (Fenneman, 1931). However, the character of the longitudinal profile of Long Canyon and its easterly extension, Gregory Canyon, is complex, and can be better understood by a consideration of the geology and geomorphology of a small portion of the Colorado Piedmont section of the Great Plains province immediately to the east. Structurally, this area is a homocline, with a series of sediments about 10,000 feet thick dipping easterly, away from the Precambrian core of the Front Range at about 53 degrees. The homocline is broken by several faults, as indicated on the geologic map (Plate 1). At the base of Flagstaff Mountain, faulting cuts out much of the section. The "dikes" in the Boulder Creek granite outcrop area are fault zones, the usage of the word "dike" being derived from miners' terminology. The stratigraphy of the area is summarized in Table 6. Two units, the upper member of the Dakota group and the Fountain formation, form prominent ridges. East of the Dakota hogback, the Fort Hays member of the Niobrara formation forms a minor ridge. The Lyons sandstone forms a small ridge along the face of the flatirons of the Fountain formation. Quaternary pediment "gravels," alluvium, and, in small part, landslide debris, mantle much of the bedrock outcrops. Long Canyon is underlain entirely by Boulder Creek granite.

All of the profiles in Plate 1 were made from measurements of the Eldorado Springs and Louisville topographic maps. The locations of the profiles are shown on the geologic map in Plate 1. The long profile of Long Canyon, its tributary, Panther Canyon, and Gregory Canyon was carried no farther east because the only map available for such an extension is the old Boulder quadrangle, a reconnaissance map published in 1904. The profile consists of three parts. The uppermost part is a smooth curve, concave upward, which crosses the most important structural feature in the basin, the Maxwell "Dike," without a break. The lowest part of the profile is also a smooth curve, concave-up, which crosses the Boulder Creek granite-Fountain formation contact without a break. The middle part of the profile is less regular, but is also concave-up. The two lower parts of the profile have gradients much steeper than that of the upper part of Long Canyon. These profile characteristics indicate for Long Canyon and Gregory Canyon a history consisting of a period of erosion and gradation to form the profile preserved in the upper reach, followed by two rejuvenations. Because this investigation attempts in part to relate the characteristics of stream profiles to their geologic and climatologic environment, it is important to determine whether or not the topography of Long Canyon is in equilibrium with present conditions. One method of approach is to determine the time of the formation of the topography. The series of profiles in Plate 1 is used in this determination.

In a general consideration of Plate 1, the profile of Bear Canyon shows a three-fold division comparable to that of Gregory Canyon. The uppermost part of the profile is smooth and concave-up, but is not as steep as Long Canyon at its head. The lowest section is a smooth curve, concave upward, graded smoothly across the outcrop area of the resistant Dakota group. The middle part of the profile is nearly straight. A block of Fountain formation in fault contact with the Boulder Creek granite along the Maxwell "dike" causes no interruption of this part of the profile. Here, too, the profile characteristics indicate a history of gradation of a stream profile, followed by two rejuvenations. Six profiles were drawn down pediment surfaces, the profiles being continued over the Dakota hogback and up the face of the Flatirons. All of the profiles except those of Gregory Canyon and pediment AA' were aligned in Plate 1 by placing the highest outcrop of the Dakota group in the same position horizontally. This method was used because the Dakota is easily recognized on the topographic map, and because this resistant unit would be expected to form a barrier to down-cutting streams (Tator, 1952). The profile of pediment AA' was aligned by causing the flatiron part of the profile to coincide with similar sections of profiles B and C. Gregory Canyon is about 250 feet below the surface of pediment AA', so the Gregory Canyon-Long Canyon profile was placed to fall 250 feet below pediment AA' in Plate 1.

One might interpret the profiles as follows. The uppermost parts of the profiles of both Gregory Canyon and Bear Canyon were once graded to a pediment comparable in altitude to that preserved on Rocky Flats, but which has been completely destroyed in the area under study. (The Rocky Flats profile was measured 3 miles south of

Bear Canyon.) This was eroded, and a new pediment surface, here called the Table Mountain surface, was formed. No effect of Table Mountain pedimentation is preserved in the profiles of Gregory and Bear Canyons. The Table Mountain surface was trenched, and the Shanahan Hill pediment surface was formed. The middle part of Bear Canyon may have been graded to the Shanahan Hill surface. Entrenchment of the Shanahan Hill surface was followed by formation of the intermediate pediment surface, which has since been eroded to a depth of 150 feet. The middle part of Gregory Canyon may have been graded to this intermediate pediment. To determine the age of the topography in Long Canyon, then, it is necessary to determine the age of the pediment gravels on Rocky Flats.

Malde (1955) considered the Rocky Flats gravel to be of Late Pliocene or early Pleistocene age on the basis of a high caliche content, similar to that of a unit dated by Hunt (1954) in the Denver area on the basis of stratigraphy and fossils. However, Hunt's evidence was not conclusive. A sample of ash which Hunt collected from these gravels was found by the Kansas Geological Survey (Hunt, 1954) to be similar to the Pearlette ash, regarded by the Kansas survey as Yarmouth ago. Thus, this tenuous chain of evidence suggests that the Long Canyon topography was formed some time in the interval between late Pliocene and Yarmouth times. Malde (1955) suggests that the Rocky Flats gravels are probably similar in age to the Spottlewood pediment of the northern piedmont (Bryan and Ray, 1940) and the Deadman Canyon Surfaces of the Colorado Springs area (Tator, 1952). Bryan and Ray assigned no age to the Spottlewood pediment other than pre-Wisconsin. Tator considered the Deadman Canyon Surfaces to be probably Middle Pleistocene, which tends to strengthen the interpretation of Yarmouth age for Rocky Flats and Long Canyon.

This age determination problem may be approached from another viewpoint, that of the age or ages of the erosion surface or surfaces present in the Front Range. Long Canyon, being below the high surfaces, would be younger than these surfaces. One is faced here with considerable diversity of opinion not only as to the age of the surfaces, but as to their number and nature. Van Tuyl and Lovering (1935) found a total of eight partial peneplains, three berms or straths, and five terraces, ranging in age from Eocene to Recent. They considered the Flagstaff Hill surface to be Upper Miocene or Lower Pliocene. This surface was described as having an altitude of 7,000 feet on Flagstaff Hill, the type locality, just north of Gregory Canyon, and to be preserved on spurs above Middle Boulder Creek. This would suggest that Long Canyon is no older than Pliocene, roughly in accord with Malde's interpretation of Pliocene or Pleistocene age for the Rocky Flats gravels. Wahlstrom (1947), on the other hand, concluded that just one peneplain existed, and that it reached its maximum extent in late Pliocene or early Pleistocene time. Tator (1952) accepted Wahlstrom's interpretation. According to this interpretation, Long Canyon is probably Pleistocene, roughly in accord with the interpretation of Yarmouth age for the Rocky Flats gravels. It would appear that this approach yields no conclusive age determination, but suggests that Long Canyon assumed roughly its present form some time between late Pliocene and Yarmouth times, or roughly in a time interval ranging from 280,000 to 150,000 years ago (Emiliani, 1955).

This old topography has probably been modified by several stages of alluviation and entrenchment since that time. Such a modification, this one man-imposed, can be observed at the present time. Runoff water from the road on the western divide of the Long Canyon basin has been diverted into tributaries Q and U, both of which have incised their floors to a depth of several feet. Tributary Q has cut through eight feet of alluvium and into weathered granite to a depth of about one foot. Along the main course of Long Canyon downstream from tributary Q widespread sand deposits indicate recent alluviation, probably by material eroded from the channel of tributary Q and deposited because of the sudden decrease in gradient at the junction of Long Canyon and tributary Q. In Long Canyon, channels other than those disturbed by recent engineering work show neither recent alluviation nor trenching, which indicates the topography is essentially in equilibrium with its natural environment, despite the very considerable age of the larger features of the basin. The presence of alluvium in the lower reaches of tributaries Q and U prior to the present man-caused erosion is indicative that the last minor natural change in conditions was one favoring valley-filling rather than erosion.

Relation of H, L, and H/L to order

A part of the Eldorado Springs topographic map was enlarged photostatically to the scale of 1:12,000 to provide a base for a map study of profile characteristics for comparison with the field data. All streams indicated by V's in the contour lines were traced out, but only streams corresponding in position with those measured in the field were chosen for study. This method eliminates the possibility of any observed differences in properties of the two samples being due to sampling errors. The drainage maps prepared by the two methods are shown in Figures 29 and 30.

Figure 31, which is a graphic representation of data in Table 7, shows, first, that the map does not indicate as many streams as were found in the field. Second, the absolute values of the means for the map values of H and L are roughly equal to the corresponding values for the next higher order for the field data. Third, the mean gradients of the first-order samples are comparable, whereas that of the second-order field sample is much higher than that of the map sample. The map sample appears to show with fair reliability the relative behavior of the relations between H, L, and H/L, but the absolute values of H, L, and H/L are unreliable. This consistency is borne out by the values of probability associated with t-tests applied to the differences. H appears to increase systematically with order, and the differences between first-and second-order means is significant at the .10 level. Similarly, L appears to increase systematically with order. In this case, for the field data, the difference between first- and second-order means is not significant. For the map data the corresponding difference is significant. Both sets of data show H/L to decrease regularly with increase in order, with both differences being significant.

Stream profile characteristics

An inspection of the field-measured profiles in Figure 32 shows that the forms are variable, ranging from concave-up (C) to convex-up (P_1) to irregular (Q_1), with many profiles nearly linear (N, L, O_1, P_2, etc.). From this one may conclude that an idealized profile in this area would consist of a series of linear segments, each segment representing a different order, with length increasing with order and gradient decreasing with increase in order. Explanation of this behavior is discussed elsewhere in this paper.

MANITOU PARK AREA

Description of the area

The Manitou Park area treated here includes the area drained by all of the tributaries of Trout Creek upstream from Manitou Park Lake (see Figure 14 and Plate 2). Manitou Park, as shown on the old Platte Canyon topographic map on the scale 1:125,000, extends farther north, but this study was confined to that area draining into Manitou Park Lake, because sediment records were available for that area. The map includes parts of the Mount Deception, Woodland Park, Divide, and Signal Butte topographic map sheets, all on the scale 1:24,000, prepared by photogrammetric methods. Trout Creek is a tributary of the South Platte River. Vegetative cover ranges from grassland in the vicinity of the town of Divide to forest, consisting of western yellow pine (Pinus ponderosa), Douglas fir (Pseudotsuga taxifolia), and aspen (Populus tremuloides), with some spruce (Picea engelmanni and P. pungens) on the highlands. The forest cover is typically more dense on north-facing slopes, with open, grassy areas common on south-facing slopes. The altitude of the basin ranges from 7,735 feet at Manitou Park Lake to 10,605 feet on Raspberry Mountain, south of the town of Divide. The weather station nearest to the Manitou Park area is roughly 10 miles northeast of Woodland Park, on the east side of the Rampart Range. Climate data for the station (Monument 2W) are summarized in Table 1 (U. S. Weather Bureau, 1955). Most precipitation falls during the spring and summer. Because the station is considerably below Manitou Park and lies on the east side of the Rampart Range, the climate is probably somewhat cooler and wetter than Table 1 indicates.

The area is entirely within the southern Rocky Mountain physiographic province (Fenneman, 1931). Manitou Park is a topographic basin, elongated in a north-south direction, between the Rampart Range on the east and a similar highland to the west. As is commonly the case in the Rocky Mountain area, the Park coincides with an area of relatively soft sediments folded or faulted down below the present general summit level. In Manitou Park, the structure is basically a north-south trending syncline, with part of the west limb cut out by faulting. The stratigraphy of the area is summarized in Table 8, and the distribution of outcrops is shown in Plate 2. Sweet (1952) has mapped in considerable detail the Paleozoic section along the east side of the basin. The Rampart Range is composed almost entirely of Pike's Peak granite, with a narrow band of westerly dipping Paleozoic quartzite and limestones covering some of the spurs along the west side of the range. Soldier Mountain is capped by an outlier of the latter unit. The detailed stratigraphy of this map unit is described in Table 8. The dip of this belt of sediments is westerly, ranging from 15 to 70 degrees. Southwesterly plunging anticlinal and synclinal noses pass into the basin near Soldier Mountain. A southwesterly plunging synclinal nose is mapped just east of Manitou Park Lake. A small north-south fault, upthrown to the west, breaks the pre-Pennsylvanian sediments just east of this syncline. An anticlinal nose, also plunging to the southwest, exists just north of the map area. The Pennsylvanian Fountain formation underlies most of Manitou Park. It rests unconformably on the pre-Pennsylvanian unit, but still dips westerly at the contact. The highland just west of Manitou Park is underlain by Pike's Peak granite. This granite is separated from the Fountain formation by the northwesterly trending Ute Pass fault, which is here probably a reverse fault, upthrown to the west.

On the crest of the Rampart Range, south of the head of Loy Gulch, and extending for an undetermined distance to the southeast, is a deposit of rounded boulders, cobbles, and gravel, consisting of a mixture of lithologies including volcanic rock, which is not indigenous to the Rampart Range. The present topography developed on this deposit is very gently rolling, with a gradual northwesterly slope. This set of circumstances might be interpreted as indicative of an old, stream-worn erosion surface, perhaps a pediment, extending toward the area of Tertiary volcanics northwest of the town of Cripple Creek. The gravel may be one of the Pliocene sediments partially mantling the Rocky Mountain peneplain, as described by Atwood and Atwood (1938, p. 965). It is here correlated with the Ogallala gravel, of Pliocene age, after Lee (1922). This interpretation would require that the erosion of the present valley of Trout Creek, in the vicinity of Woodland Park (and of Fountain Creek, just to the south), took place in Quanternary time.

A lower, and presumably younger, gravel mantles an irregularly shaped area starting about a mile southwest of Woodland Park and extending west and southwest outside the basin of Trout Creek. In a road cut along Highway 24, about half a mile northwest of the Silver Spur Ranch, badly weathered, stratified gravels rest on a surface of weathered Pike's Peak granite, which surface dips westerly at about 20 degrees. A small hill of granite rises above the gravel just east of the small stream valley east of the road cut, and granite is exposed in the valley walls. Apparently, this old gravel was deposited by running water on an irregular surface of the granite, filling in the low areas of the old topography. This gravel was described by Cross (1894) as "apparently glacial drift." It is here interpreted as glacial outwash, either pre-Wisconsin or early Wisconsin in age. It may be some of the material "in the vicinity of Pike's Peak," considered by Atwood and Atwood (1938, p. 977) to be early Pleistocene. South of Divide, Raspberry Mountain rises about 1,200 feet above the gravels on the east side of the basin, and a much lower hill rises above the gravels to the west. Both hills are underlain by Pike's Peak granite. The pre-outwash gravel surface apparently had at least 1,200 feet of relief.

The outcrop of the Fountain formation is widely mantled by pediment gravels of several ages. The highest surface, designated by the symbol Q_1, is preserved only in a few scattered remnants around Woodland Park, east of Manitou Park Lake, south of Soldier Mountain, and northeast of Manitou Park Grange Hall. At the last named locality, a few remnants of Fountain formation, with the gravel stripped off, still stand above the younger surfaces. Sweet (1952) called the highest pediment gravel the Woodland Park formation, which he considered to be Tertiary in age. Remnants of the oldest pediment stand roughly 80 to 100 feet above the intermediate surface, which is the most widespread of the three. The isolated monuments of Fountain formation along Quinlan Gulch and around Manitou Park Lake are probably remnants of this intermediate surface, from which the gravel has been removed. The intermediate surface, designated Q_2 on the map, stands as much as 100 feet above the youngest, or Q_3, surface. The youngest pediment gravels form a smooth surface around the margin of the intermediate surface, and occupy re-entrants in that surface. All three of the surfaces are cut by numerous small channels which are even better seen on air photographs than on the available large-scale topographic maps. Many of the courses of Trout Creek and its tributaries are underlain by alluvium.

The course of Trout Creek is unusual in that it rises in highlands west of Manitou Park, flows into the Manitou Park basin, and just west of Manitou Park Grange Hall flows back into the highlands, entering the basin again two miles south of Manitou Park Lake. This peculiar course is indicative of superposition of the stream course on the granite from softer material that once covered both the granite and the sediments cropping out now in Manitou Park. This softer material could have been gravel similar to the outwash gravels around the town of Divide.

Divisions of Manitou Park area

From a geomorphic standpoint, the Manitou Park area may be divided into four districts: (1) the Pike's Peak granite--pre-Pennsylvanian sediment outcrop area of the Rampart Range (Rampart Range granite area); (2) the extensive outcrop area of Pike's Peak granite west of the Ute Pass fault (Rule Creek granite area); (3) the area of widespread outwash gravels in the vicinity of the town of Divide (Divide gravel area); and (4) the lowland of Manitou Park itself (Manitou Park basin). Both the Rampart Range and Rule Creek granite areas are heavily forested. The Pike's Peak granite, on weathering, forms large, rounded masses, which are bordered by very coarse grus. The soil formed from this grus is very coarse, and, apparently quite permeable. In a few areas, as at the head of the north fork of White Gulch, drainage ditches from the Rampart Range road have been diverted into natural drainage. The increased discharge at the head of the washes has resulted in active gullying there. The channel is a foot deep in White Gulch. The material removed from the gullies is strewn in gravel sheets that reach (at White Gulch) about 1,600 feet downstream from the head of the Gulch. With the exception of these man-disturbed zones, the granite areas appear to be subject to very little erosion. On south-facing slopes, the grassy bottoms of the low-order tributaries are but rarely cut by a permanent channel. The mouths of the first-order valleys are marked with grass-covered alluvial fans, so there can be little doubt that these depressions are stream valleys, despite the lack of permanent channels. Valley-bottoms on north-facing slopes, where the timber cover is thicker, are commonly filled with thick accumulations of leaves, squirrels' pine cone caches, and deadfall. Such features would not be preserved if erosion were active at the present time. This would indicate that if any inequilibrium exists in these granite areas, it is in the direction of alluviation, rather than active gullying. Considered in the light of the previous discussion, the two granite areas appear to be unlikely sources for sediment now accumulating in Manitou Park Lake.

The Divide gravel area is similar to the granite areas in its gravelly soil and lack of gullying. It would seem, then, that the most likely source of sediment is Manitou Park basin, with its extensive pediment and alluvial deposits. The widespread occurrence of active gullies in this area confirm this impression. The sediment yield, then, is probably much higher in Manitou Park basin and lower in the other three areas than the average figure given by the sediment data. Records from ponds in each of the four areas would be needed to test this conjecture. Because of the probable high, but unknown percentage of the total sediment yield from Manitou Park basin, which is but 20% of the entire basin area, it would be inaccurate to attempt to relate the profile characteristics measured in the Rampart Range granite area to the sediment yield as determined in Manitou Park Lake.

Comparison of field and map data

Altitudes were obtained by field survey in North Fork of White Gulch in the northwest quarter of section 5, T. 12 S., R. 68 W., El Paso County, at the heads and mouths of 21 first-order stream segments. A map of the channels indicated on the contour map alone is shown in Figure 34. The latter figure shows just 8 first-order tributaries, some of which are shown by the field studies to be largely second order segments. For the field data, the arithmetic mean of the altitude differences is 50.0 feet, with a standard deviation of 19.5 feet. For the map data, the mean is 96.2 feet, with a standard deviation of 32.4 feet. Because the two samples were taken from precisely the same areas, there is no possibility of sampling error.

Altitudes were obtained at the heads and mouths of 21 first order tributaries in North Fork of Loy Gulch in the northeast quarter of section 8, of the same township and range as above. Figure 33 is a map of the stream channels in this area as located in the field; the channels indicated by the contour map alone are shown in Figure 34. In this case, 15 unbranched tributaries are indicated by the map study, again with some shown by field-study to be partly second-order segments. The mean altitude difference for the field data is 49.0 feet, with a standard deviation of 23.6 feet. For the map data, the mean is 64.0 feet, with a standard deviation of 22.6 feet. Here again there is no possibility of obtaining the difference by chance sampling variations alone.

Figure 35 casts considerable light on the problem raised by the differences between the means computed from field and map data. Histogram d, map data of Loy Gulch, shows an increase in percentage frequency from the high values of H down to about 45 feet, and then a sudden decrease. Because the contour interval of the map is 40 feet, it would seem quite logical to say that the map is incapable of showing all channels where the altitude difference is less than 40 feet. In the field data (histogram b) 43 per cent of the channels have an altitude difference of less than 40 feet. This explanation does not seem to apply to the White Gulch data. In map data (histogram c) the percentage frequency dips markedly at an altitude difference of 85 feet. A map with a contour interval of 40 feet should be able to show features whose altitude difference falls between 85 and 40 feet. Moreover, many of the channels not shown on the topographic map are quite apparent on the air photographs examined stereoscopically by the writer. In field data of this area (histogram a) 7, or 33 percent, of the first-order tributaries have an altitude difference of less than 40 feet. Therefore, it would seem that even recent, large-scale topographic maps, prepared by photogrammetric methods, are not necessarily adequate to show all of the unbranched tributaries in a given area, and that the map should be checked, either in the field, or at least against air photographs, before one attempts to make quantitative land form studies on the basis of map data. The maps used in the Manitou Park area all comply with National Map Accuracy standards. In this connection, it may be of value to note that the bifurcation ratio (Horton 1945) or the ratio of the number of first-order segments to the number of second-order segments, based on the White Gulch field data, is 4.20, whereas it is 4.00 for the map data. For the Loy Gulch field data, the bifurcation ratio is 5.25, and for the map data it is 5.00. In both areas, despite the errors in both the number of streams present and the values of the altitude differences as shown on the map, the bifurcation ratios given by the map data are comparable to those computed from the field data. In both cases, the value for the field data is about 5 per cent higher than the value for the map data. Because the number of valleys concerned is small, the significance of this 5 per cent value is highly questionable.

Relation of H, L, and H/L to order

Figure 36 shows map data on H, L, and H/L for four orders in the Mt. Deception quadrangle; Figure 37 gives regressions. In all of the other basins studied, mean values of H either showed no significant variation with order or else increased systematically with order. In this case, H appears first to decrease, then to increase with order. L appears to increase with order, whereas H/L definitely decreases with increase in order. Apparently only H is atypical in its relationship to order. This anomaly may be due to one or more of the numerous rejuvenations that have affected the lower area in Manitou Park basin working headward into the Rampart Range. The writer observed several hanging valleys in the course of the altimeter measurements. These smaller valleys, which generally trend north-south, have gentle gradients in their upper reaches, and drop very steeply down to the larger valleys draining westward into Manitou Park. Apparently, the entire Manitou Park area has been so seriously affected by its complex geomorphic history that it is not well suited to a study of this type. However, it is interesting to note that here most statistical relationships are consistent with those of other regions. This might be construed to indicate that the length relationships have not been altered drastically by the rejuvenation, but are somewhat characteristic of the area, rather than the stage of development.

WIDOW WOMAN CANYON AREA

Description of the area

The basin of the middle fork of Widow Woman Canyon is about 12 miles southwest of Trinidad, Colorado, in parts of sections 8, 16 through 20, and 30, T. 34 S., R. 65 W., and sections 13 and 23 through 26, T. 34 S., R. 66 W., Las Animas County, Colorado (Figure 14). For convenience, the area will be referred to simply as the Widow Woman Canyon area, with the understanding that not all of Widow Woman Canyon is under discussion. The area is within the Valdez topographic map quadrangle, mappled by multiplex methods by the U. S. Geological Survey in 1951. The map is on the scale of 1:24,000, with a contour interval of 20 feet. Widow Woman Canyon is a tributary of the Purgatoire River, a part of the Arkansas River system. The altitude ranges from 6,720 feet to about 7,760 feet. The area is covered by a woodland of scrub oak (_Quercus leptophylla_ and _Q. gambelii_), a juniper (_Juniperus scopulorum_), and pinyon (_Pinus edulis_), with some western yellow pine (_Pinus ponderosa_) at higher elevations (Shantz and Zon, 1924). Table 1 contains a summary of climate data gathered at the Trinidad airport. Most precipitation falls in the spring and summer. The weather station in the city of Trinidad (elevation 6,030 feet) recorded 14.52 inches of precipitation in 1955, compared with 13.29 inches at the airport (U. S. Weather Bureau, 1955), which indicates a general increase in precipitation with increase in altitude. Widow Woman Canyon is considerably higher than the weather stations, so the climate there is probably slightly cooler and wetter than the table would indicate.

The Widow Woman Canyon area is in the Park Plateau, a part of the Raton section of the Great Plains physiographic province (Fenneman, 1931). The lower part of the basin is underlain by the Cretaceous and Paleocene Raton formation, described by Johnson and Wood (1956) as an alternating sequence of buff, gray, and olive-gray, fine- to coarse-grained arkose, graywacke, and sandstone beds; gray to dark gray silt-stone and silty shale beds, and numerous coal beds. In the arenites, the feldspar grains are commonly white and weathered. The higher divides are probably underlain by rocks of the lower facies of the Paleocene Poison Canyon formation (Johnson and Wood, 1956), which differs from the Raton formation in that the feldspar grains are commonly pink and unweathered, the sandstones are coarser grained, and coal is generally absent. The writer holds these differences to be of little significance for a purely geomorphic study, and considers the area to be one of homogeneous lithology. Minor dikes and sills are present in this part of the Park Plateau (Hills, 1901), but, unlike areas to the north, their topographic influence is generally minor. Widow Woman Canyon is on the east flank of the Raton structural basin, with the beds dipping very gently in a general westerly to northwesterly direction.

Relation of H, L, and H/L to order

Method of sampling in the Widow Woman Canyon area has been explained in the discussion of methods. Figure 38 shows histograms of H, L, and H/L for four orders. Regressions of H, L, and H/L on order and tests of significance are shown in Figure 37.

The following conclusions are drawn on the basis of the map data. The mean values of H for the lower three orders are roughly equal. For orders greater than one, H appears to increase with order. However, the regression analysis for this set of data shows the slope of the regression line to be not significant at the .10 level. Therefore, this apparent increase may be due to sampling variations alone, and is not necessarily damaging to the theory that H tends to approach a constant within a given basin as the basin approaches a steady state. The mean values of L increase systematically with order. Gradient decreases with increase in order. The results of the regression analyses show the slopes of lines fitted to the latter two sets of data to be significant at the .05 level. An idealized profile made up of the mean characteristics of the first-, second-, etc., order profiles would consist then of segments, each segment having a constant H, independent of order, a value of L that increases with order, and a gradient that varies inversely with order.

Stream profile characteristics

To investigate the nature of the segments making up the composite profile, the writer measured from the map five long profiles, which are shown in Figure 39. The profiles are shown broken down into segments by order. The most common form for each segment is an approximately straight line. Some of the segments are convex-up, a few markedly concave-up. It should be remembered that these profiles were obtained from a map with a contour interval of 20 feet, which is too large to show the fine details of a profile. The profiles in Figure 39 are similar in appearance (but not in scale) to those measured in the field in the Cheese Ranch basin (Figure 17). In both sets of profiles, the over-all aspect is linear, but with a few concave-up reaches. The resistant members of the alternating sandstone-shale lithology of the Raton and Poison Canyon formations might cause small nick points in the profiles, similar to the turf-supported nick points found in the Cheese Ranch basin. These rock-supported nick points might have the same effect as the turf-supported ones, giving the profiles a gross aspect of linearity, but a detailed aspect of numerous concave-up reaches.

The available data do not permit an evaulation of the effect of rejuvenation on the profiles, but such a rejuvenation is observable in the lower reaches of Widow Woman Canyon. Here the stream has cut through 4 or 5 feet of alluvium to expose the sandstone and coal of the Raton formation in the stream bed. Such a rejuvenation may be the cause of the rather large mean value of H for fourth-order segments.

In summary, the stream profiles of the Widow Woman Canyon area appear to be segmented. Each segment has a form varying between a straight line and an up-concave curve that might be fitted by an exponential or logarithmic function. The change from one segment to the next corresponds roughly to the change from one order to the next.

CHILENO CANYON AREA

Description of the area

The basin of Chileno Canyon is about 10 miles north of Azusa, California, in T. 2 N., R. 10 W. (unsurveyed), Los Angeles County, California (see Figure 40). The basin is in the Chileno Canyon topographic map quadrangle, mapped by the U. S. Geological Survey in 1933-34 on the scale 1:24,000, with a contour interval of 25 feet. Chileno Canyon is tributary to the west fork of San Gabriel River. Altitudes in the basin range from 2,025 feet at the mouth to 5,500 feet on the divide. Native vegetation in the area consists of Chapparal, a sparse woodland of stunted hardwood trees and shrubs. Common species are: highland live oak (Quercus wislizeni), scrub oak (Q. dumosa), holly-leaf cherry (Prunus ilicifolia), sumac (Rhus laurina), wild lilac (Ceanothus hirsutus), manzanita (Arctostaphylos glauca), and chamise (Adenostoma fasciculata) (Shantz and Zon, 1924). Climate data gathered at two stations near the area are summarized in Table 1. Llano Shawnee Hills Ranch is about 20 miles northeast of Chileno Canyon, and Valyermo Ranger Station is about 10 miles east of the area. At both stations, most of the precipitation falls during the winter and early spring. Summers are exceedingly dry. Llano Shawnee Hills Ranch is northwest of the San Gabriel Mountains, whereas the Valyermo Ranger Station is in the mountains, so the data for the latter station are probably more representative of the climate at Chileno Canyon.

Chileno Canyon is in the San Gabriel Mountains, a part of the Angeles section of the Pacific Border province (Fenneman, 1931), or the Transverse Range province (Jenkins, 1938). The area is underlain by rocks referred to as the basement complex, consisting of well-banded metamorphic gneisses, meta-sediments, massive gneisses, granite, and granodiorite, with some diorite and gabbro of various ages (Calif. Dept. Public Works, 1934). No single rock unit forms a large part of the range. The bedrock is very deeply weathered. The San Gabriel fault, a steep reverse fault (Calif. Dept. Public Works, 1934), roughly parallel to the San Gabriel River, crosses the extreme southern tip of the basin. With the exception of this southern tip, Chileno Canyon is in the great interior block of the San Gabriel Mountains, a block characteristically devoid of large faults, but within which the rocks are badly fractured (Miller, 1928, p. 211).

Relation of H, L, and H/L to order

Values of means, variances, and standard deviations for H, L, and H/L for each order are shown in Figure 41. Regression data (Figure 42) indicate that the means value of H varies irregularly with order. The mean value of L appears to increase systematically with order. The mean value of H/L appears to vary inversely with order. Apparently H', as defined previously in this paper, increases with order. L' increases as an exponential function of order, and H'/L' decreases regularly with increase in order, approaching zero asymptotically. The latter two results are, as in the Salt Run area, in agreement with Horton's (1945) laws of stream length and stream slope. When the logarithm of the mean gradient is plotted against order, the curve is nearly linear, suggesting that gradient varies as an inverse exponential function of order. The statistical significance of the relationships between H, L, and H/L and order was determined by regression analysis, the results of which are shown in Figure 42. The regression analysis was applied to the non-cumulative data only. The slope of the regression of log H on order is not significant at all three levels used, which tends to confirm the idea that H is a constant, independent of order. If this be so, H' would increase linearly with order. The linear nature of the increase is masked in Figure 42 by the use of a logarithmic scale for values of H. Slopes of the regression lines of log L and H/L on order are significantly different from zero at all levels, so there is little reason to doubt that L varies directly with order and H/L inversely with order.

Stream profile characteristics

A detailed single-channel profile of the main stem of Chileno Canyon was prepared from the enlarged map, starting with a first-order segment near the highest part of the divide and extending to the mouth of the canyon (Figure 43). This profile, arithmetically scaled on both axes, is a nearly smooth curve without distinct segments. The logarithmic plot (Figure 43) is generally up-concave with a suggestion of segmentation by orders. The segmentation seems apparent between the third-and fourth-order segments and between the fourth- and fifth-order segments. Orders 1, 2, 4, and 5 are nearly linear segments, but order 3 is markedly curved.

A composite profile of the Chileno Canyon basin (Figure 44) consists of a series of segments of increasing order, with the segment of a particular order having the mean H and mean L found from the map data (Figure 41) for that order. The individual triangles thus produced by each order are placed in series to form the composite profile. The composite profile shows up-concave forms strikingly. Of greater interest is the lack of any increasing trend in average vertical drop, H, in successive orders. The values of H are 301, 231, 330, 200, and 300 in that order. It has already been shown (Figure 42) that the slope of the reression of H on order is not significantly different from zero at any of the probability levels used. Obviously, the up-concavity is produced by the large and steady increase in length of segments, L, in the downstream direction. This increase of L with order is well displayed in the regression diagram of Figure 42.

Following the previous procedures (Salt Run Area) the mean slope, S, of each order was treated as a function of downstream distance, using distance from head, X, plus a constant L_g, which in this case was measured as 430 feet. (In this region of relatively high drainage density, L_g is appreciably shorter than that for the Salt Run area whose low drainage density is responsible for the L_g value of 1000 feet.) Figure 45 A, B, C, D shows the relation of slope to distance using arithmetic, exponential, logarithmic, and power forms of plotting. Neither the arithmetic nor exponential plots are satisfactory because of strong up-concavity. The logarithmic plot gives a nearly straight line and is considered appreciably better than the power plot, in which a slight but distinct up-convexity is present. These results closely match those of the Salt Run area (compare with Figure 13 A, B, C, and D), even though the Chileno Canyon profile segments are steeper and shorter, order for order, and the two areas are in very different geological and climatic environments.

To relate segments in the stream profile to watershed area the writer measured by polar planimeter the areas of the various small basins contributing to each order segment of the Chileno Canyon profile. Areas were converted to per cent of area of the entire basin (3.00 square miles) and are shown in Table 9. It is important to note that, at a change in order, the total area draining into the channel increases greatly. Because discharge in a small basin is directly proportional to drainage area (Linsley, Kohler, and Paulhus, 1949, pp. 457 and 575; Hack, 1957, p. 54), the discharge of the stream would undergo a marked increase at an increase in order. In the previous discussion of causes of up-concavity the relation of discharge increase to stream slope has been analyzed.

It could be argued that many first-order streams in a given locality drain more area, and would therefore have a greater discharge than some of the second-order basins in the same area. This is true in specific cases, and the profile of the second-order stream would probably change form at such a junction. The concept of profile form being related to order is strictly a statistical one, requiring an adequate sample of stream segments for consistent behavior. Data published by Schumm (1956) indicate that the main area drained by a stream varies as an exponential function of order, following a law noted by Horton (1945, p. 194). Thus, while exceptions certainly do exist, the change in profile form will, on the average, correspond to a change in order.

SUMMARY EVALUATION OF DATA OF ALL AREAS

Relations of H, L, and H/L to order

One of the most interesting observations from the segment data of vertical drop (H) and horizontal distance (L) as functions of both order and downstream distance from origin is the tendency for the vertical drop in successive orders to remain constant. Decrease in slope takes place by increase in length (L) of each order. These observations may be discussed in the light of two principles: (1) the principle of preservation of geometrical similarity and (2) the principle of stream capacity as a function of slope (Gilbert's law of declivities).

Consider first the principle of geometrical similarity of drainage basins (Strahler, 1958, p. 291). Two drainage basins are geometrically similar when all corresponding length measures are related by the same ratio and all dimensionless form properties (ratios of lengths) are constant. Strahler's studies of drainage basins indicate that geometrical similarity is closely preserved in the horizontal, or plan, aspects of small watersheds despite great differences in absolute scale. On the other hand the vertical, or relief aspects of the same basins do not preserve geometrical similarity. Strahler (1958, p. 293) compared only first and second order basins among regions; the principle may not be valid when applied to successive orders of basins in the same watershed. Hack (1957, p. 63-64) tends to confirm the last supposition by finding that stream length varies as the 0.6 power of area in basins spanning nearly four orders of magnitude (.01 to 100 sq. mi.). An exponent of 0.5 is required if geometrical similarity is to be perfect. The value of 0.6 requires that basins become somewhat longer and narrower as their size increases. The important point is that the lengths increase systematically with increasing basin area, hence with increasing order. If vertical drop (H) also increased in a corresponding ratio there would be no change in slope. But a decrease in slope is required by the greater efficiency of stream flows of increasing discharge (Gilbert's law of declivities). Hence slope can only diminish if vertical drop increases less rapidly than length increases in the downstream direction, or if vertical drop remains constant with order (a special case), or if vertical drop decreases with length. Why vertical drop (H) seems to be about constant for each order (instead of, say, decreasing with order) is not understood. One can simply say that on the basis of the measured profiles the requisite slope decrease is effected by maintenance of a constant unit of drop for each increase in order. Carried to a logical conclusion, this relationship requires that order is a direct function of altitude, and that streams of each order will occupy equal altitude ranges, provided that all contribute to a trunk segment of the same order. Thus, if a watershed were of the fifth order with the mouth of the trunk segment situated at, say 2000 feet, and with a characteristic value of H of 300 feet, the first order segments should occupy the altitude range 3200-3500 feet. This means that the summit elevations should occupy a level about 3500 feet, plus the average value of the added constant, H_g.

The observed constant value of H, independent of order, is the basis for the proposal of a theory that, in a basin developed in homogeneous rock and in a homogeneous climate, when a steady state is attained, the mean altitude change for any given order is a constant. Rejuvenation destroys this relationship. The theory stands in need of further testing.

The writer's data for the cumulative values of L and H/L confirm Horton's laws of stream length and stream slope.

Single channel profile characteristics

From inspection of single channel profiles, it is concluded that profiles are generally segmented, the change in segments occurring at the change in order, which corresponds to an abrupt increase in discharge. This agrees with the findings of Mackin (1948, p. 491-492). The regression data support the idea that the individual segments are concave-up, but do not provide clear-cut evidence for a determination of which form of equation best fits the observed profiles. Nearly linear profiles observed in the Colorado test areas may possess a similar subtle concavity. Certainly the special conditions causing the linear profiles observed by Maxson (1950) in the Panamint Range cannot be applied to the small streams investigated by the writer.

Composite profile characteristics

Idealized composite profiles consist of segments of succeeding order, each segment having the mean values of altitude change and length for the proper order. On the basis of inspection, the composite profiles are judged best-fitted by a logarithmic equation. The importance of this finding is that it tends to vitiate the derivation of the longitudinal profile as controlled by particle abrasion following Sternberg's law of abrasion (Shulits, 1941). In a headwater region, where one might except vigorous abrasion and rapid breakdown of coarse bed materials, the establishment of a logarithmic stream profile may be taken to mean either that (a) grain diameter, which, in part, controls stream gradient (Hack, 1957, p. 58) is not exponentially related to distance downstream; or that (b) if grain diameter does decrease exponentially with distance downstream, the relationship between gradient and grain size is not simple. Hack's recent report (1957, p. 58) shows both alternatives to be partly true. First, his field data show that median particle size does not always decrease in a downstream direction, much less decrease as an exponential function of distance. Second, he shows gradients of streams larger in size than the low-order streams in the present report to be a power function of the ratio of median size of the bed material to the area of the basin upstream from the point of measurement of the gradient, rather than particle size alone.

The results of the studies of the composite profiles throw doubt on the idea that comminution of bed load material is important along the courses of small streams. If Sternberg's abrasion law held in the Panamint Range streams studied by Maxson, and if Shulits' derivation is correct, the linear profiles should not be stable. Hack, as mentioned, found the median particle size to be controlled by local geologic conditions, rather than a general abrasion law. Both Hack and Maxson studied basins larger than those investigated by the writer. It is thus concluded that the cause of concavity of profiles of low order streams is the increase in discharge along the profiles.

The finding of a logarithmic curve to best fit the composite profile is in agreement with Woodford, Jones, and Green, among others. It does not agree with Hack, who used a system of plotting similar to that described in this report, but used a power function for the long profile.

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Table 1

Climate Data for Test Areas

Area	Station	Altitude (Feet)	Mean Annual Precipitation (Inches)	Low Mean Temperature (Jan)* (Degrees F.)	High Mean Temperature (July) (Degrees F.)	Mean Annual Temperature (Degrees F.)
Salt Run	Emporium	1,160	43.18	25.8	69.7	47.9
Highlands Ranch	Kassler	5,495	18.13	31.6	73.2	51.5
	Parker	6,300	14.65	25.1	69.6	46.7
Long Canyon	Boulder	5,404	18.29	32.1	71.7	50.8
	Hawthorne	5,923	21.70	-	-	-
Manitou Park	Monument 2W	7,400	19.35	27.1	66.1	-
Widow Woman Canyon	Trinidad Airport	5,746	14.08	30.9	71.6	50.8
Chileno Canyon	Llano Shawnee Hills Ranch	3,820	7.61	43.1	79.0	59.9
	Valyermo Ranger Stn.	3,700	10.29	41.8	74.4	56.9

* Coldest month of year at Emporium is February.

Table 2 - Stratigraphic Summary of Salt Run Area

Age	Formation	Thickness (in feet)	Lithology	Physiographic Expression
Pennsylvanian	Pottsville Group	50-100	Conglomerate, quartz-pebble, white to brown, coarse-grained sandstone, clay and coal.	Caps gently sloping upland surfaces, bordered by steep slopes mantled by blocks 10 to 30 feet in maximum diameter.
Mississippian	Mauch Chunk shale	10-100	Shale and shaly limestone	Forms slope below Pottsville.
	Pocono group	570	Sandstone, fine to medium grained, gray to brown, micaceous, thin or cross-bedded; red siltstone, red shale, conflomerate, few thin lenses of calcareous breccia and sandy limestone	
	Oswayo formation	300	Sandstone and shale, with calcareous zones similar to Pocono.	
	Catskill red beds	840	Sandstone, fine to medium grained, micaceous, thin bedded; siltstone; shale; calcareous zones similar to Pocono.	Crops out in areas near anticlinal axes..
Devonian	Chemung formation	1760-2100	Shale, green and gray, thin bedded; sandy shale; siltstone; fine-grained sandstone.	Floors major anticlinal valleys.

Table 3

Comparison of Field-Measured Values of Second-Order H, L, and H/L,
Cheese Ranch and Highland Ranch Basins

	H				L				H/L			
	$\bar{x}$	Antilog $\bar{x}$	S^2	S	$\bar{x}$	Antilog $\bar{x}$	S^2	S	$\bar{x}$	S^2	S	N
Cheese Ranch Basin	1.233	17.120	.5097	.7139	2.767	606.74	.4977	.7054	.0325	.00001000	.003163	6
Values of P	$.5 > P > .4$				$.7 > P > .6$				$P < .001$			
Highlands Ranch Basin	1.467	29.301	.03767	.1941	2.583	398.11	.06267	.2502	.0775	.0004900	.02214	6

Table 4

Comparison of Map-Measured Values of H, L, and H/L
Cheese Ranch and Highland Ranch Basins

	H				L				H/L			
	$\bar{x}$	Antilog $\bar{x}$	S^2	S	$\bar{x}$	Antilog $\bar{x}$	S^2	S	$\bar{x}$	S^2	S	N
Cheese Ranch Basin	1.550	35.48	.07600	.2757	2.983	962.3	.1667	4082	.0400	.0001875	.01370	6
Values of P	$.8 > P > .7$				$.1 > P > .05$				$01 > P > .001$			
Highlands Ranch Basin	1.400	25.12	.08700	.2950	2.5500	354.8	.1080	.3286	.0700	.0002775	.01666	6

Table 5

Comparison of Values of H, L, and H/L of
First- and Second-Order Segments, Map and Field Data

Cheese Ranch and Highlands Ranch Basins

a. Cheese Ranch

		First-Order Mean	P	Second-Order Mean
H	Map Data	26.424	$.3 > P > .2$	35.481
	Field Data	15.101	$.8 > P > .7$	17.140
L	Map Data	456.03	$.01 > P > .001$	961.61
	Field Data	284.44	$.05 > P > .02$	606.74
H/L	Map Data	.0572	$.01 > P > .001$	.0400
	Field Data	.0553	$P < .001$	.0325

b. Highlands Ranch

		First-Order Mean	P	Second-Order Mean
H	Map Data	25.823	$.05 > P > .02$	25.119
	Field Data	16.106	$.01 > P > .001$	29.301
L	Map Data	328.85	$.7 > P > .6$	354.81
	Field Data	216.77	$.01 > P > .001$	398.11
H/L	Map Data	.0813	$.3 > P > .2$	.0700
	Field Oata	.0951	$.1 > P > .05$	.0775

TABLE 6 - STRATIGRAPHIC SUMMARY OF LONG CANYON AREA

Age	Sym.	Formation	Thickness	Lithology	Physiographic expression
Quaternary	Qal	Alluvium	4½ feet [1]	Sand & gravel	Restricted to active flood plains.
	Qls	Landslide debris	Variable	Boulders, cobbles, gravel, sand and silt.	Mantles large area on east flank of Flagstaff Mtn. Small slump blocks on flanks of pediments.
	Q	Pediment "gravel"	25-50 feet [2]	Boulders, cobbles, gravel and sand, poorly sorted.	Caps pediment surfaces along mountain front.
Cretaceous	Kp	Pierre formation	5000-8000' [3]	Shale, dark gray to black, and soft, brown or gray-brown sandstones.	Forms gently rolling hills, commonly mantled by Quaternary deposits.
	Kn	Niobrara formation: Fort Hays member	30 feet [3]	Limestone, light gray, massive, fine-grained.	Forms minor ridges.
		Niobrara formation: Smoky Hill member	300-500' [3]	Shale, gray, limey, and discontinuous white limestones and limey sandstones.	Similar to Pierre formation
	Kb	Benton formation	500 feet [3]	Shale, black, fissile, with thin zones of limestone, bentonite, and ironstone concretions.	Forms valley between Dakota and Fort Hays ridges.
	Kd	Dakota group	320 feet [5]	Upper unit; quartzite or sandstone, light gray, massive. Middle unit: shale, black, sandy shale, and ferruginous siltstones. Lower unit: sandstone, pink-weathering, massive, conglomeratic, poorly cemented.	Upper unit forms crest of prominent hogback. Middle and Lower units form part of back face of hogback.
Jurassic	Jm	Morrison formation	400 feet [5]	Sandstones and shales, variegated. Thin marlstones in lower part. Includes thin tongue of Entrada sandstone at base.	Forms back face of hogback.
Triassic and Permian	TRl	Lykins formation	600 feet [4]	Shale, red, sandy, and thin limestone and gypsum beds.	Forms floor of valley between Lyons and Dakota ridges.
Permian	Pl	Lyons sandstone	200 feet [4]	Sandstone, cream to bright red, medium-grained, well-sorted, cross-laminated.	Forms minor ridge below flatirons.
Pennsylvanian	PF	Fountain formation	1000 ft. [3]	Conglomerate, coarse, maroon; silica-cemented; arkosic sandstone; and lenticular red and green shale. (Includes Flagstaff rhyolite sheet).	Forms prominent flatirons along mountain front.
Precambrian	bcg	Boulder Creek granite		Quartz monzonite to sodic granite, dark gray, coarse-grained, gneissic, locally porphyritic.	Forms rugged highlands of the Front Range.

1. Malde (1955)
2. Lee (1900)
3. Hunter (1955)
4. Lovering & Goddard (1950)
5. Fenneman (1905)

Table 7

Summary of Properties of Long Canyon Stream Profiles

	Order		Field Data	Map Data
H	First	$\bar{x}$	1.925	2.260
		Antilog $\bar{x}$	84.14	181.97
		5^2	.04829	.06767
		S	.2198	.2601
		N	20	10
	Values of P		.1>P>.05	.1>P>.05
	Second	$\bar{x}$	2.107	2.525
		Antilog $\bar{x}$	127.94	334.97
		S^2	.09619	.04250
		S	.3102	.2062
		N	7	4
	Third	$\bar{x}$	2.450	
		Antilog $\bar{x}$	281.84	
		5^2	.03000	
		5	.1732	
		N	3	0
L	First	$\bar{x}$	2.395	2.700
		Antilog $\bar{x}$	248.31	501.11
		S^2	.05840	.02722
		S	.2416	.1650
		N	20	10
	Values of P		.2>P>.1	P<.001
	Second	$\bar{x}$	2.607	3.275
		Antilog $\bar{x}$	404.58	1,883.6
		5^2	.1662	.02917
		S	.4077	.1707
		N	7	4
	Third	$\bar{x}$	3.283	
		Antilog $\bar{x}$	1,918.7	
		S^2	.01333	
		5	.1156	
		N	3	0
H/L	First	$\bar{x}$	.3525	.3800
		5^2	.004336	.01192
		5	.06585	.1092
		N	20	10
	Values of P		P<.001	.01>P>.001
	5econd	$\bar{x}$	.2679	.1875
		S^2	.002857	.002292
		S	.053451	.04788
		N	7	4
	Third	$\bar{x}$	.1583	
		5^2	.000834	
		S	.02888	
		N	3	0
	Fourth	H/L	.0868	
		N	1 (incomplete)	0

TABLE 8 - STRATIGRAPHIC SUMMARY - MANITOU PARK AREA

Age	Sym.	Formation	Thickness	Lithology	Physiographic expression
	Qal	Alluvium	Variable	Sand and silt.	Restricted to active flood-plains
	Qls	Landslide debris		Gravel, sand & silt.	Restricted to small land-slide $1\frac{1}{4}$ mi. northeast of Divide.
	Q	Undifferentiated alluvial deposits	Variable	Gravel, sand and silt.	Limited to a few minor, isolated terraces.
Quaternary	Q_3	Youngest pediment deposits	10-25 ft.	Gravel, sand and silt	Lowest of series of pediments in Manitou Park. Forms surface around margin and in reentrants of Q_2.
	Q_2	Middle pediment deposits	10-25'	Cobbles, gravel, sand and silt.	Middle level pediment. Most widespread of the series.
	Q_1	Oldest pediment	40 ft.	Gravel, sand and silt.	Highest level pediment. Forms isolated remnants above Q_2 surface.
	Qog	Old outwash gravels		Cobbles, gravel, sand and silt, badly weathered.	Mantles irregularly shaped area around Divide.
Tertiary?	Tg	Tertiary gravels		Boulders, cobbles, gravel, sand and silt, well rounded.	Mantles small area of summit of Rampart Range south of Loy Gulch.
Pennsyl-vanian	Pf	Fountain formation	600' approx.	Sandstone, red, maroon, and white; arkose; conglomerate; red and green shale.	Underlies Manitou Park. Mantled by pediment deposits. Forms few small, isolated buttes.
Mississip-pian	M€	Hardscrabble limestone	45.5'	Limestone, light buff to dark brown, massive, fine-grained, few beds of pink to gray-white dolomite.	Undifferentiated Mississippian to Cambrian sediments crop out on spurs on west side of Rampart Range.
		Williams Canyon Limestone	43'	Limestone, dolomitic thin-bedded, gray to buff, lavender- to purple-mottled, fine-grained; 6 feet of white, thin-bedded, medium-grained, calcareous, sandstone at top.	Little different from Pikes Peak granite in physiographic expression.
Ordovician	M€	Manitou Limestone	65'	Limestone, buff to dark buff, thin-bedded, fine-grained; pink, medium to fine-grained limestone at top.	
Cambrian		Ute Pass dolomite	9.5'	Dolomite, red, glauconitic, sandy, medium-grained	
		Sawatch Quartzite	52.5'	Sandstone, red, pink, brown, and white, medium-grained, glauconitic.	
Precambrian	ppg	Pikes Peak granite		Granite, pink, coarse-grained, consisting of potash feldspar, quartz, and minor amounts of biotite.	Forms dissected highlands east and west of Manitou Park.

Table 9

Percentage Areas of Several Orders of Stream Basins in Chileno Canyon

Order	Two	Three	Four
Percentage Area I	1.1%	8.3%	37.6%
Percentage Area II	1.1%	3.7%	15.7%

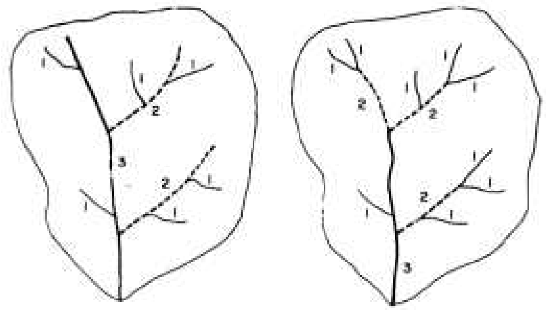
TABLE 10. Salt Run Area. Data of regressions of slope on distance.

A. Regression of $\log_{10}$ (S × 1000) on distance, X, from head of segment. (Data to accompany Figures 9, 10, and 11)

	Basin	Regression coef., b	Scatter $S_{y.x}$	S_x	N	t	Significance at .10	.05	.01
FIRST ORDER (Fig. 9)	Lucore	−.000 205 37	.026 145	236.218	8	−4.910	Sig	Sig	Sig
	Russell	−.000 056 08	.045 732	251.863	12	−1.024	NS	NS	NS
	Salt Run	−.000 266 37	.079 806	278.59	10	−2.790	Sig	Sig	NS
	Wheatfield	−.000 271 96	.116 27	322.152	14	−2.715	Sig	Sig	NS
SECOND ORDER (Fig. 10)	Lucore	−.000 194 26	.039 256	285.548	6	−3.160	Sig	Sig	NS
	Russell	−.000 411 66	.116 87	430.181	8	−4.009	Sig	Sig	Sig
	Salt Run	−.000 180 43	.101 843	494.669	6	−1.960	NS	NS	NS
	Wheatfield	−.000 149 83	.073 178	824.088	12	−5.597	Sig	Sig	Sig
THIRD ORDER (Fig. 11)	Lucore	−.000 069 21	.084 706	1423.85	15	−4.353	Sig	Sig	Sig
	Russell	−.000 061 03	.069 587	1058.01	11	−2.935	Sig	Sig	NS
	Salt Run	−.000 014 14	.096 704	6247.87	23	−4.285	Sig	Sig	Sig
	Wheatfield	−.000 274 45	.021 679	485.778	5	−12.300	Sig	Sig	Sig

B. Regression of $\log_{10}$ (S × 1000) on $\log_{10}$ (X′ + L_g).

	Basin	Regression coef., b	Scatter $S_{y.x}$	S_x	N	t	Significance at .10	.05	.01
FIRST ORDER	Lucore	−0.689 768	.033 094	.069 389	8	−0.383	NS	NS	NS
	Russell	−0.051 926	.043 972	.172 373	12	−0.675	NS	NS	NS
	Salt Run	−1.067 42	.080 341	.069 141	10	−2.756	Sig	Sig	NS
	Wheatfield	−1.092 88	.063 655	.081 254	14	−5.030	Sig	Sig	Sig
SECOND ORDER	Lucore	−1.012 64	.050 965	.053 010	6	−2.355	Sig	NS	NS
	Russell	−1.728 80	.113 783	.103 099	8	−4.144	Sig	Sig	Sig
	Salt Run	−1.246 39	.100 524	.073 327	6	−2.033	NS	NS	NS
	Wheatfield	−1.280 24	.066 418	.098 780	12	−6.315	Sig	Sig	Sig
THIRD ORDER	Lucore	−0.803 066	.079 600	.127 848	15	−4.826	Sig	Sig	Sig
	Russell	−0.280 822	.088 957	.139 328	11	−1.391	NS	NS	NS
	Salt Run	−0.417 247	.094 298	.217 481	23	−4.514	Sig	Sig	Sig
	Wheatfield	−3.914 97	.028 236	.034 114	5	−9.460	Sig	Sig	Sig



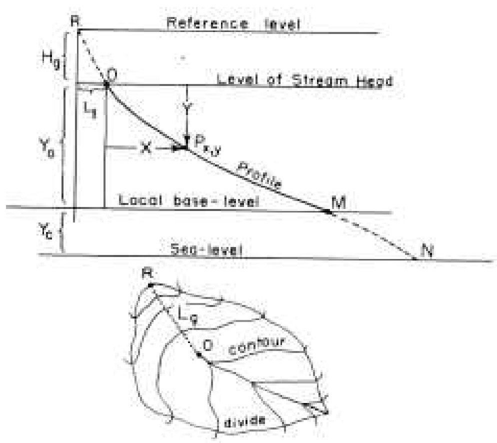
Order u	Number Nu
1	6
2	2
3	1

A. Horton numbering system

Order u	Number Nu
1	9
2	3
3	1

B. Strohler numbering system

Figure 1



Points:
- R Reference point
- O Stream head
- M End of segment, gaging station, or local baselevel
- N Mouth at sea level

Constants:
- L_g Horizontal distance of overland flow on orthogonal from reference point R to head O.
- H_g Vertical drop from R to O.
- Y_o Vertical distance from stream head, O, to local baselevel, M.
- Y_c Vertical distance between local baselevel and sea level.

Variables:
- Y Drop in elevation from stream head, O, to any point P on stream profile.
- X Horizontal distance from stream head, O, to any point P on stream profile.

Figure 2

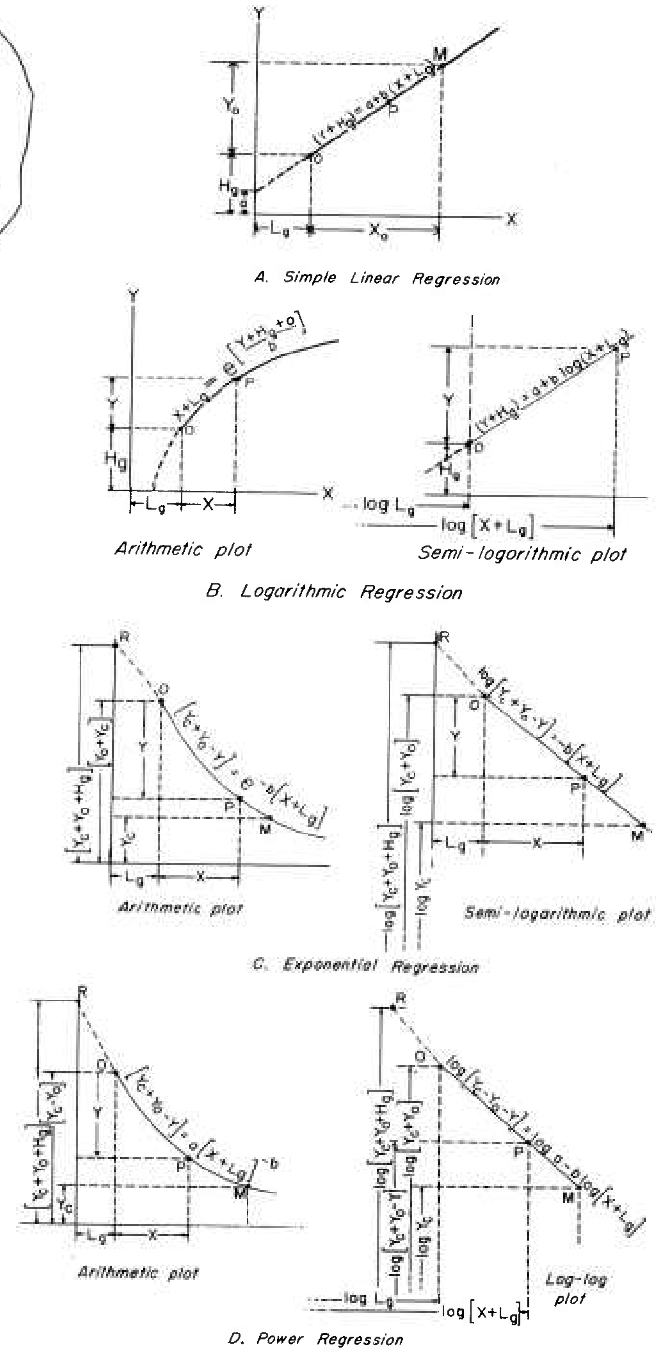
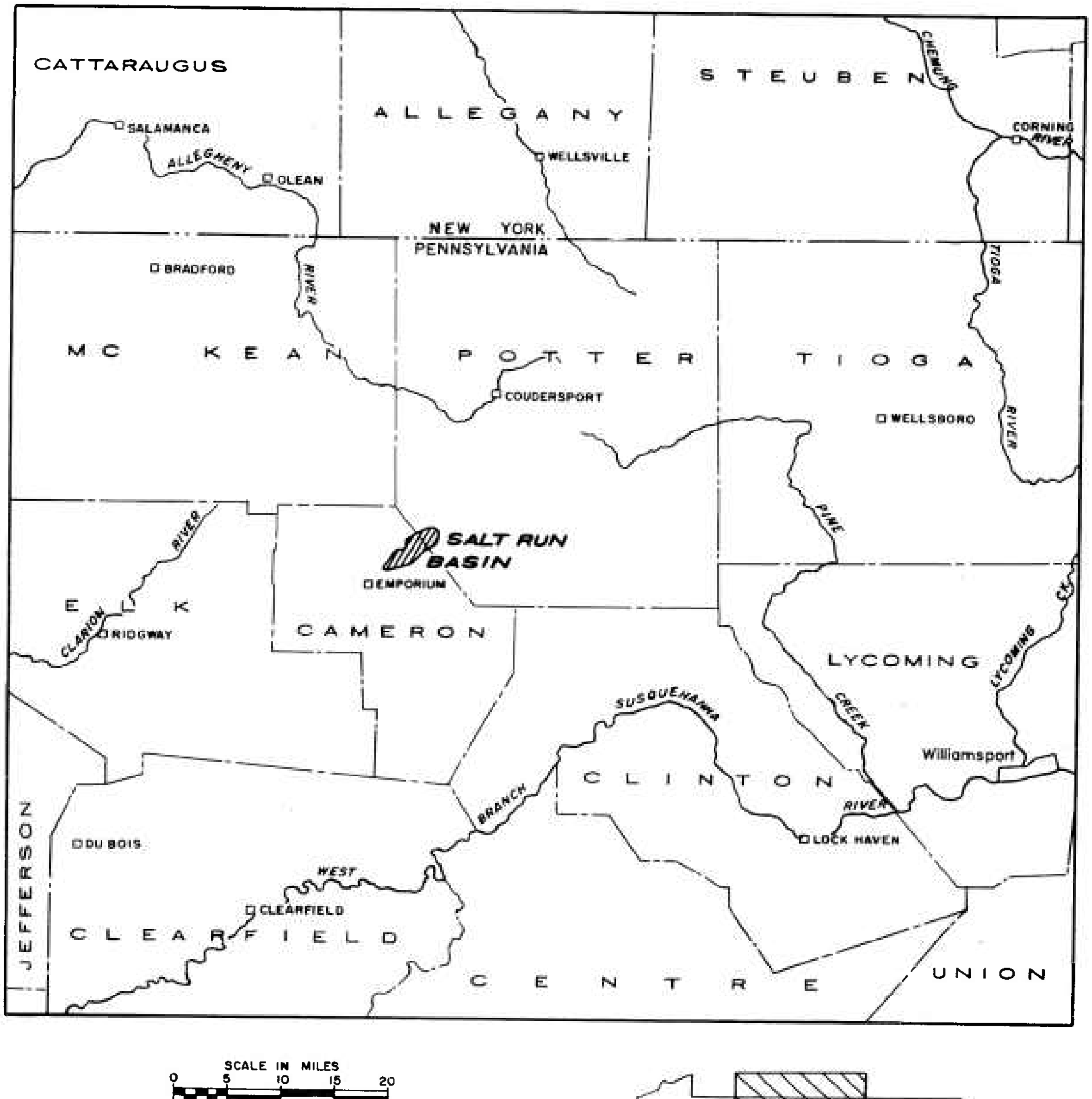


Figure 3



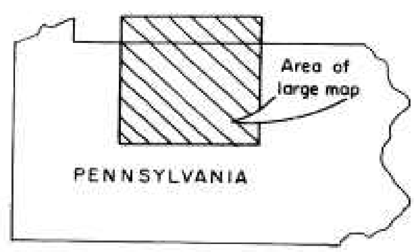


Figure 4

INDEX MAP
SHOWING
LOCATION OF SALT RUN AREA

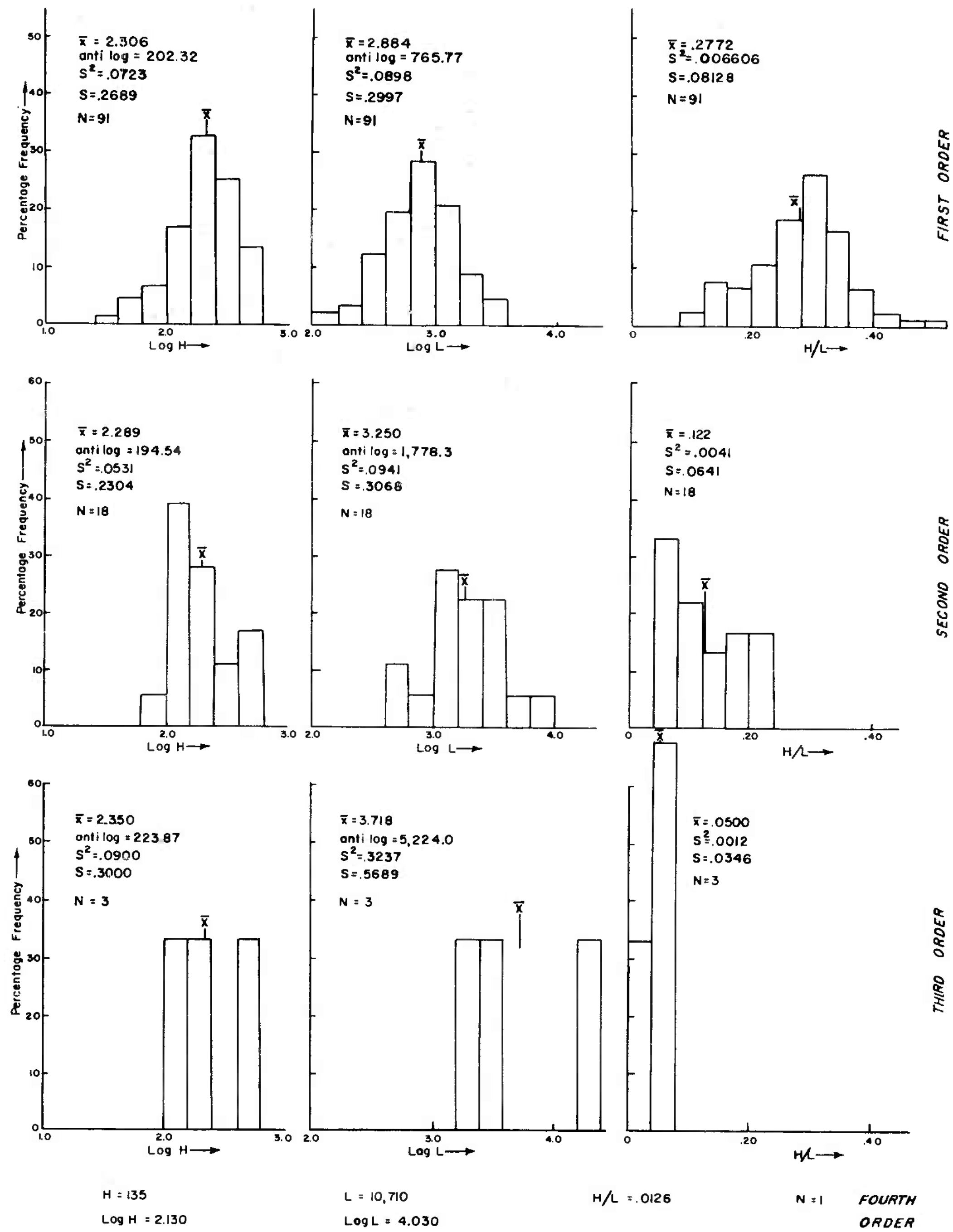


Figure 5

HISTOGRAMS
SHOWING RELATION OF
H, L AND H/L TO ORDER
SALT RUN AREA

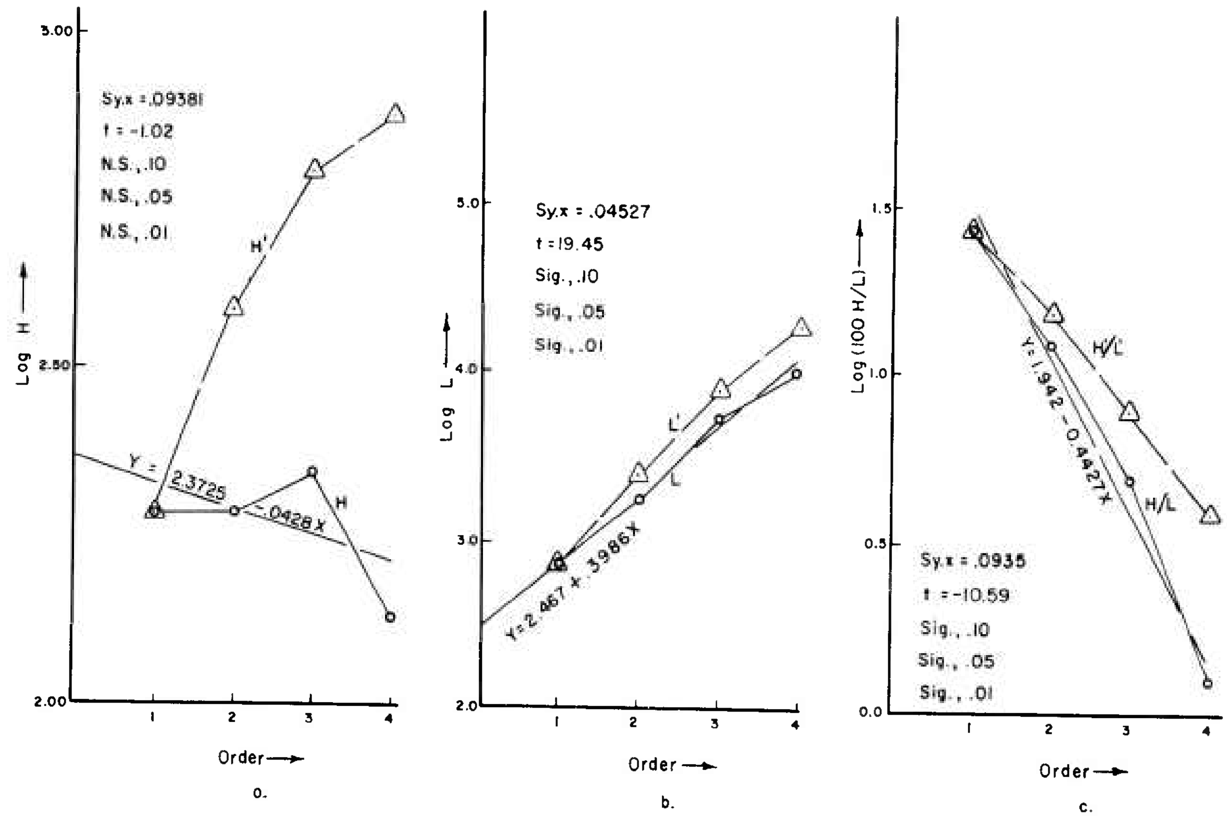


Figure 6

RELATION OF H, L & H/L TO ORDER
SALT RUN AREA

Regression Analyses Apply to Non-cumulative Data Only

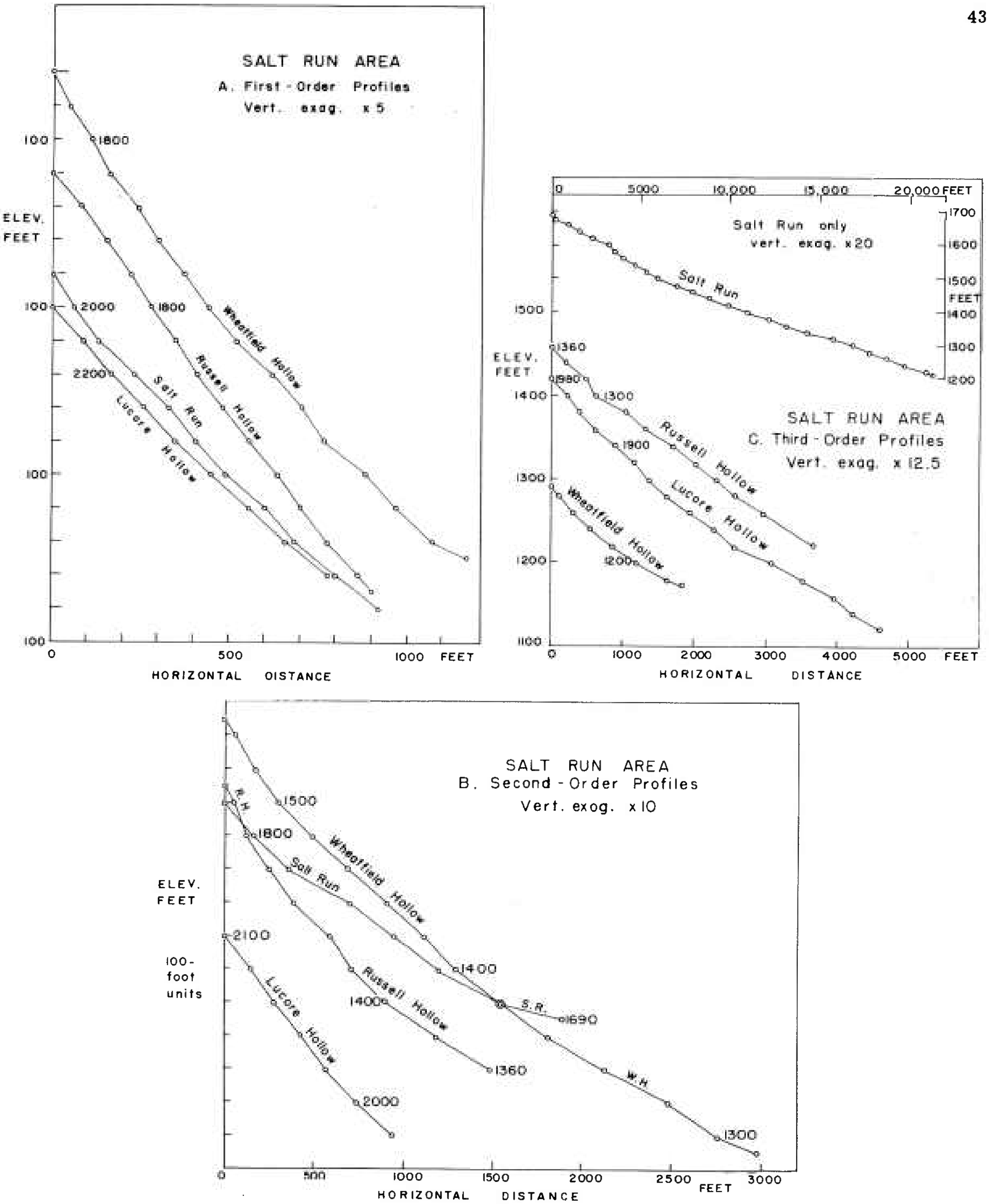

SALT RUN AREA
A. First - Order Profiles
Vert. exag. x 5
ELEV. FEET
1800
2000
1800
2200
Wheatfield Hollow
Russell Hollow
Salt Run
Lucore Hollow
100
0
500
1000 FEET
HORIZONTAL DISTANCE
Salt Run only
vert. exag. x 20
Salt Run
0
5000
10,000
15,000
20,000 FEET
1700
1600
1500
1400
1300
1200
FEET
SALT RUN AREA
C. Third - Order Profiles
Vert. exag. x 12.5
ELEV. FEET
1360
1980
1300
1900
1200
Russell Hollow
Lucore Hollow
Wheatfield Hollow
1500
1400
1300
1200
1100
0
1000
2000
3000
4000
5000 FEET
HORIZONTAL DISTANCE
SALT RUN AREA
B. Second - Order Profiles
Vert. exag. x 10
ELEV. FEET
100-foot units
1500
R.H.
1800
Wheatfield Hollow
Salt Run
2100
1400
S.R.
1690
Russell Hollow
1400
Lucore Hollow
1360
W.H.
2000
1300
0
500
1000
1500
2000
2500
3000
FEET
HORIZONTAL DISTANCE

Figure 7

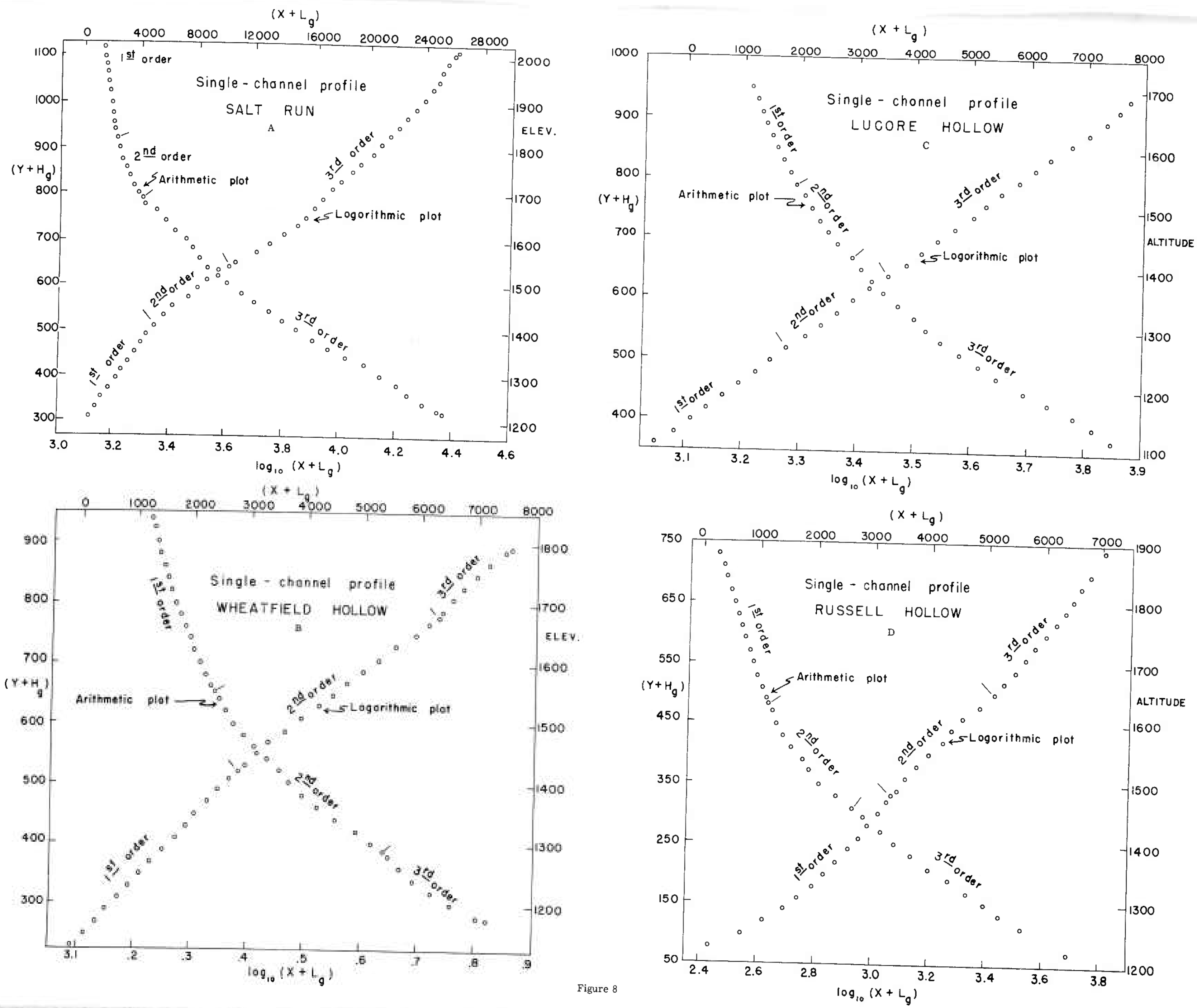

Single - channel profile
SALT RUN
A
1st order
2nd order
3rd order
Arithmetic plot
Logorithmic plot
(X + Lg)
(Y + Hg)
ELEV.
log10 (X + Lg)
Single - channel profile
LUCORE HOLLOW
C
ALTITUDE
Single - channel profile
WHEATFIELD HOLLOW
B
Single - channel profile
RUSSELL HOLLOW
D

Figure 8

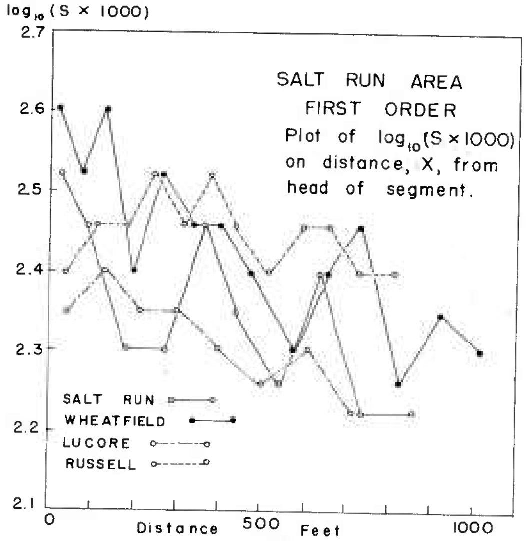


Figure 9

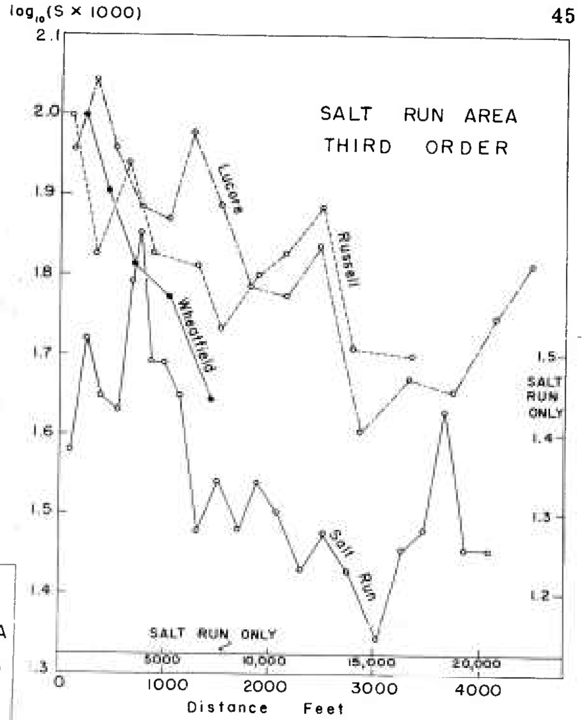


Figure 11

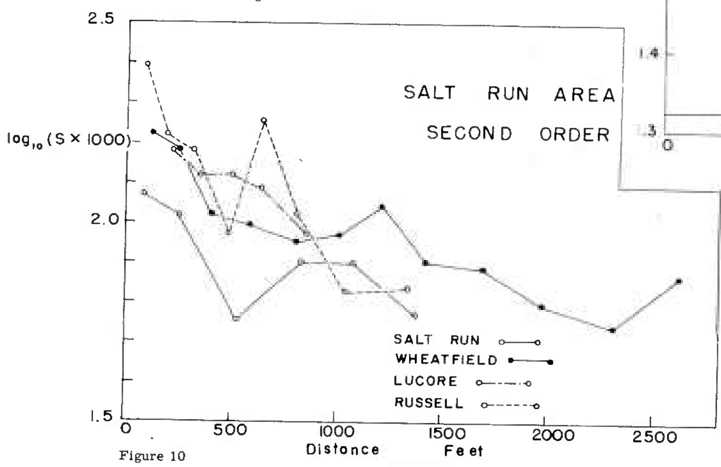


Figure 10

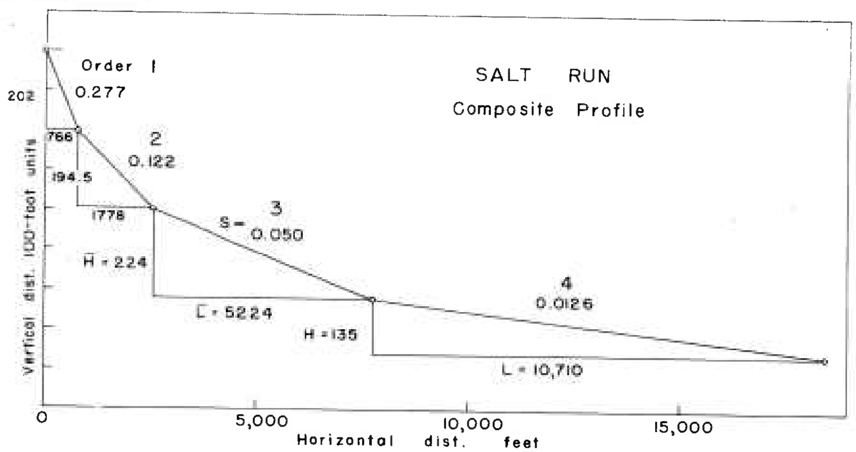
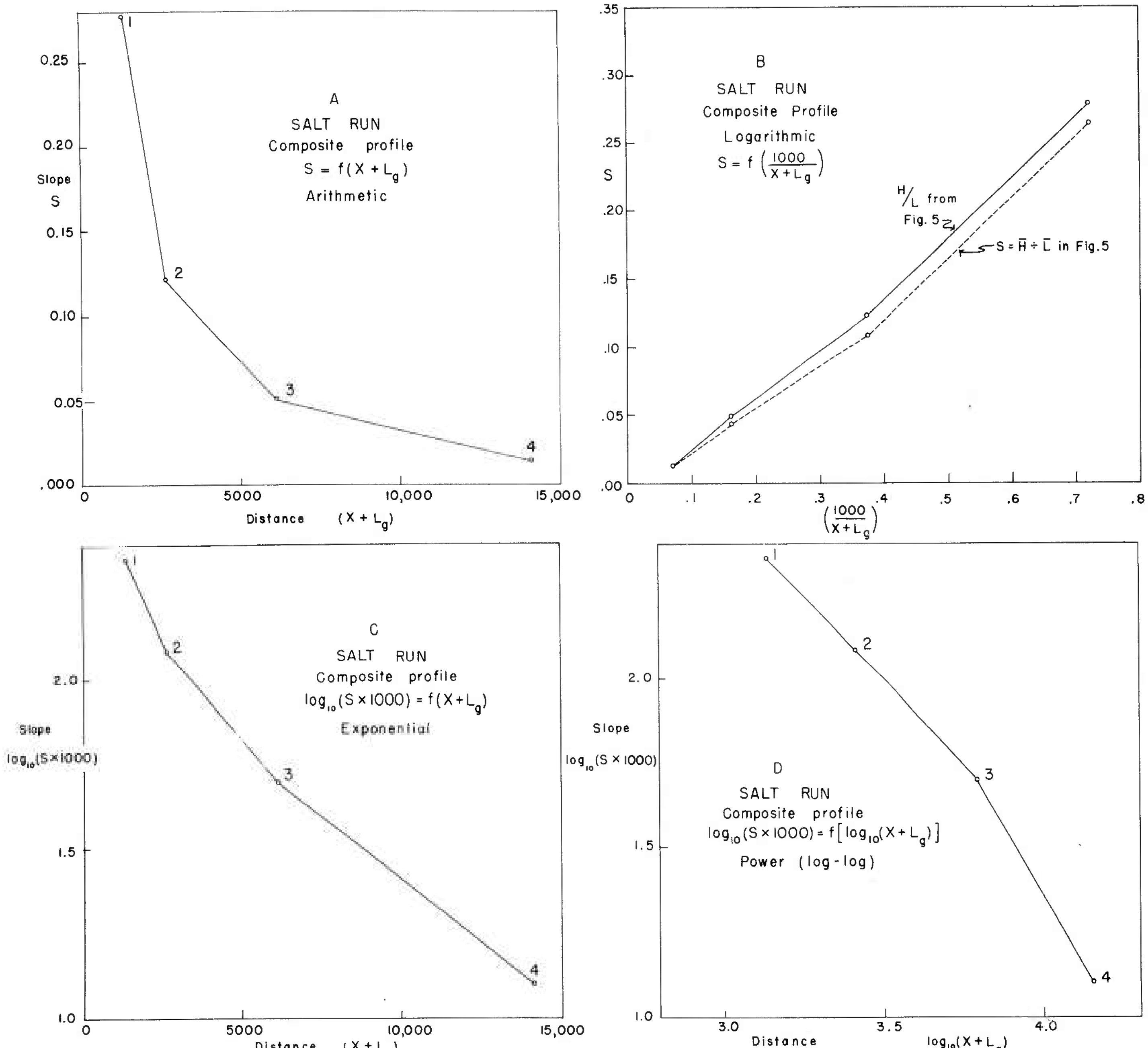
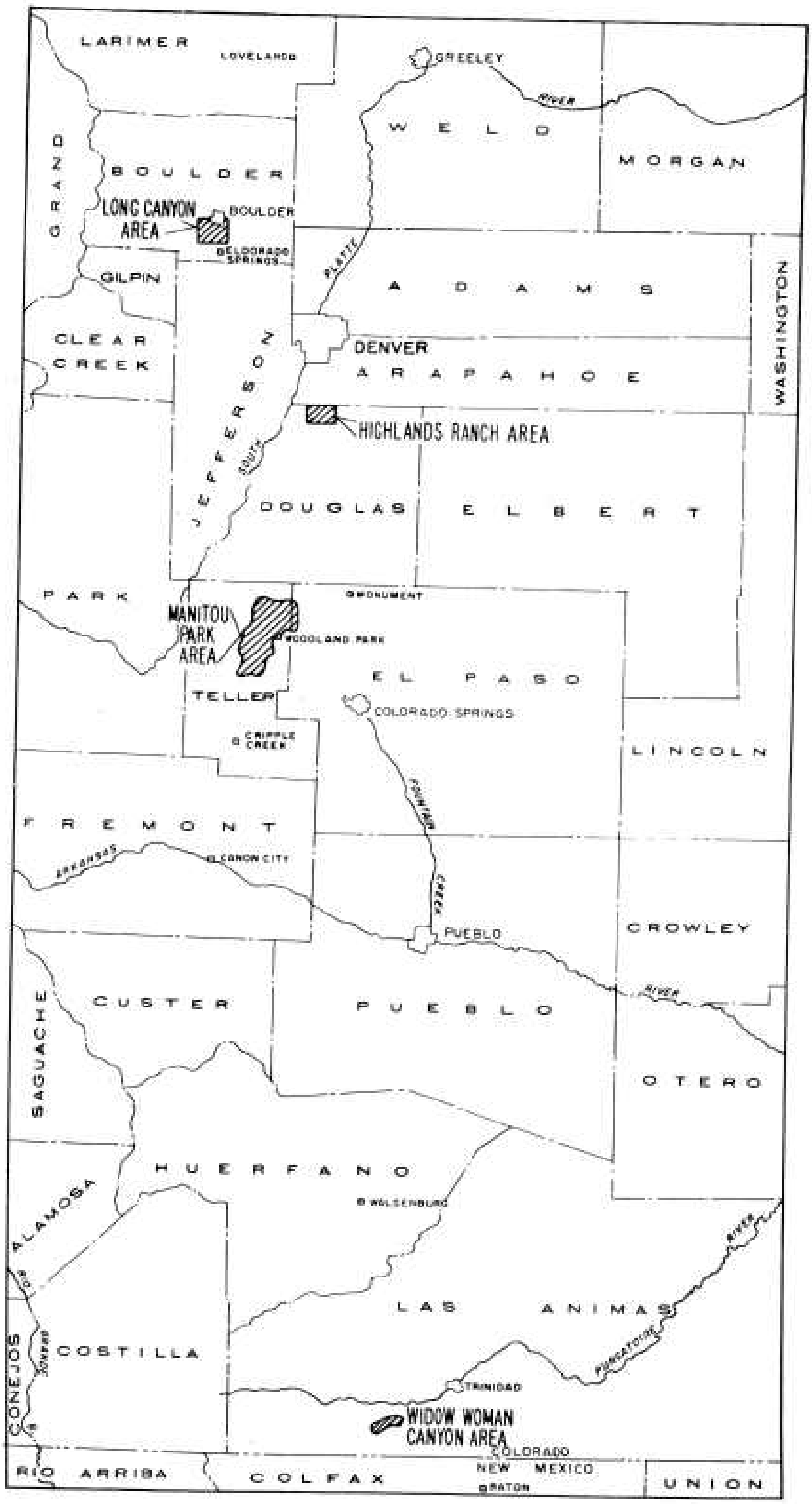


Figure 12



A
SALT RUN
Composite profile
S = f(X + L_g)
Arithmetic
Slope S
0.25
0.20
0.15
0.10
0.05
.000
0
5000
10,000
15,000
Distance (X + L_g)
1
2
3
4
B
SALT RUN
Composite Profile
Logarithmic
S = f (1000 / X+L_g)
H/L from Fig. 5
S = H̄ ÷ L̄ in Fig.5
S
.35
.30
.25
.20
.15
.10
.05
.00
0
.1
.2
.3
.4
.5
.6
.7
.8
(1000 / X+L_g)
C
SALT RUN
Composite profile
log₁₀(S×1000) = f(X+L_g)
Exponential
Slope log₁₀(S×1000)
2.0
1.5
1.0
0
5000
10,000
15,000
Distance (X + L_g)
1
2
3
4
D
SALT RUN
Composite profile
log₁₀(S×1000) = f[log₁₀(X+L_g)]
Power (log-log)
Slope log₁₀(S × 1000)
2.0
1.5
1.0
3.0
3.5
4.0
Distance log₁₀(X + L_g)
1
2
3
4

Figure 13



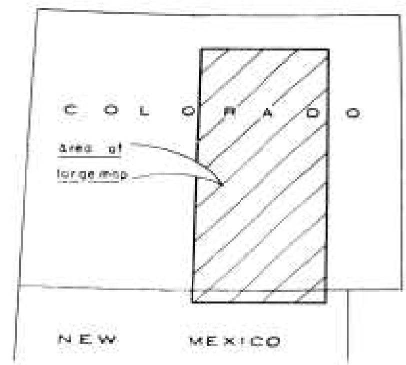


Figure 14

GENERAL INDEX MAP
FOR TEST AREAS
IN COLORADO

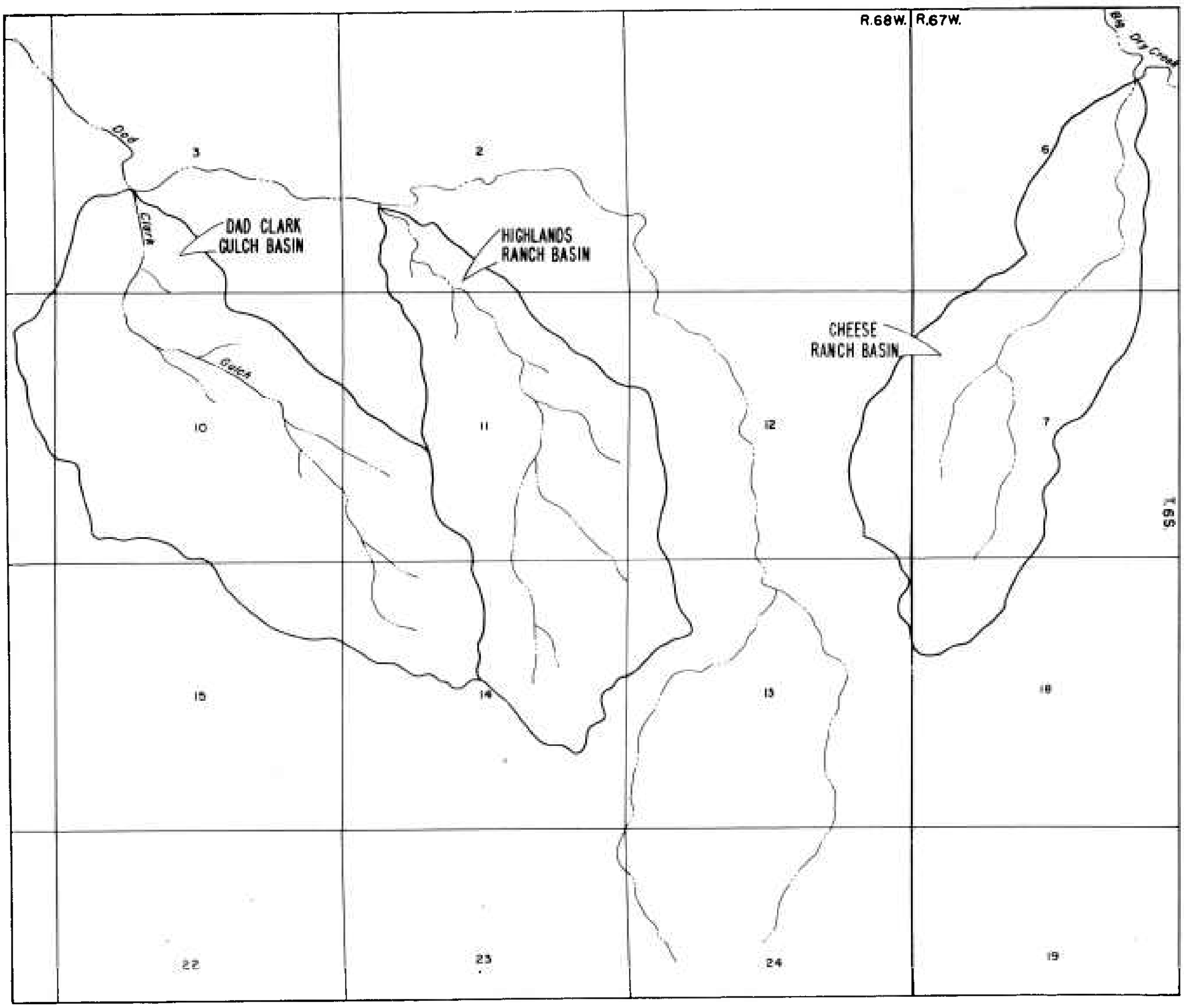


Figure 15

INDEX MAP OF HIGHLANDS RANCH AREA

(3rd. & 4th. Order Segments shown in 3 Basins)

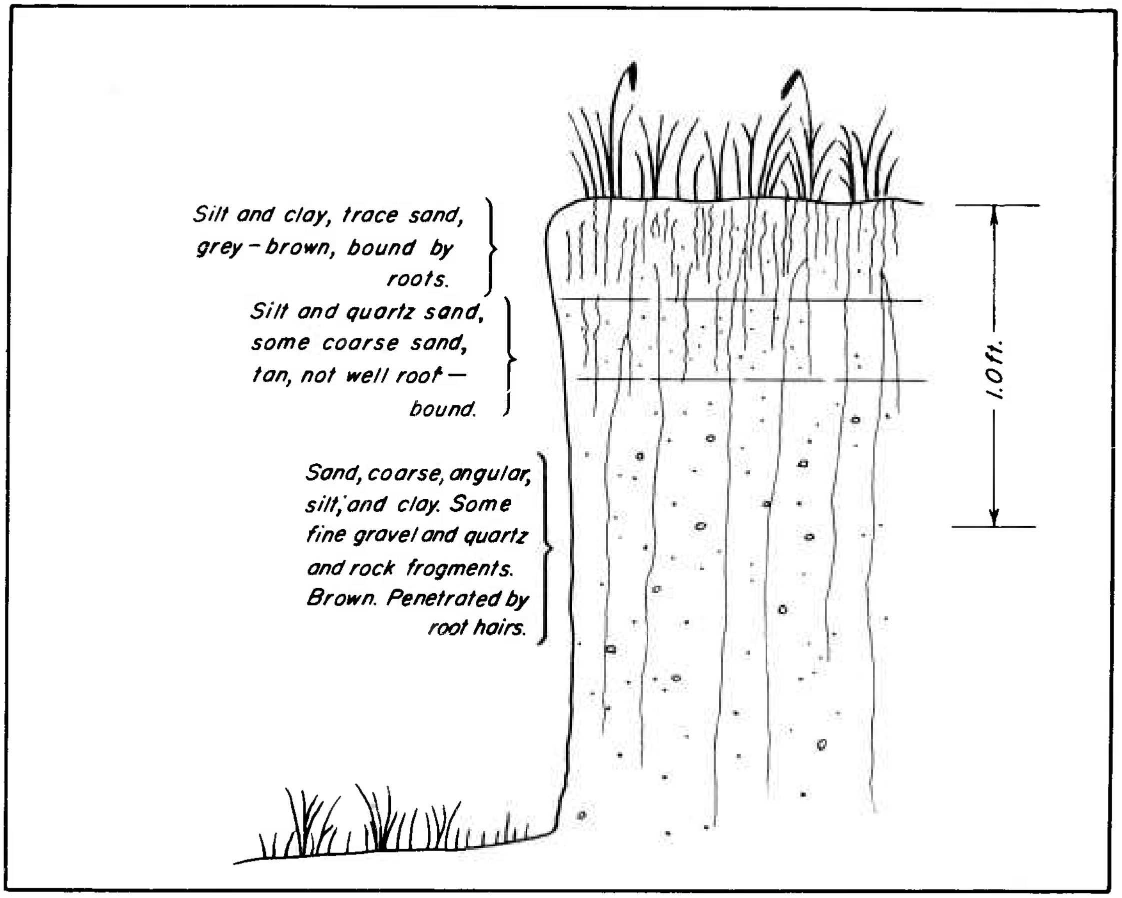


Figure 16

SOIL PROFILE

CHEESE RANCH BASIN

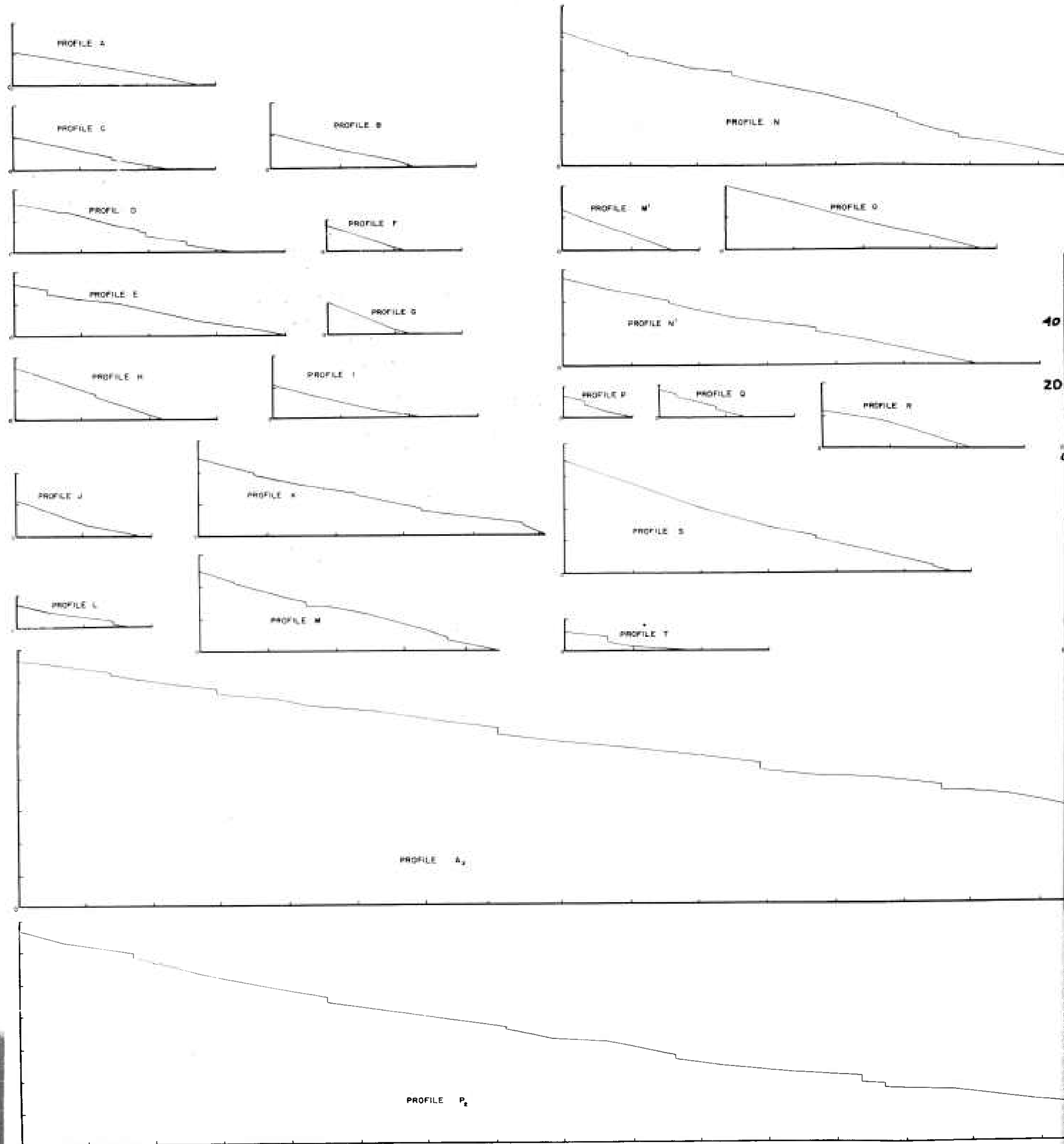


Figure 17

FIELD MEASURED PROFILES — CHEESE RANCH BASIN

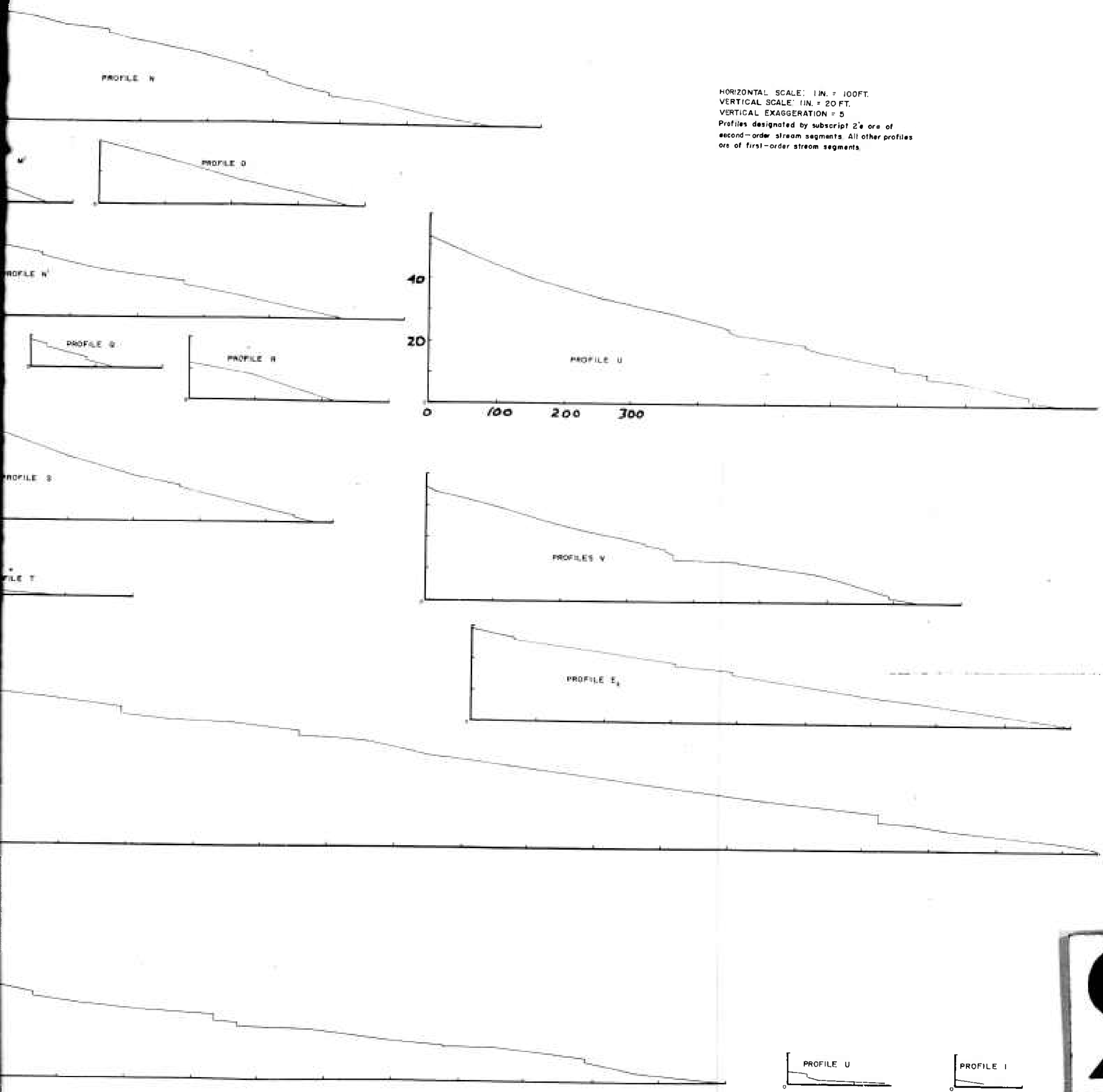
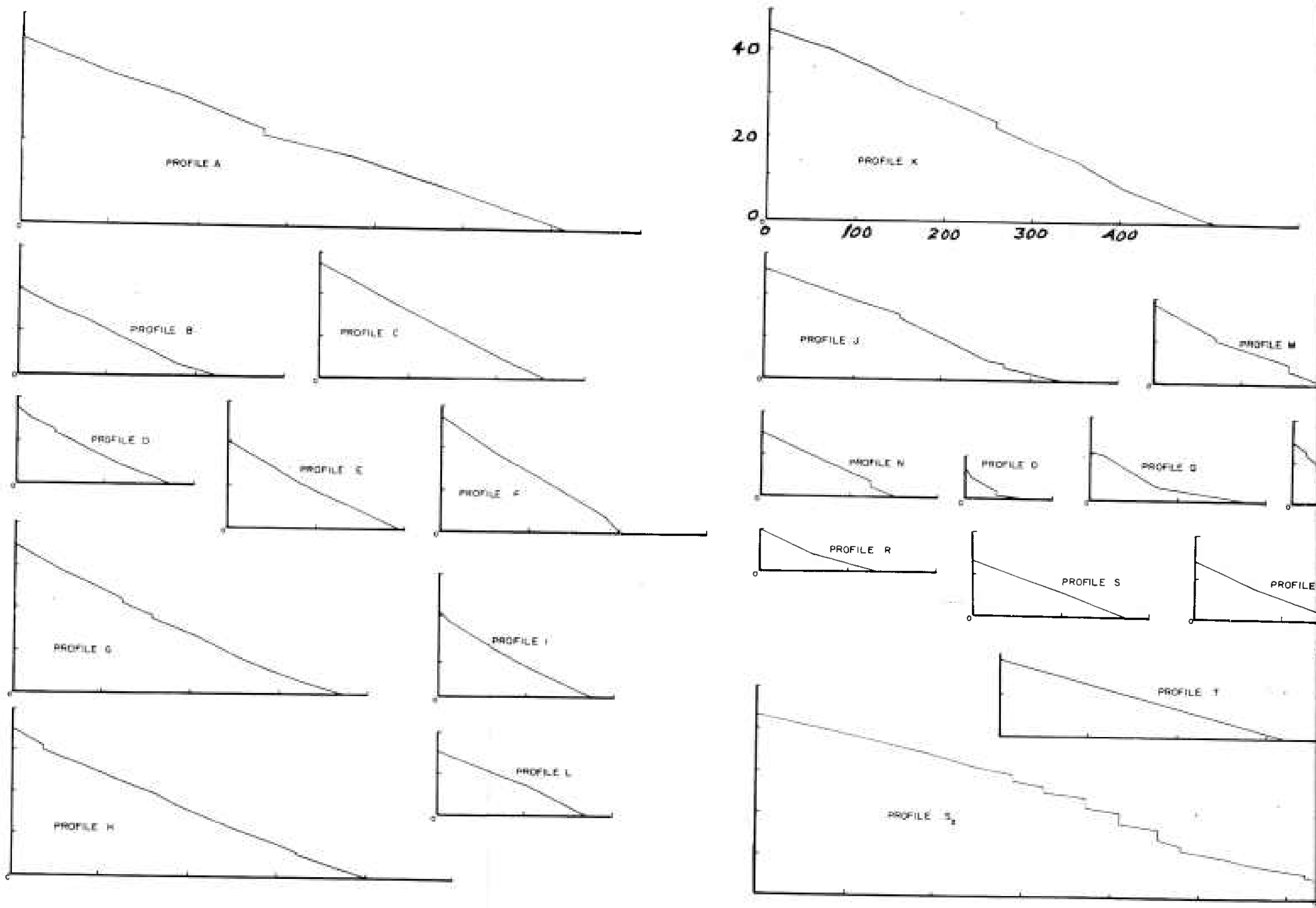
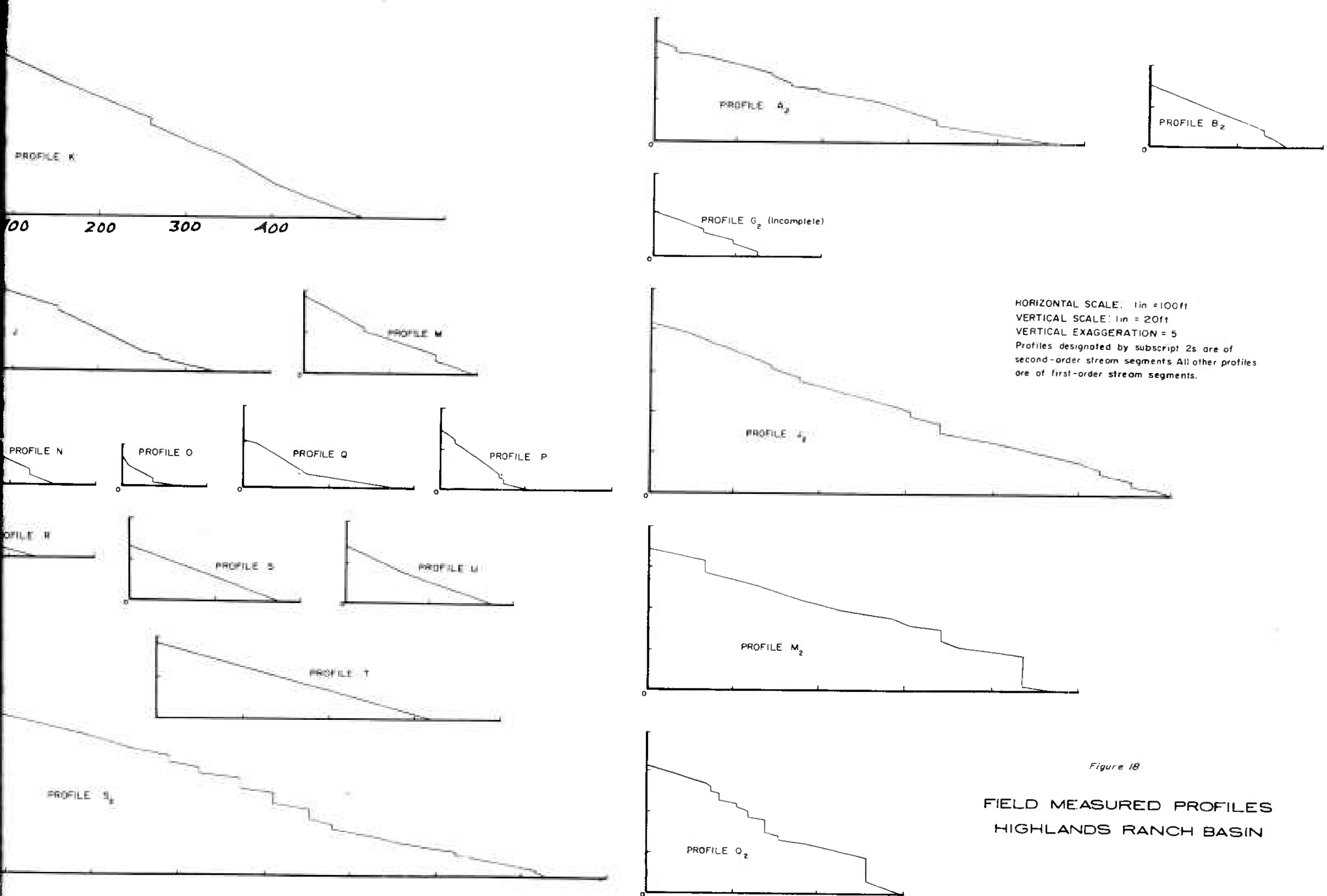


Figure 17

MEASURED PROFILES — CHEESE RANCH BASIN



PROFILE A
40
20
0
0
100
200
300
400
PROFILE K
PROFILE B
PROFILE C
PROFILE J
PROFILE M
PROFILE D
PROFILE E
PROFILE F
PROFILE N
PROFILE O
PROFILE R
PROFILE S
PROFILE G
PROFILE I
PROFILE T
PROFILE H
PROFILE L
PROFILE S2



HORIZONTAL SCALE: 1in = 100ft
VERTICAL SCALE: 1in = 20ft
VERTICAL EXAGGERATION = 5
Profiles designated by subscript 2s are of second-order stream segments. All other profiles are of first-order stream segments.

Figure 18

FIELD MEASURED PROFILES
HIGHLANDS RANCH BASIN

2

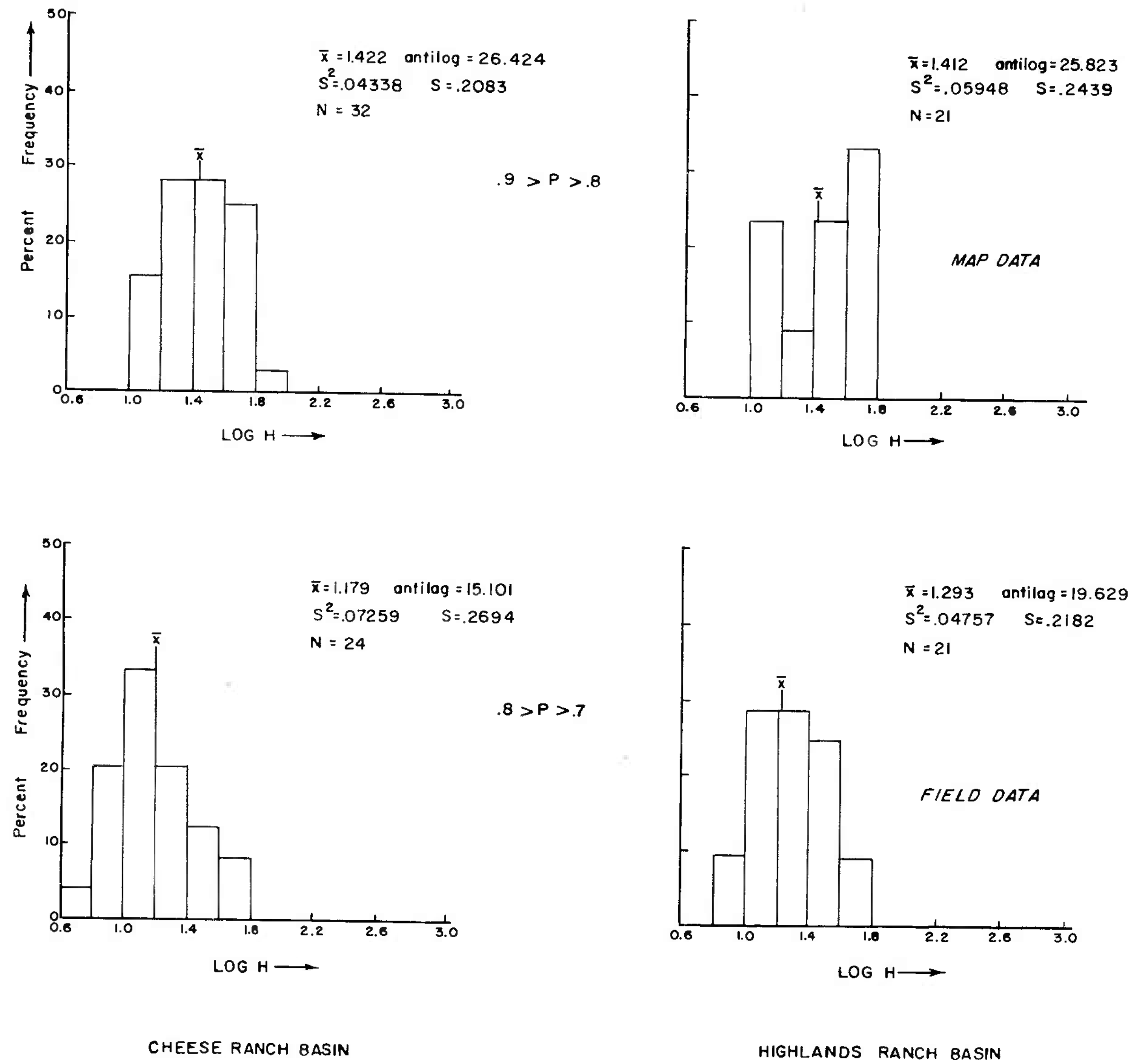


Figure 19

COMPARISON OF FIRST ORDER H

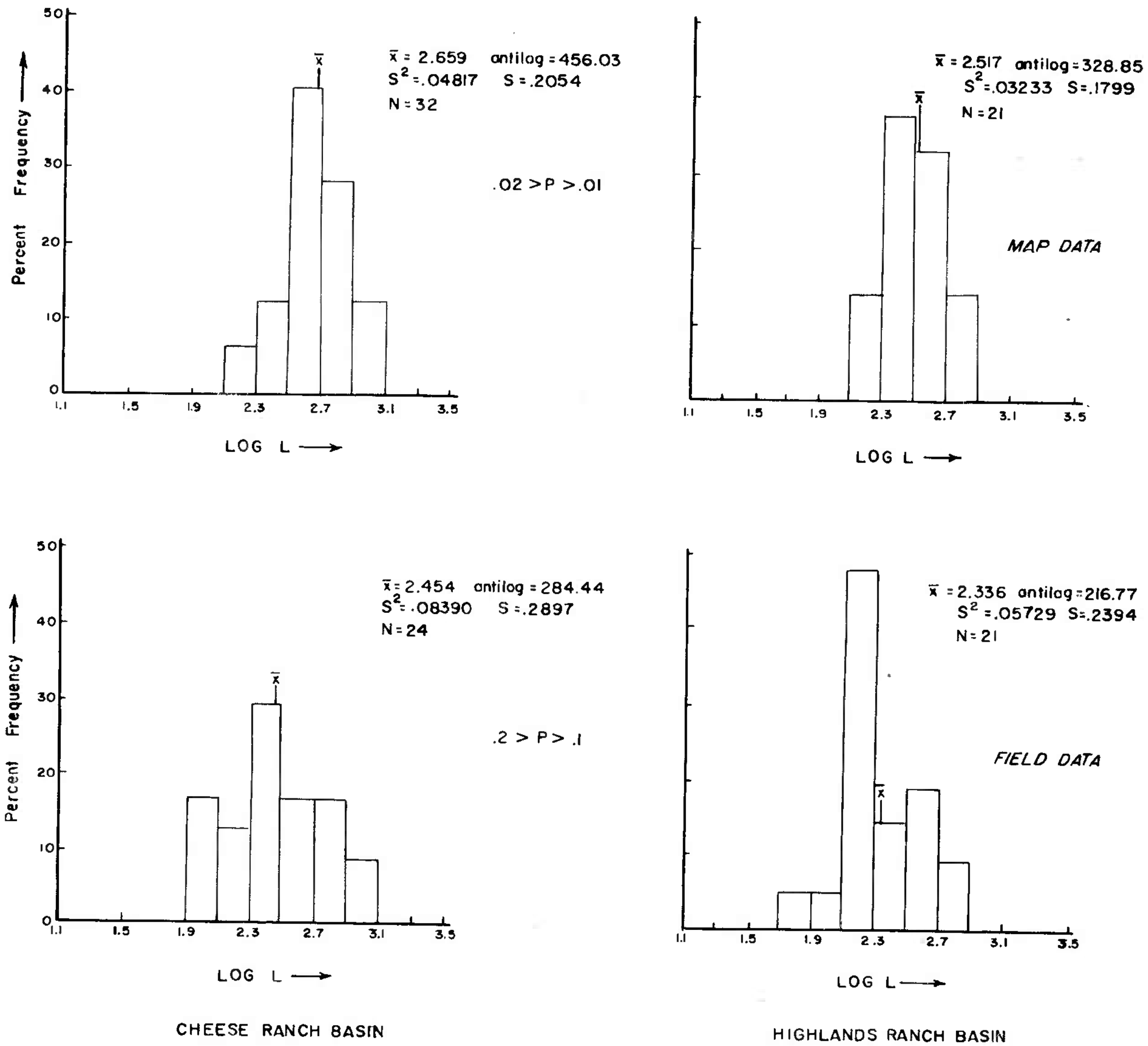


Figure 20

COMPARISON OF FIRST ORDER L

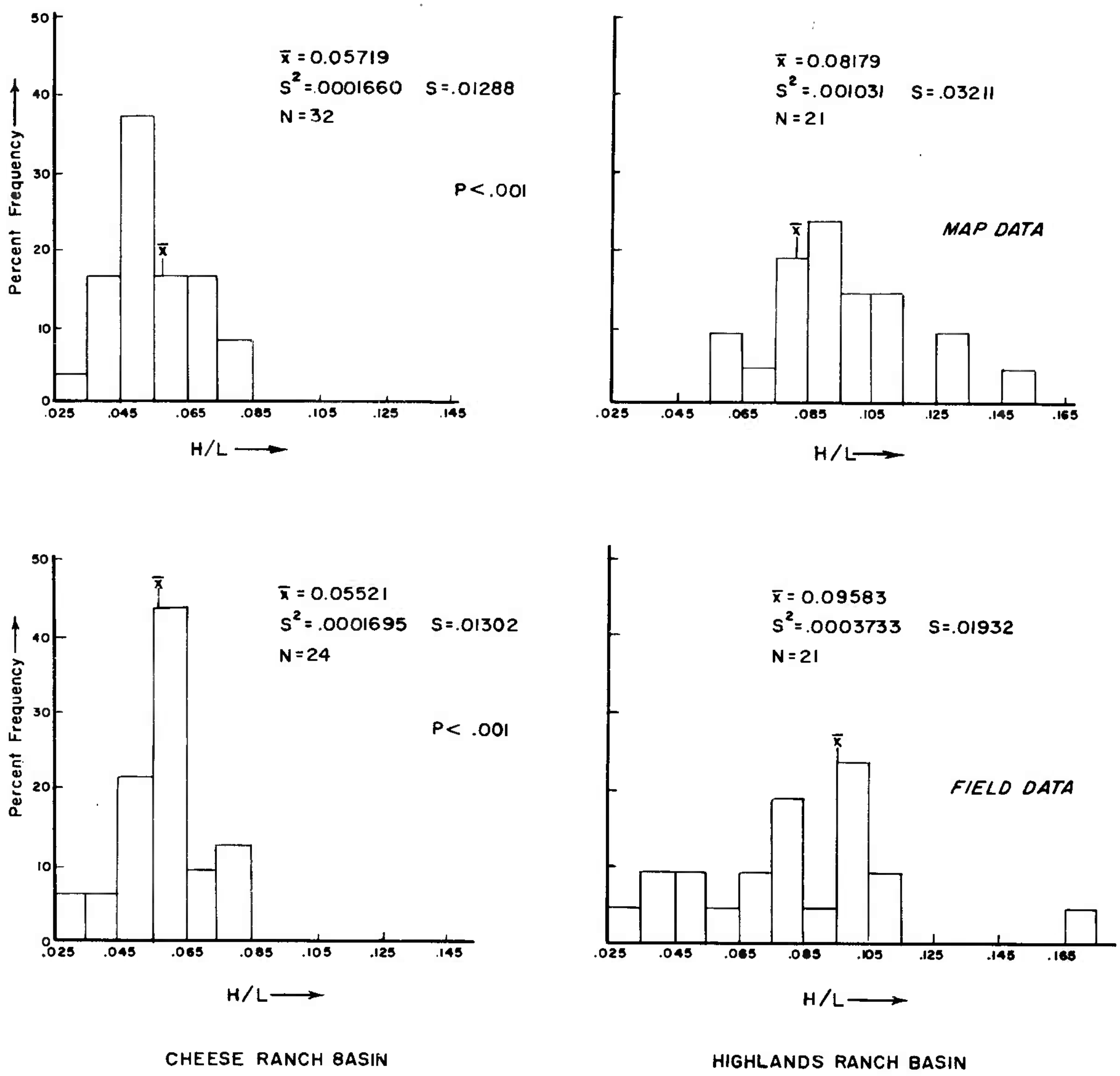
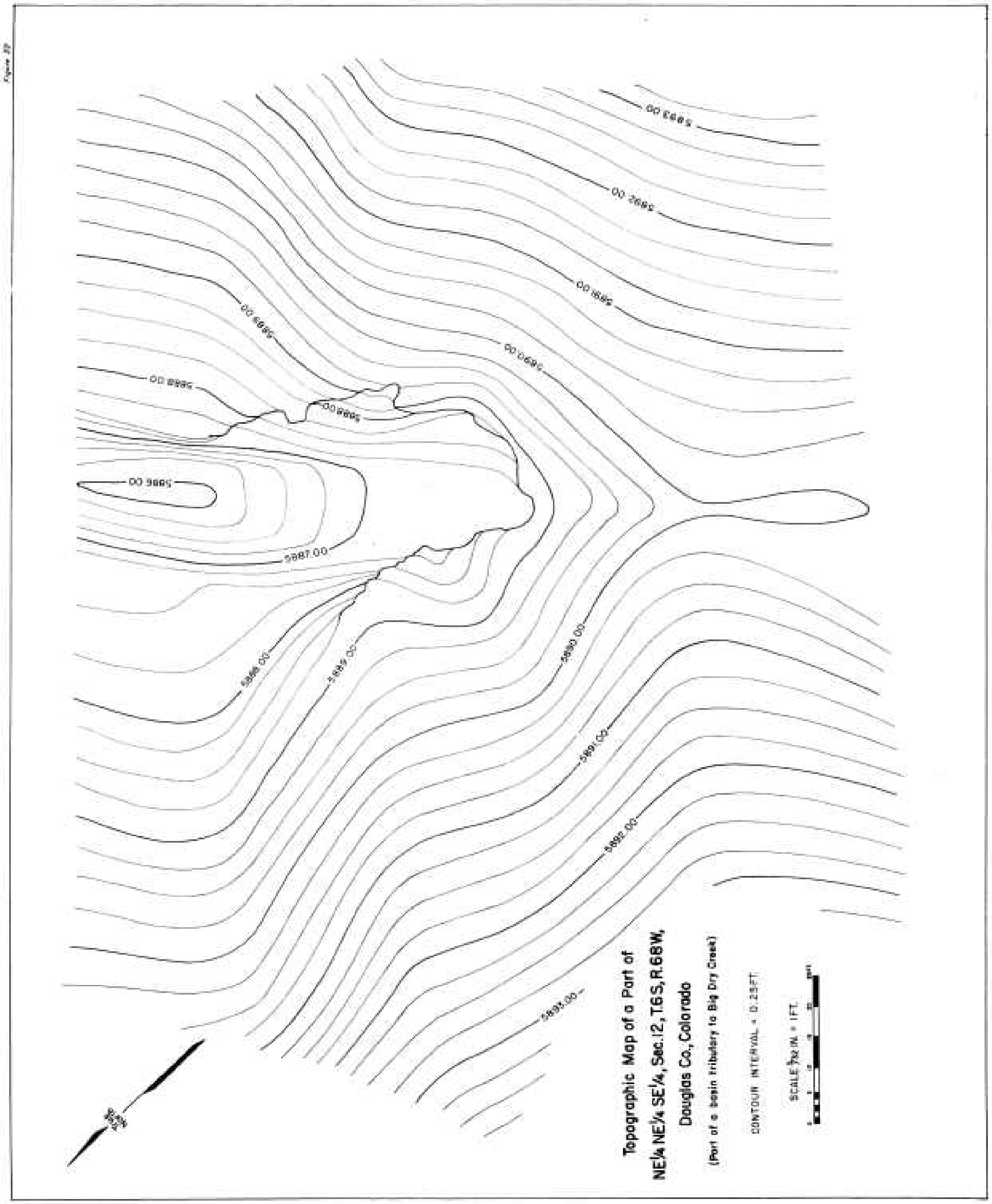


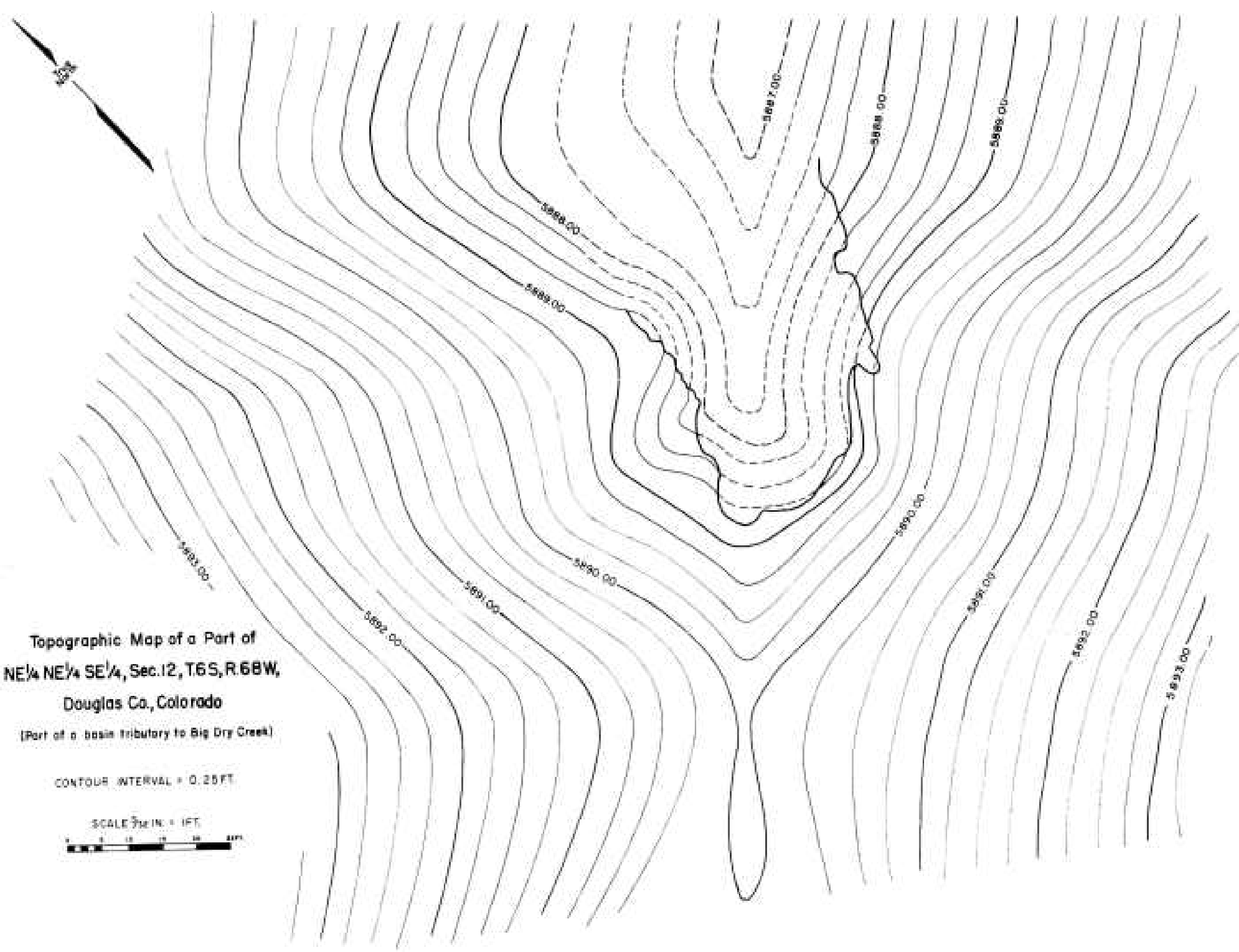
Figure 21

COMPARISON OF FIRST ORDER H/L



Topographic Map of a Part of NE¼ NE¼ SE¼, Sec. 12, T.6S, R.68W, Douglas Co., Colorado (Part of a basin tributary to Big Dry Creek)

Figure 23



Topographic Map of a Part of
NE1/4 NE1/4 SE1/4, Sec.12, T.6S, R.68W,
Douglas Co., Colorado
(Part of a basin tributary to Big Dry Creek)

CONTOUR INTERVAL = 0.25 FT.

SCALE 3/32 IN. = 1FT.

Hypothetical Topographic Map of Basin
Reconstructed as though "Nickpoint" did not exist

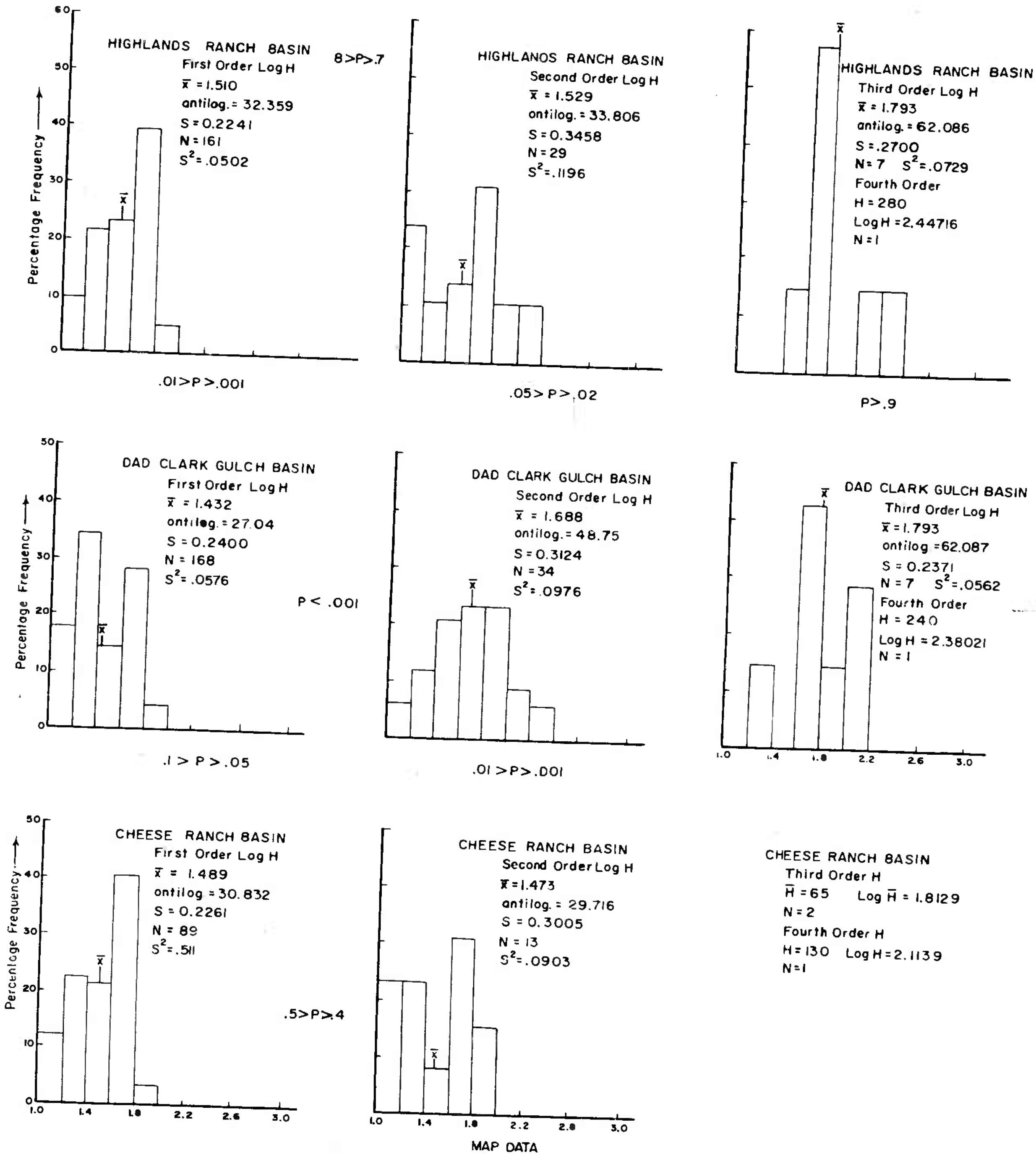


Figure 24

HISTOGRAMS OF MAP-MEASURED H DATA
HIGHLANDS RANCH AREA

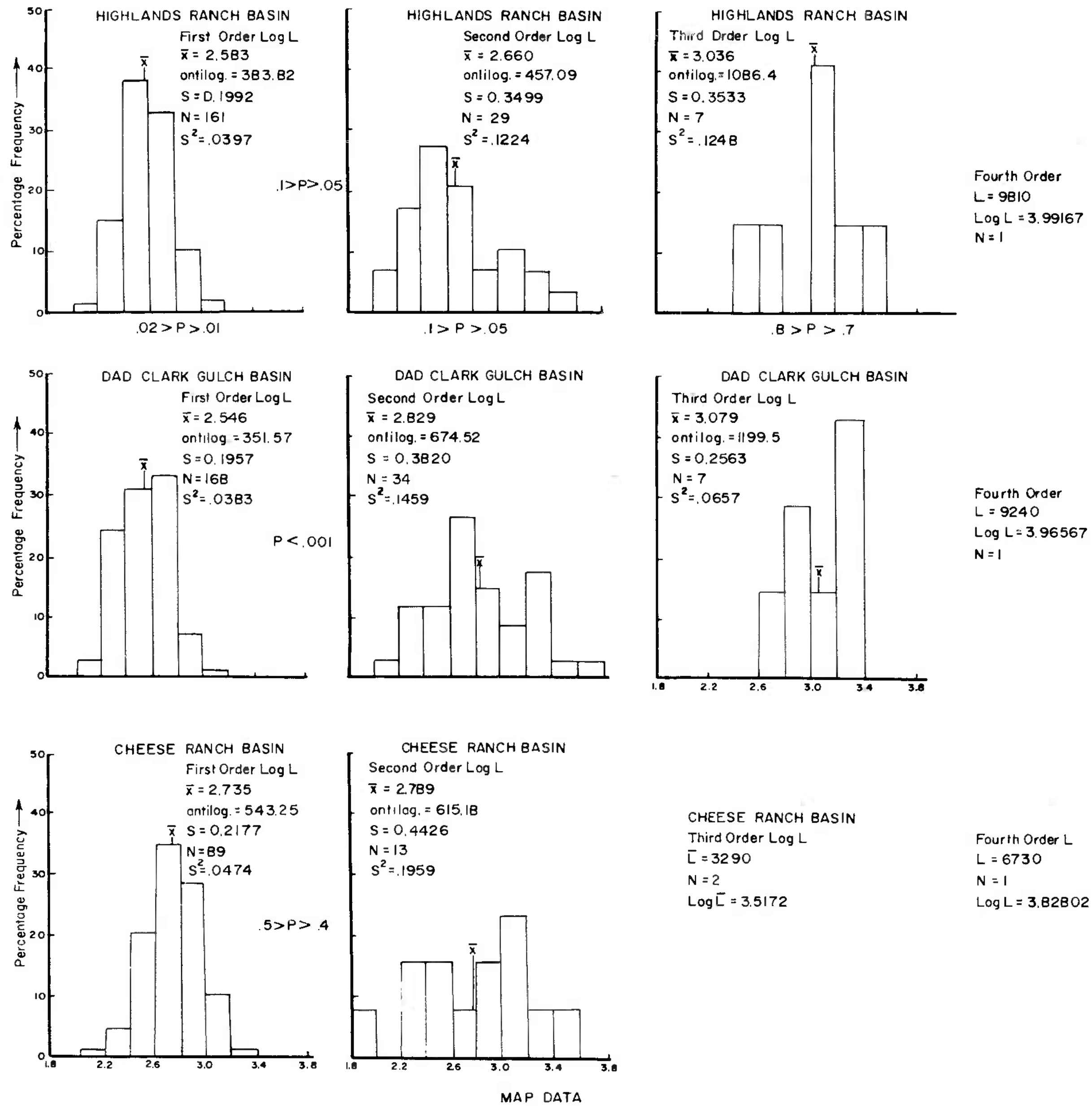


Figure 25

HISTOGRAMS OF MAP-MEASURED L DATA
HIGHLANDS RANCH AREA

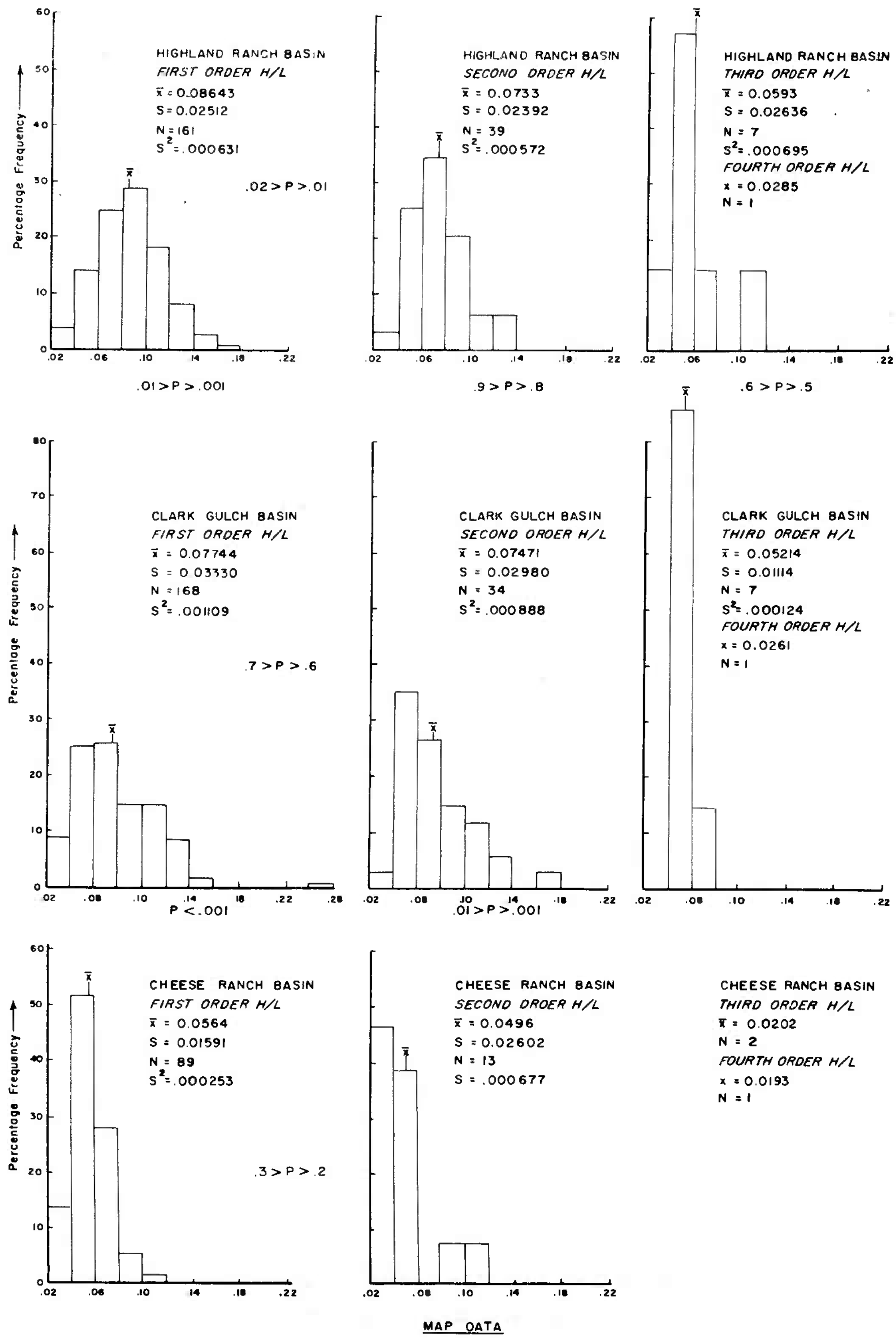


Figure 26

HISTOGRAMS OF MAP-MEASURED H/L DATA
HIGHLANDS RANCH AREA

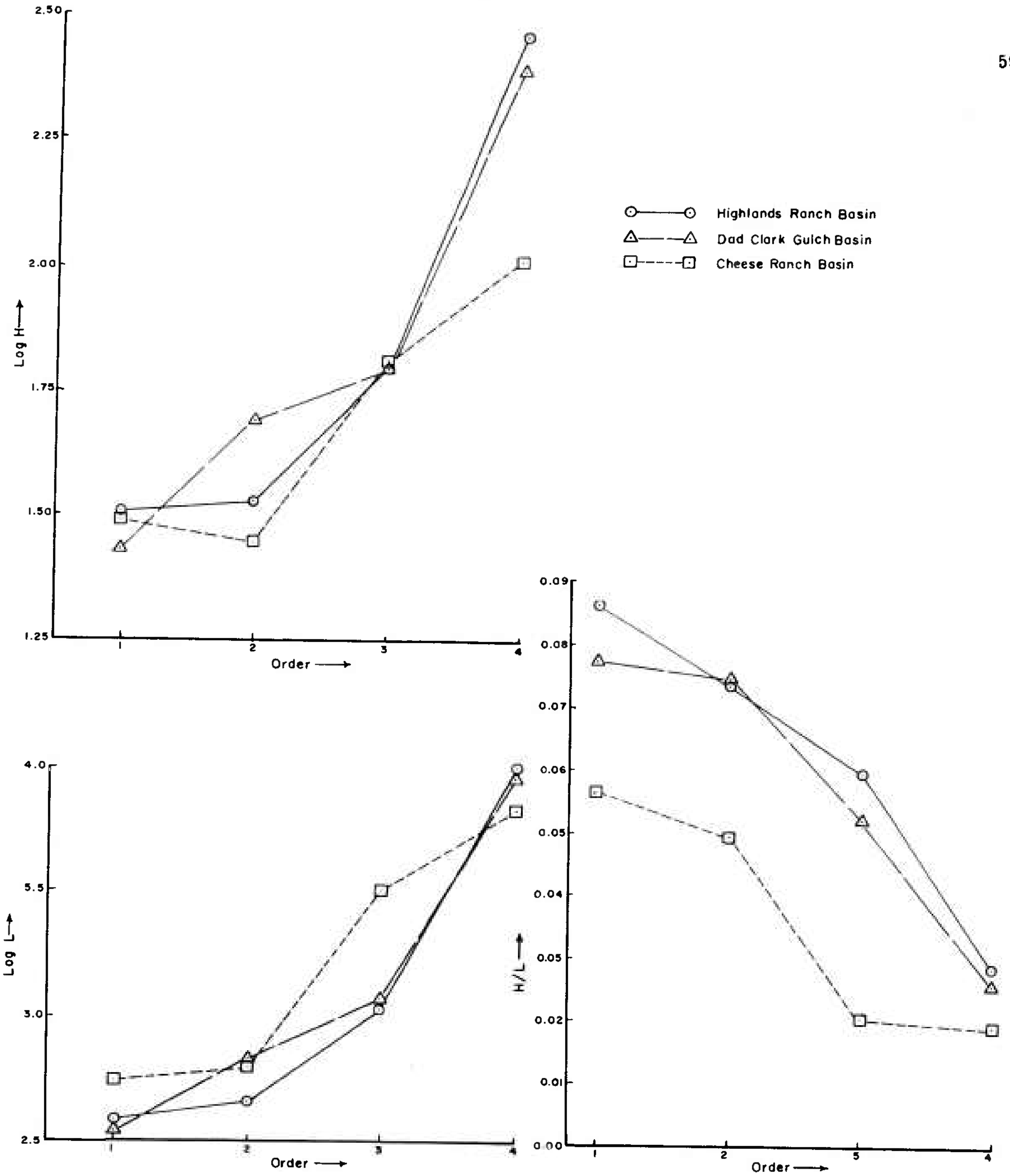


Figure 27

COMPARISON OF H,L, & H/L MAP DATA

HIGHLANDS RANCH AREA

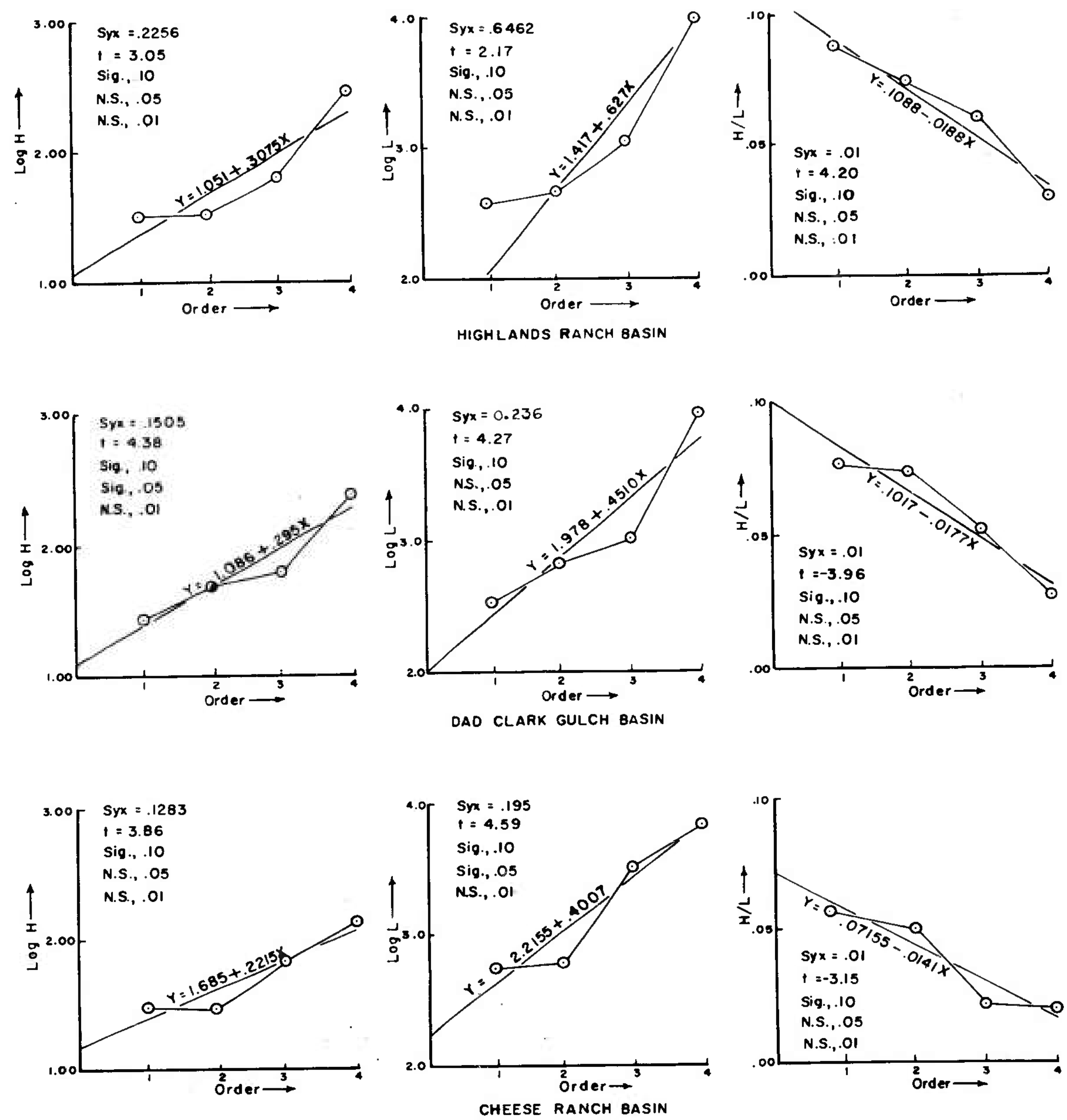


Figure 28

RELATION OF H, L & H/L TO ORDER-MAP DATA
HIGHLANDS RANCH AREA

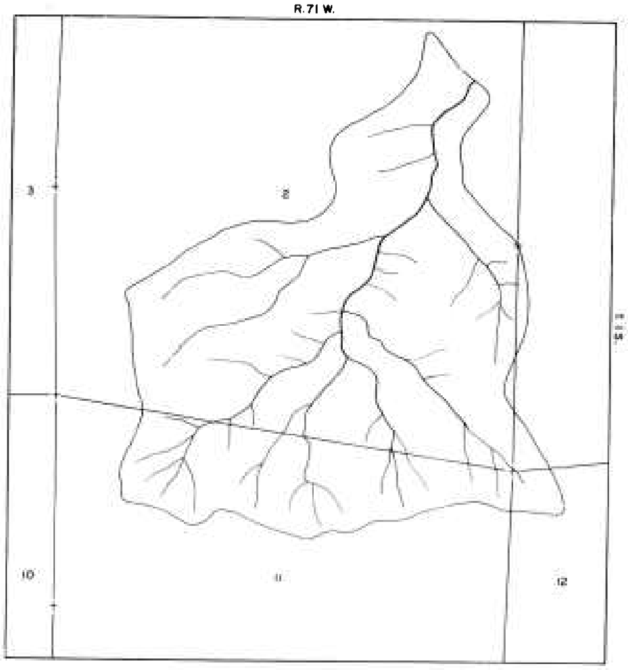


Figure 29

DRAINAGE MAP OF LONG CANYON AREA
PREPARED FROM TOPOGRAPHIC MAP

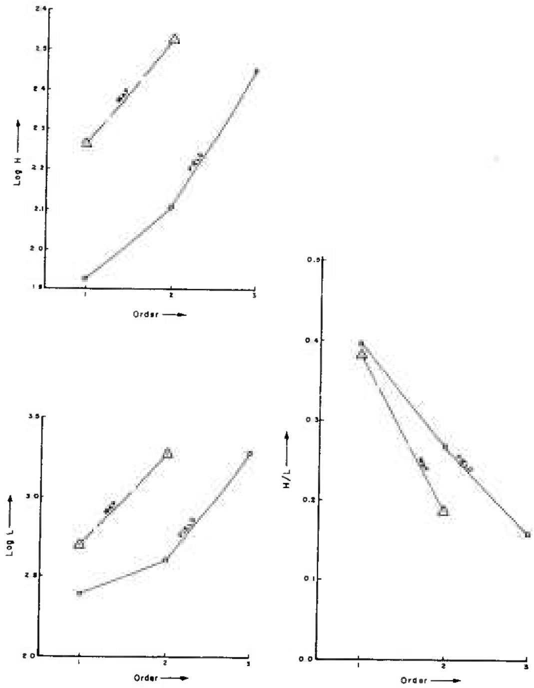


Figure 31

COMPARISON OF FIELD & MAP H,L, & H/L DATA
LONG CANYON AREA

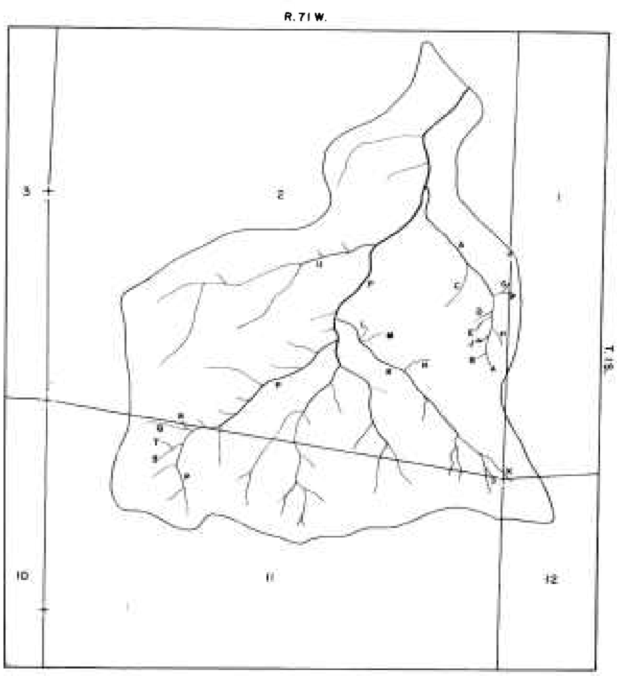


Figure 30

DRAINAGE MAP OF LONG CANYON AREA
PREPARED FROM FIELD DATA & AIR PHOTOGRAPHS.
LETTERS SHOW LOCATION OF PROFILES
IN FIGURE 32

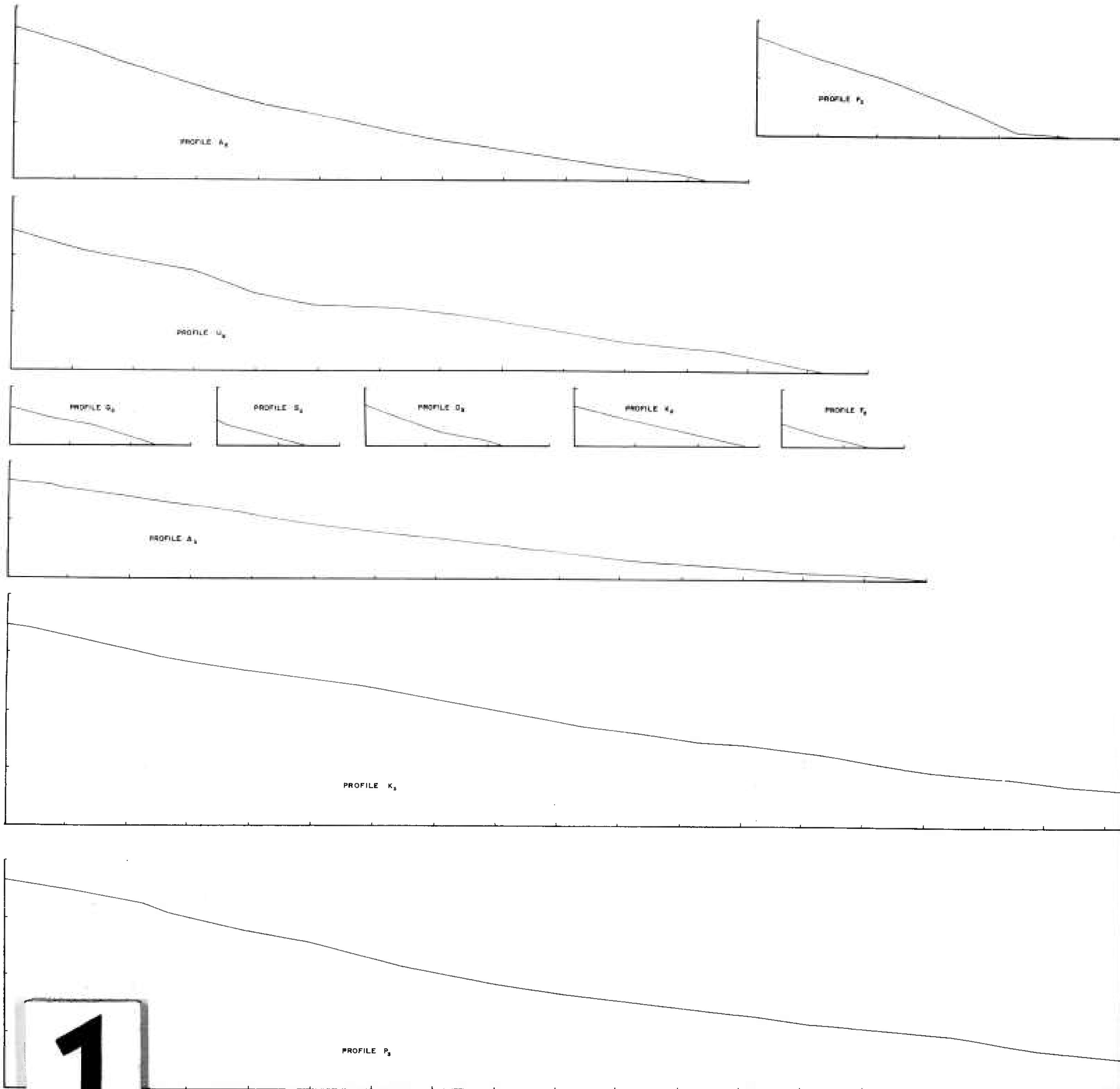


Figure 32

FIELD MEASURED PROFILES — LONG CANYON AREA

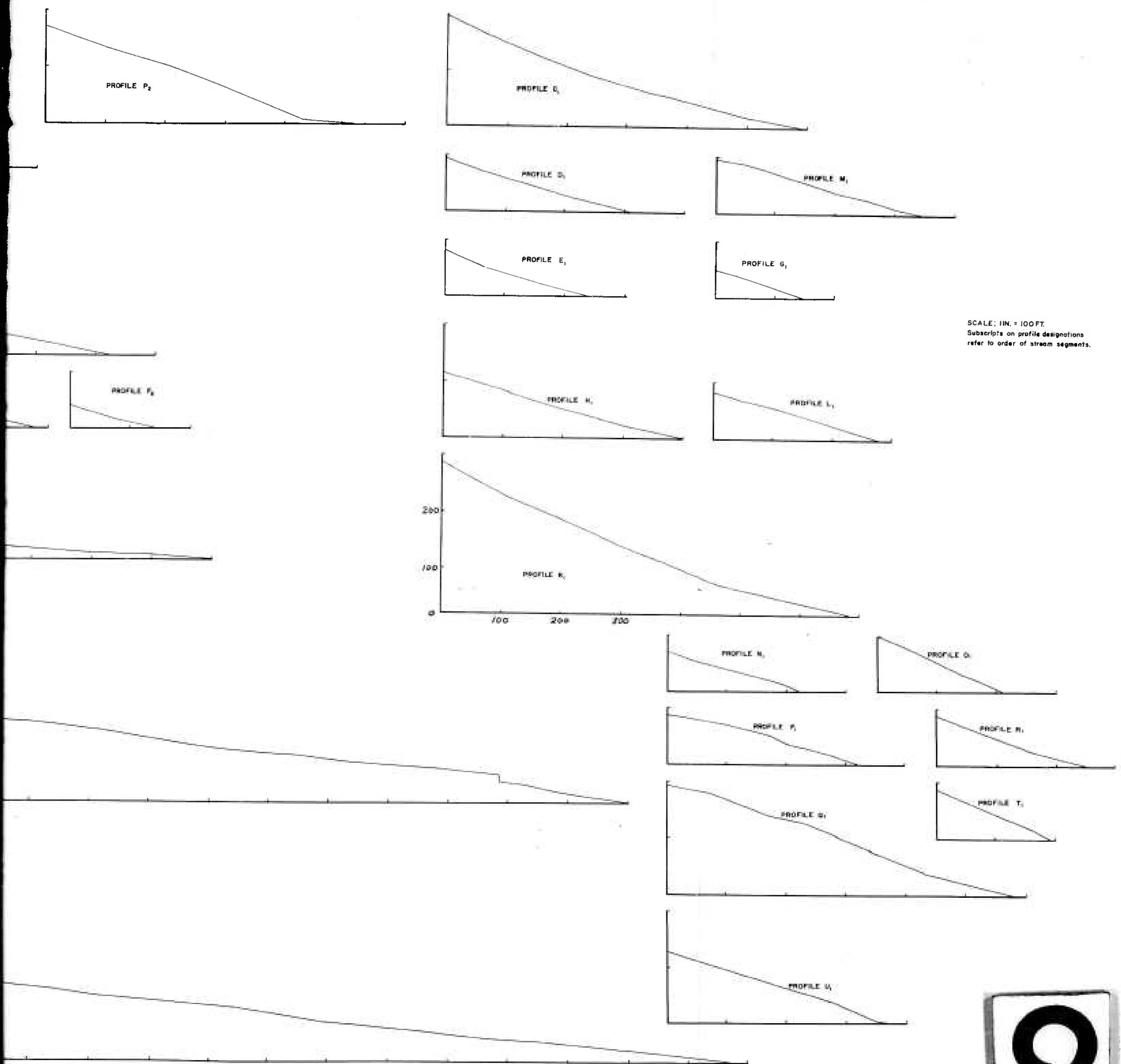


Figure 32

RED PROFILES — LONG CANYON AREA

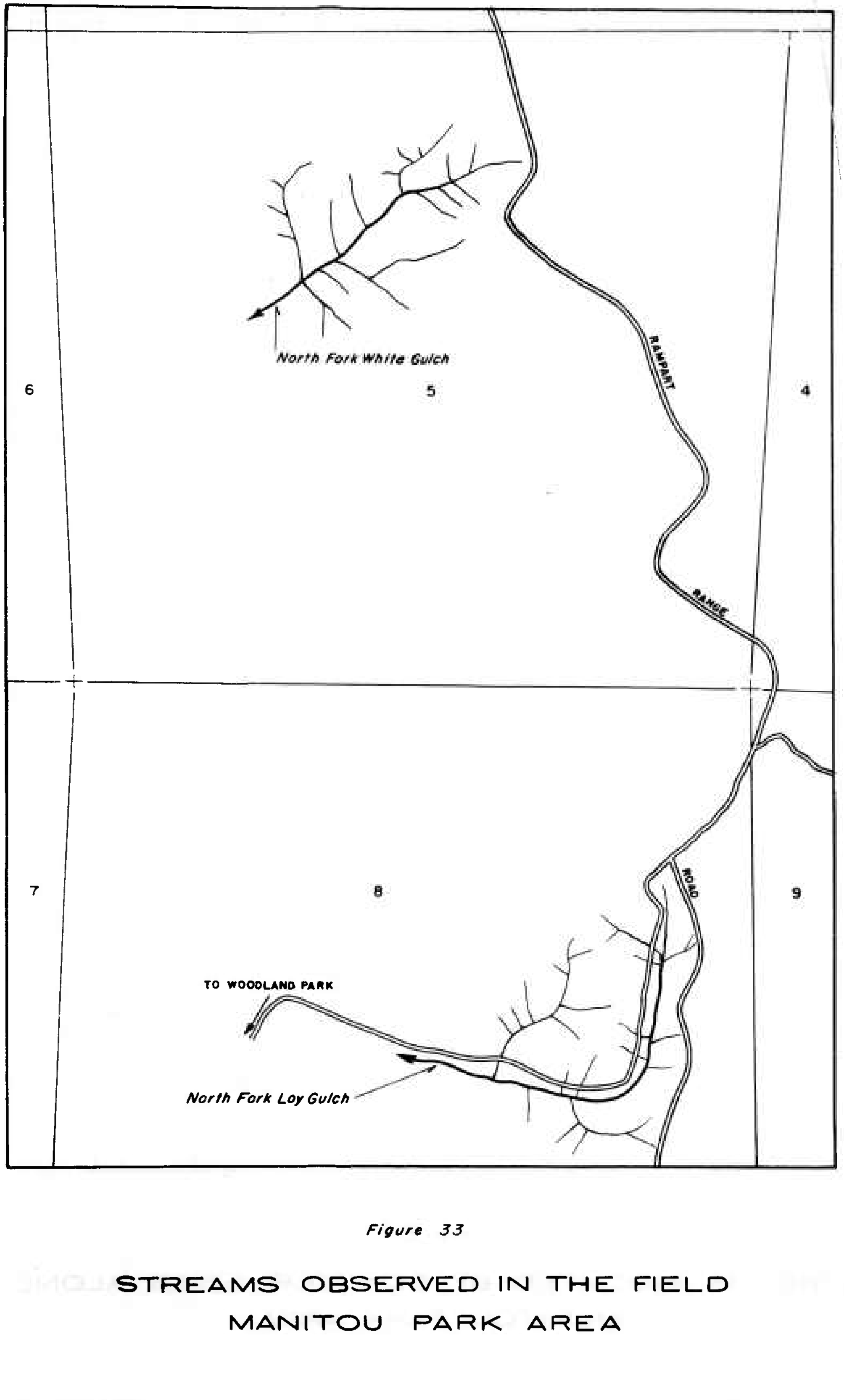


Figure 33

STREAMS OBSERVED IN THE FIELD
MANITOU PARK AREA

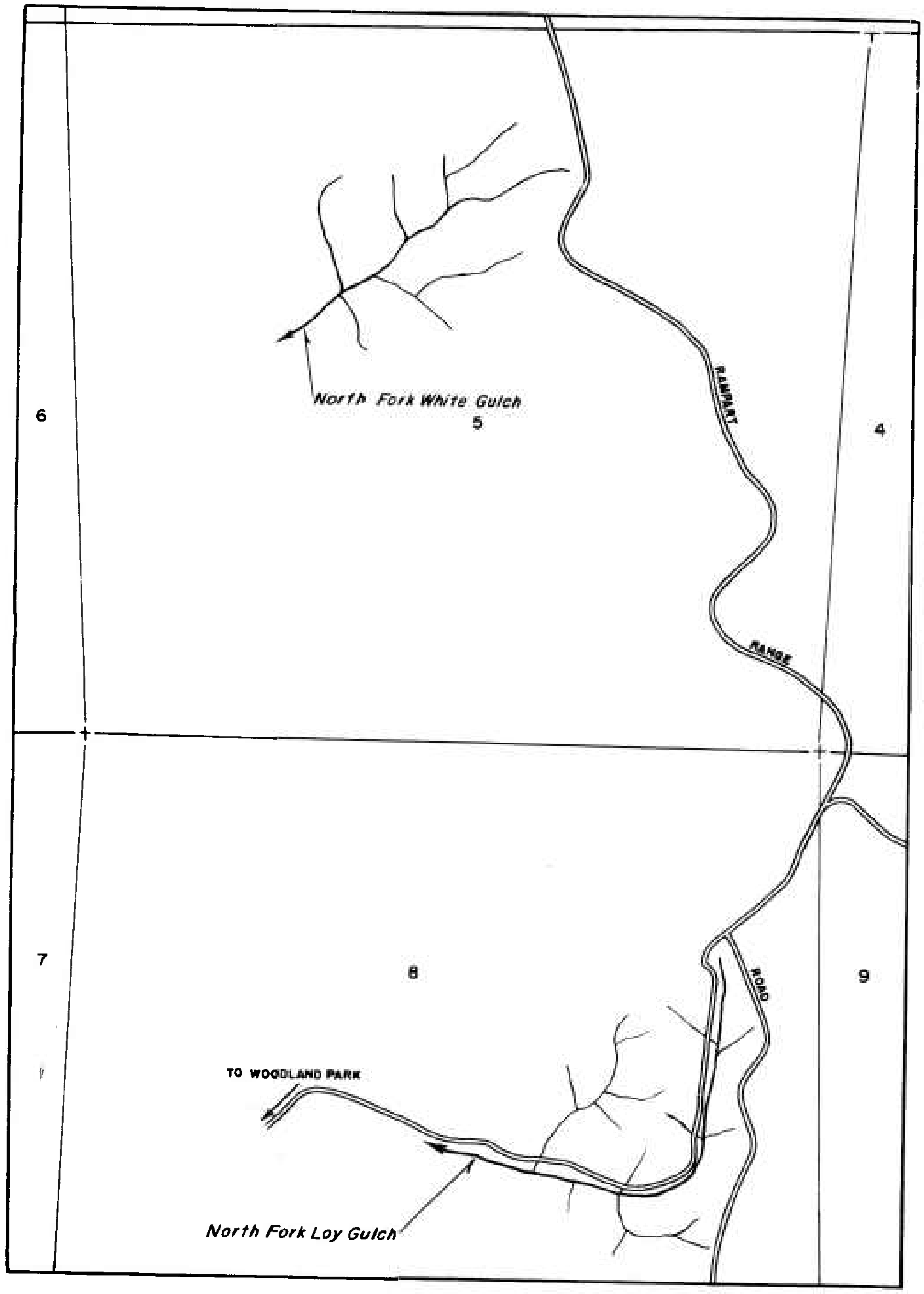


Figure 34

STREAMS INDICATED BY CONTOUR LINES ALONE
MANITOU PARK AREA

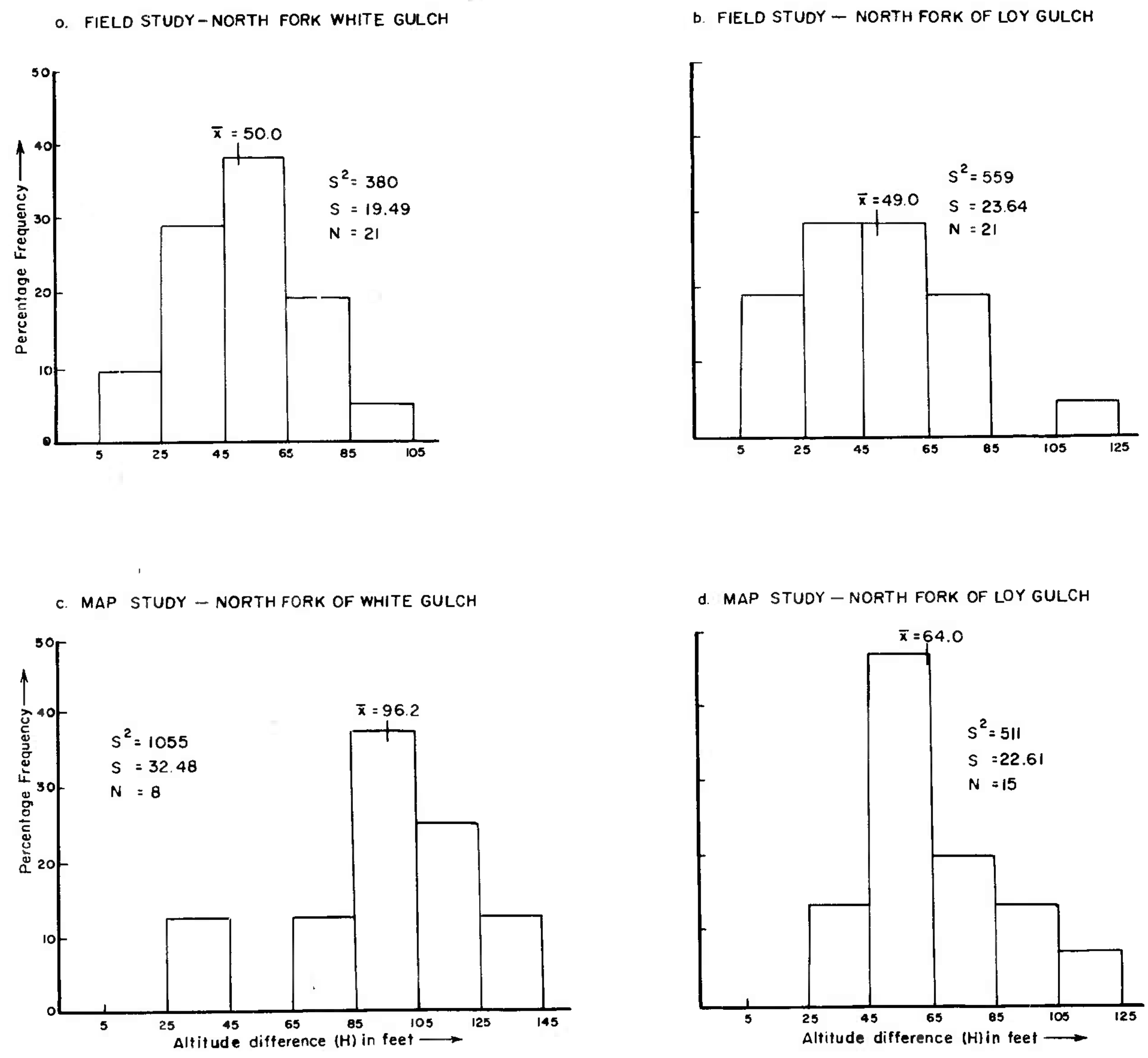


Figure 35

COMPARISON OF FIELD & MAP DATA

WHITE & LOY GULCHES

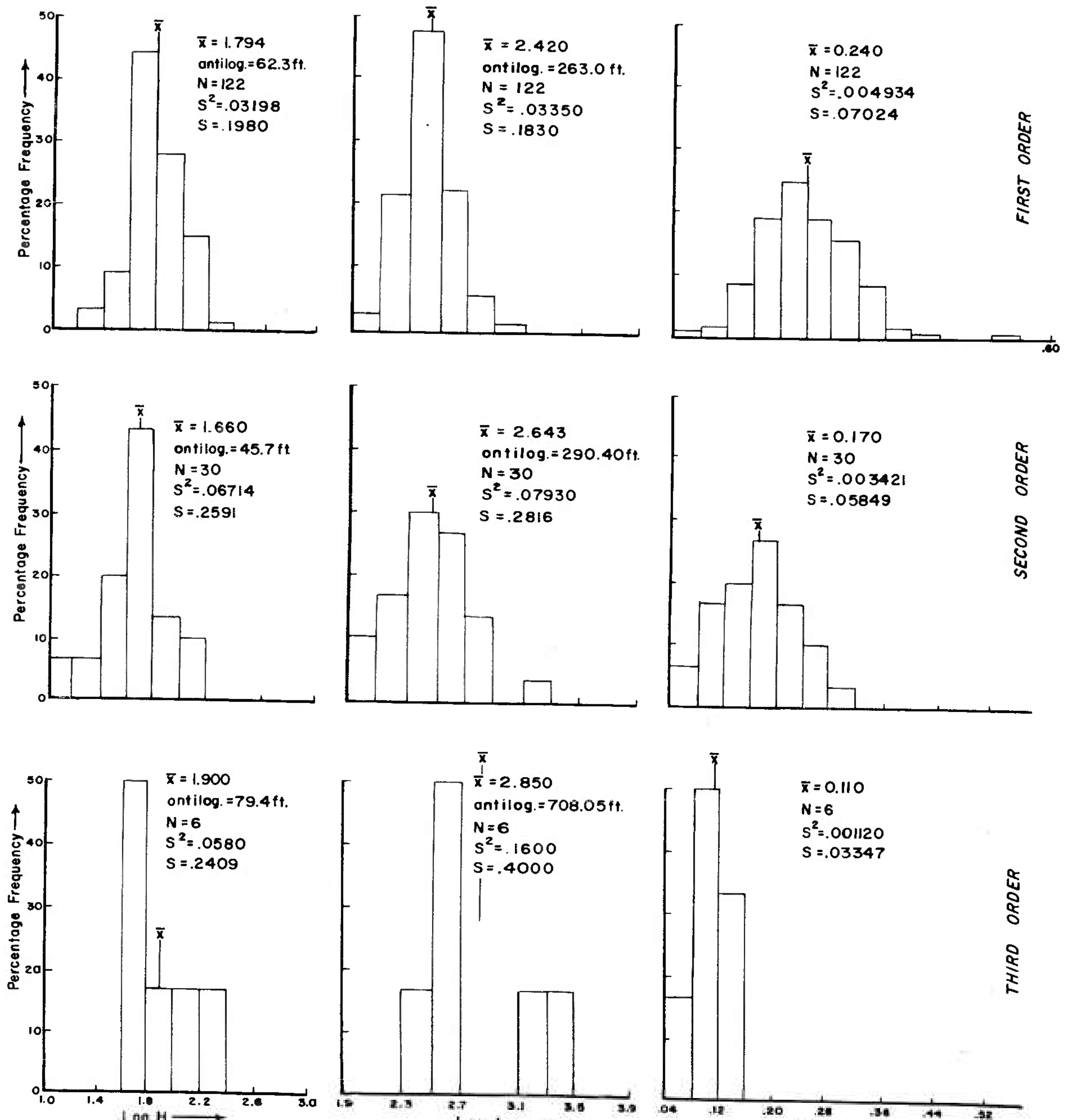


Figure 36

MOUNT DECEPTION QUAD. HISTOGRAMS

FOURTH ORDER N=2
(incomplete)
H/L = 0.0648

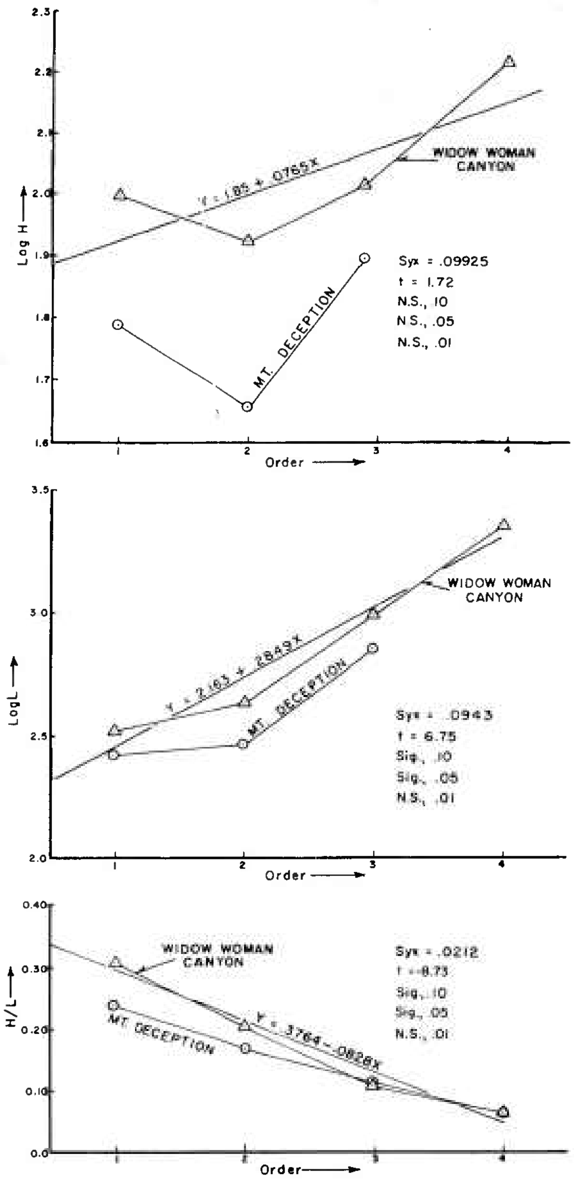


Figure 37

COMPARISON OF H, L & H/L DATA
MT. DECEPTION & WIDOW WOMAN CANYON AREAS

REGRESSION ANALYSIS APPLIES TO
WIDOW WOMAN CANYON DATA ONLY

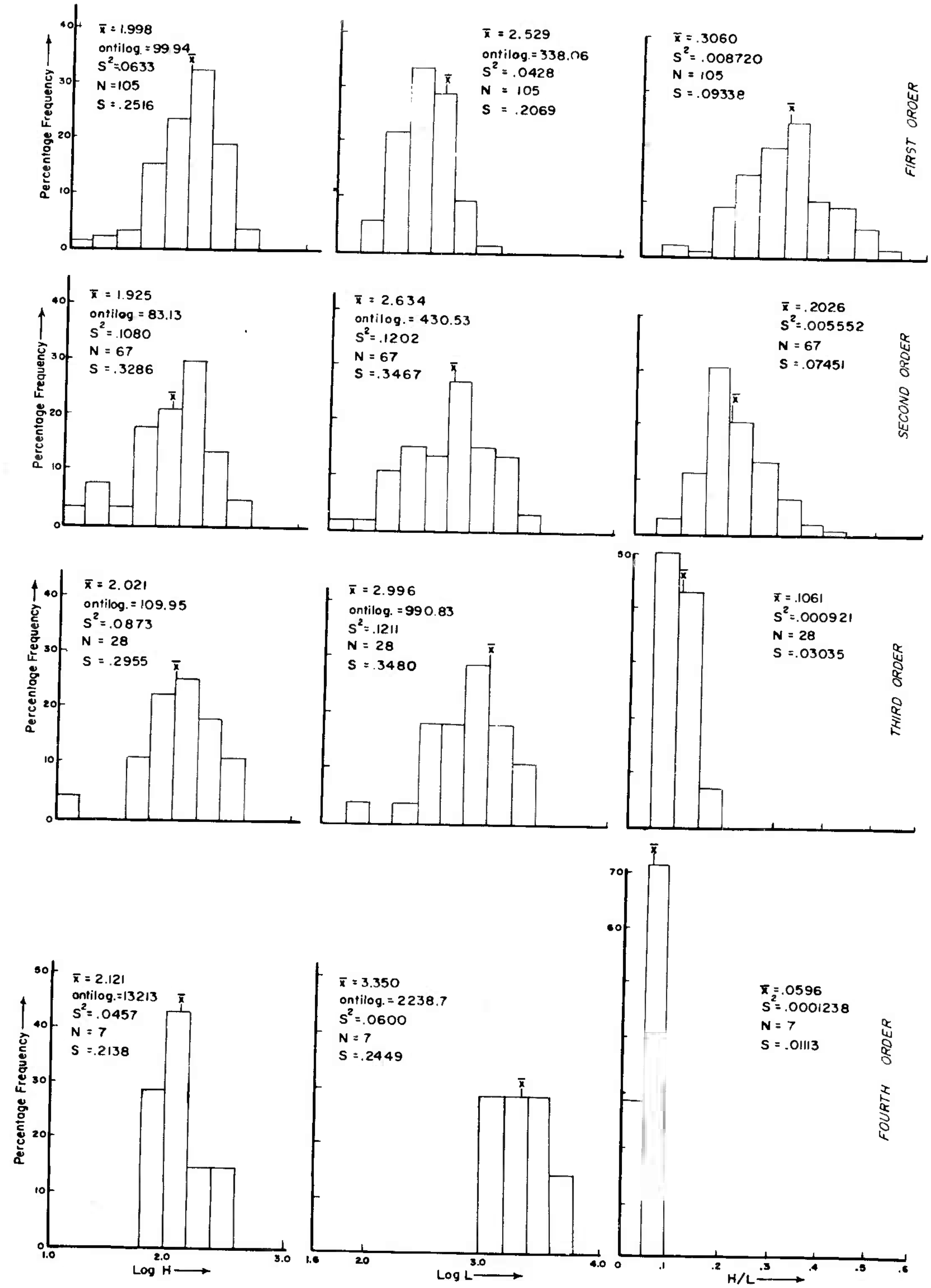


Figure 38

WIDOW WOMAN CANYON HISTOGRAMS

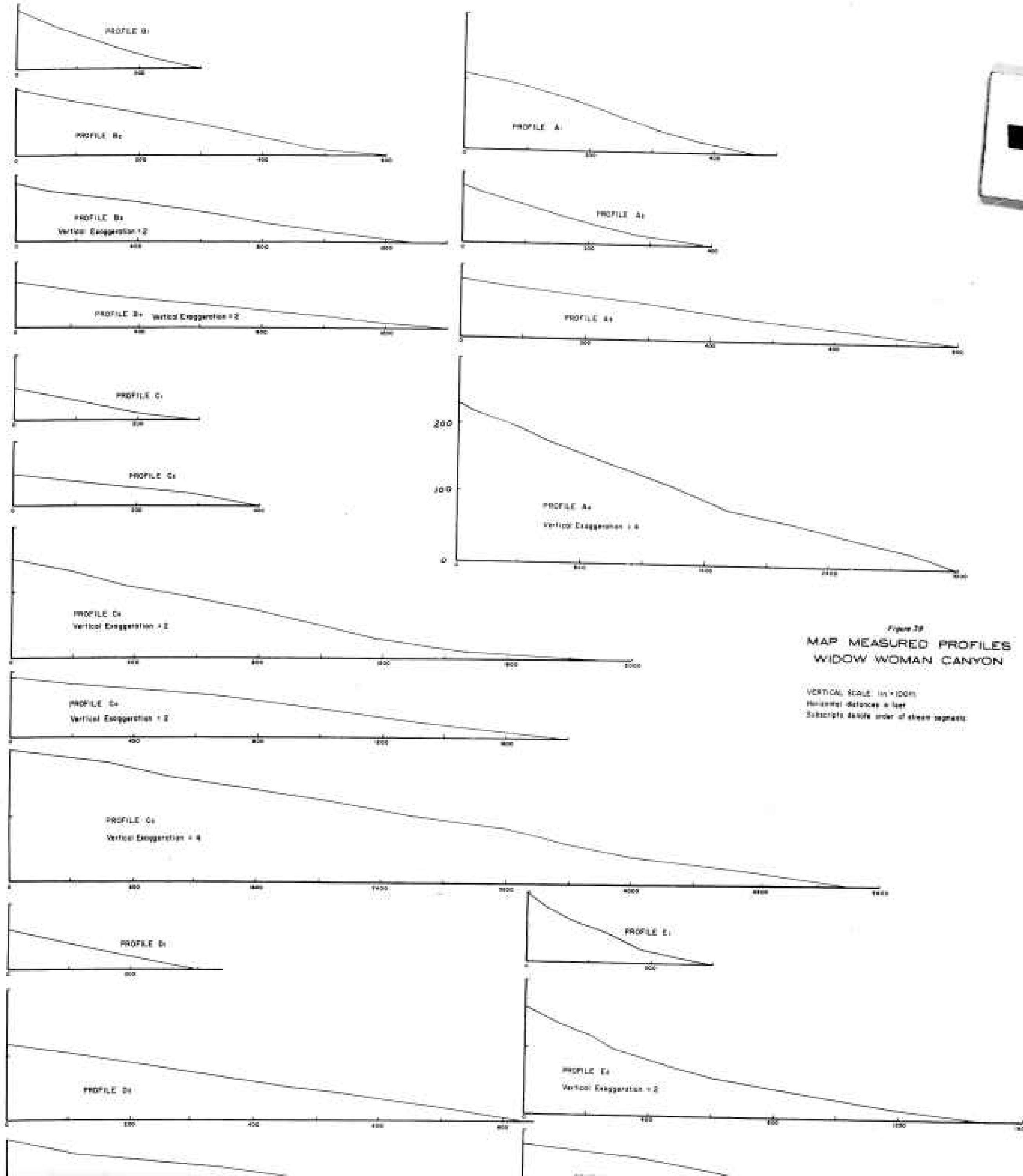


Figure 38

MAP MEASURED PROFILES
WIDOW WOMAN CANYON

VERTICAL SCALE: 1in = 100ft
Horizontal distances in feet
Subscripts denote order of stream segments

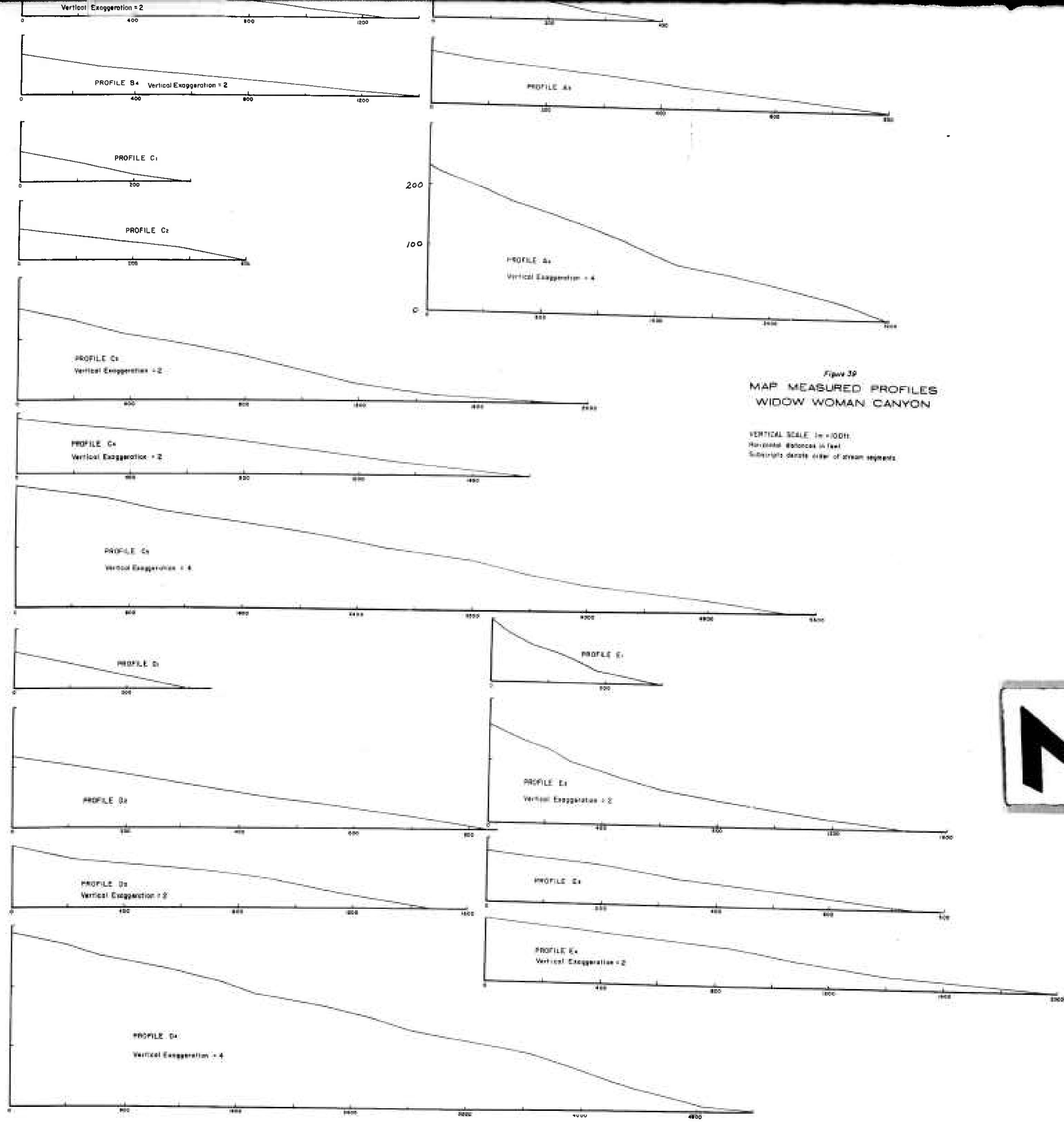
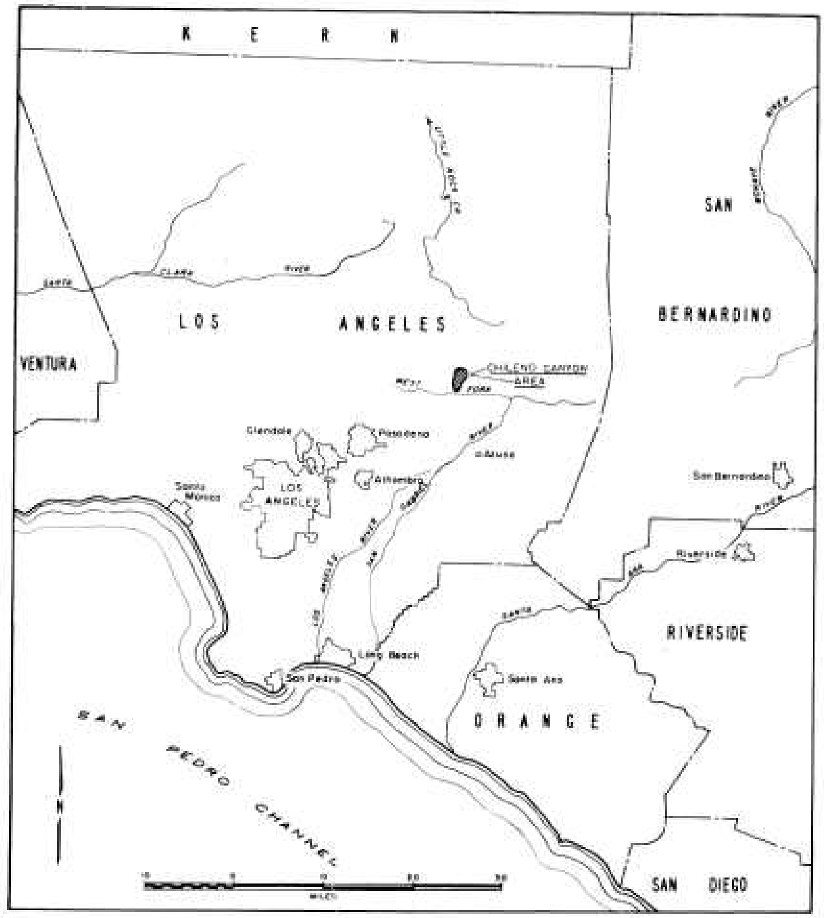


Figure 39

MAP MEASURED PROFILES
WIDOW WOMAN CANYON

VERTICAL SCALE: 1in = 100ft.
Horizontal distances in feet
Subscripts denote order of stream segments



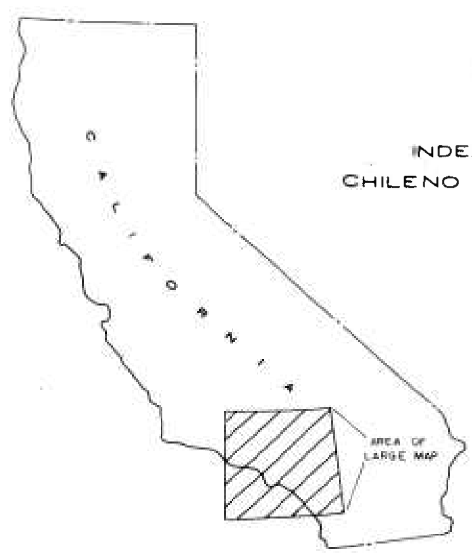


Figure 40

INDEX MAP OF
CHILENO CANYON AREA

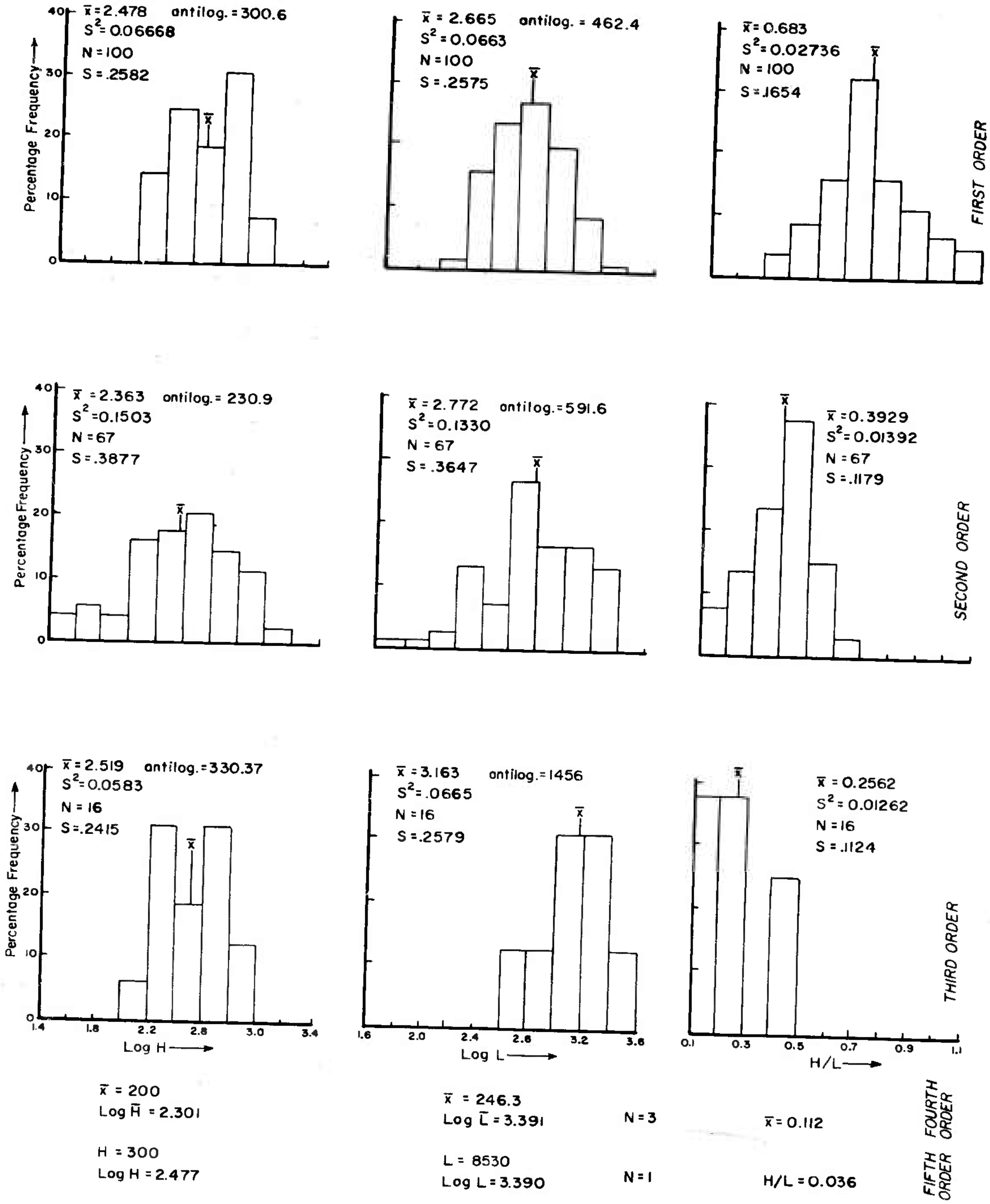


Figure 41

CHILENO CANYON HISTOGRAMS

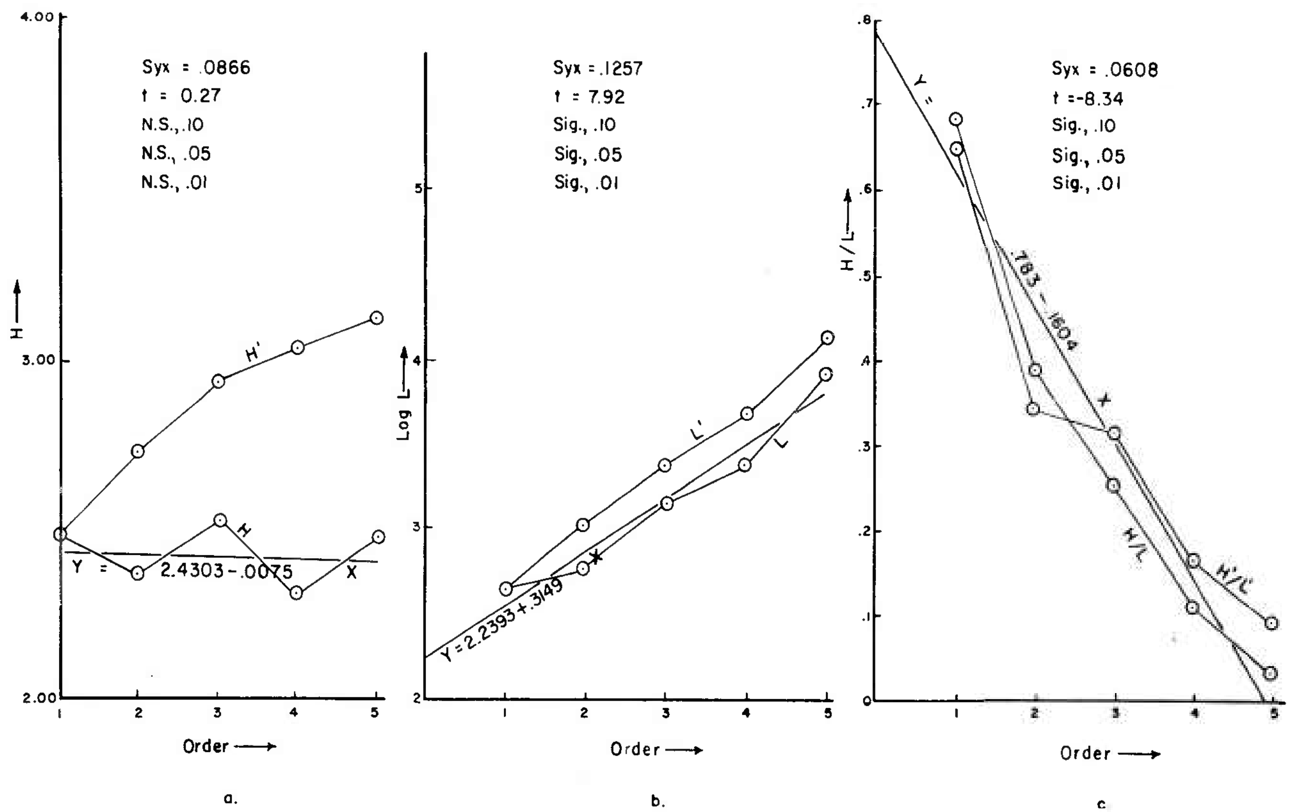


Figure 42

RELATION OF H, L & H/L TO ORDER

CHILENO CANYON AREA

REGRESSION ANALYSES APPLY TO NON-CUMULATIVE DATA ONLY

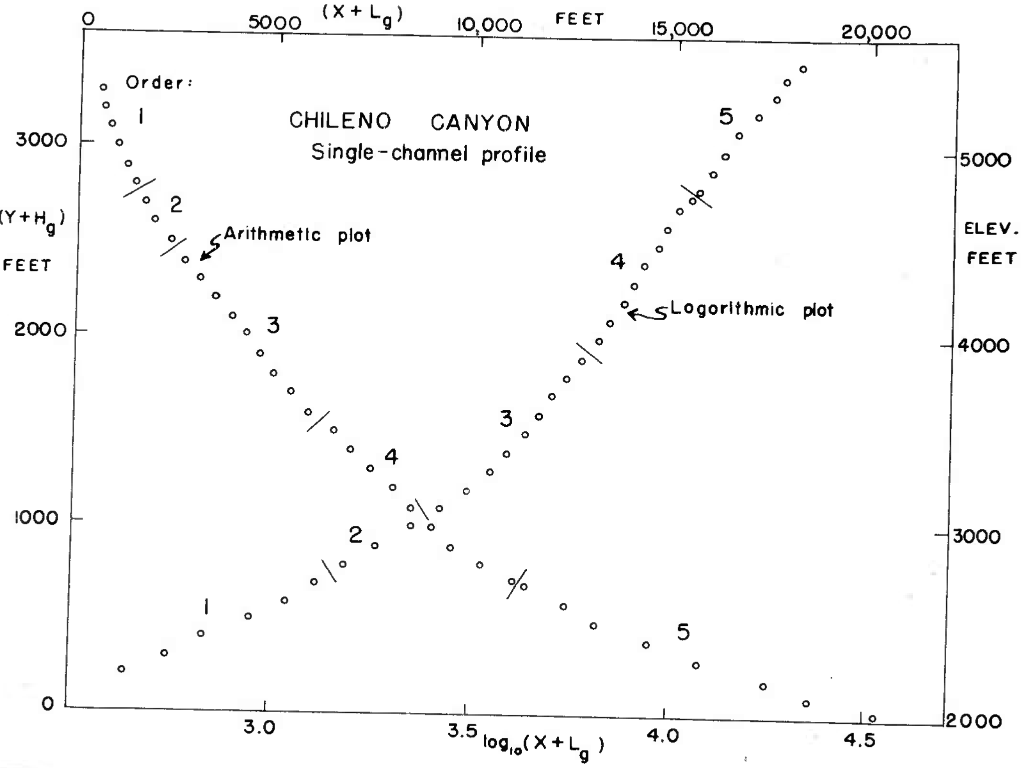


Figure 43

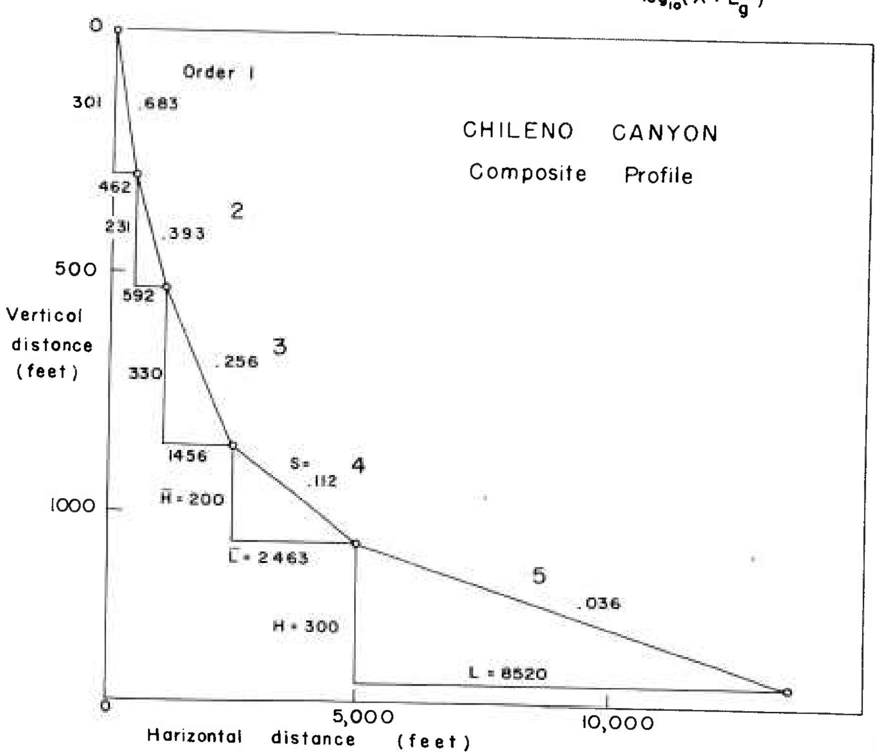


Figure 44

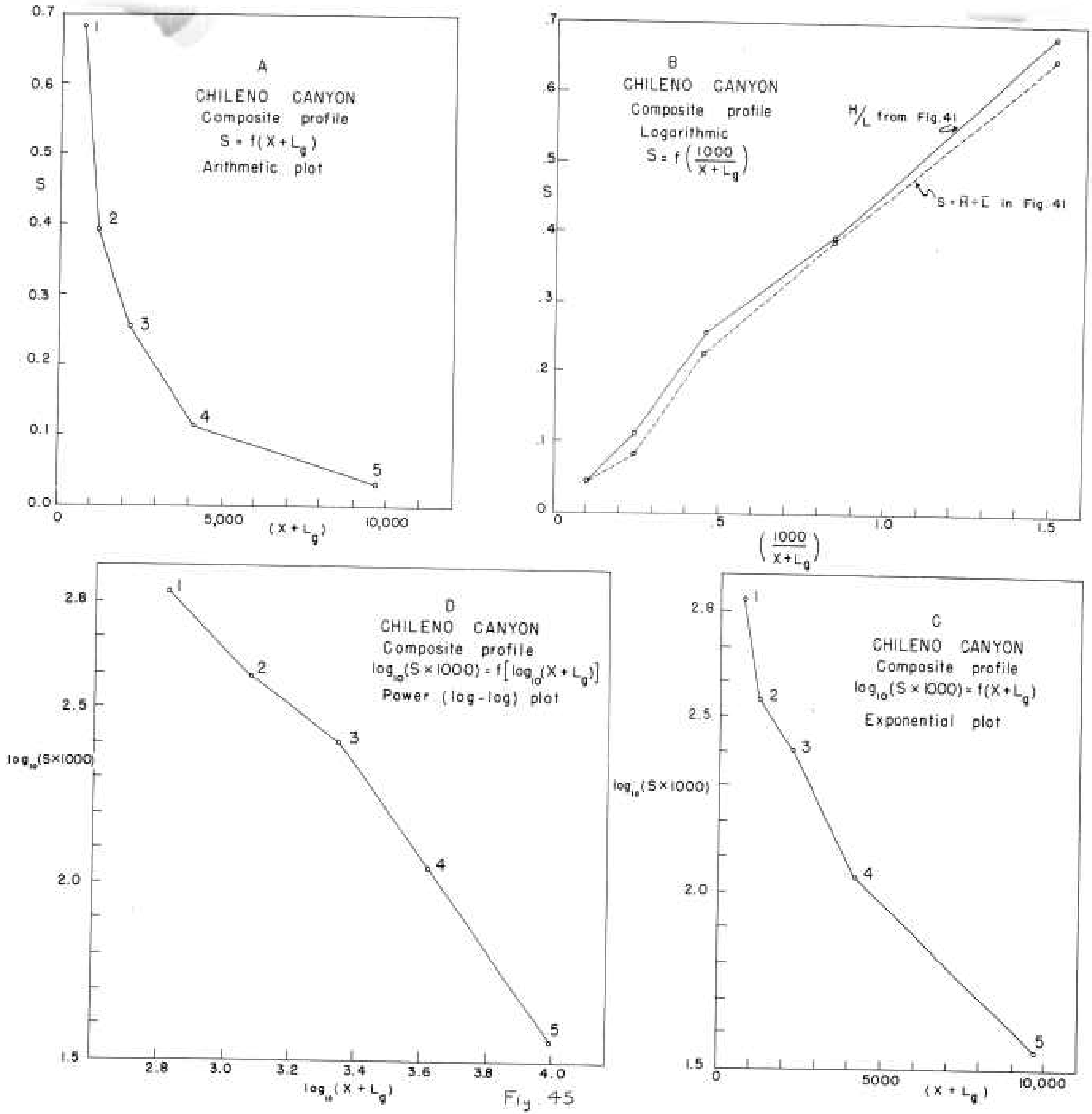
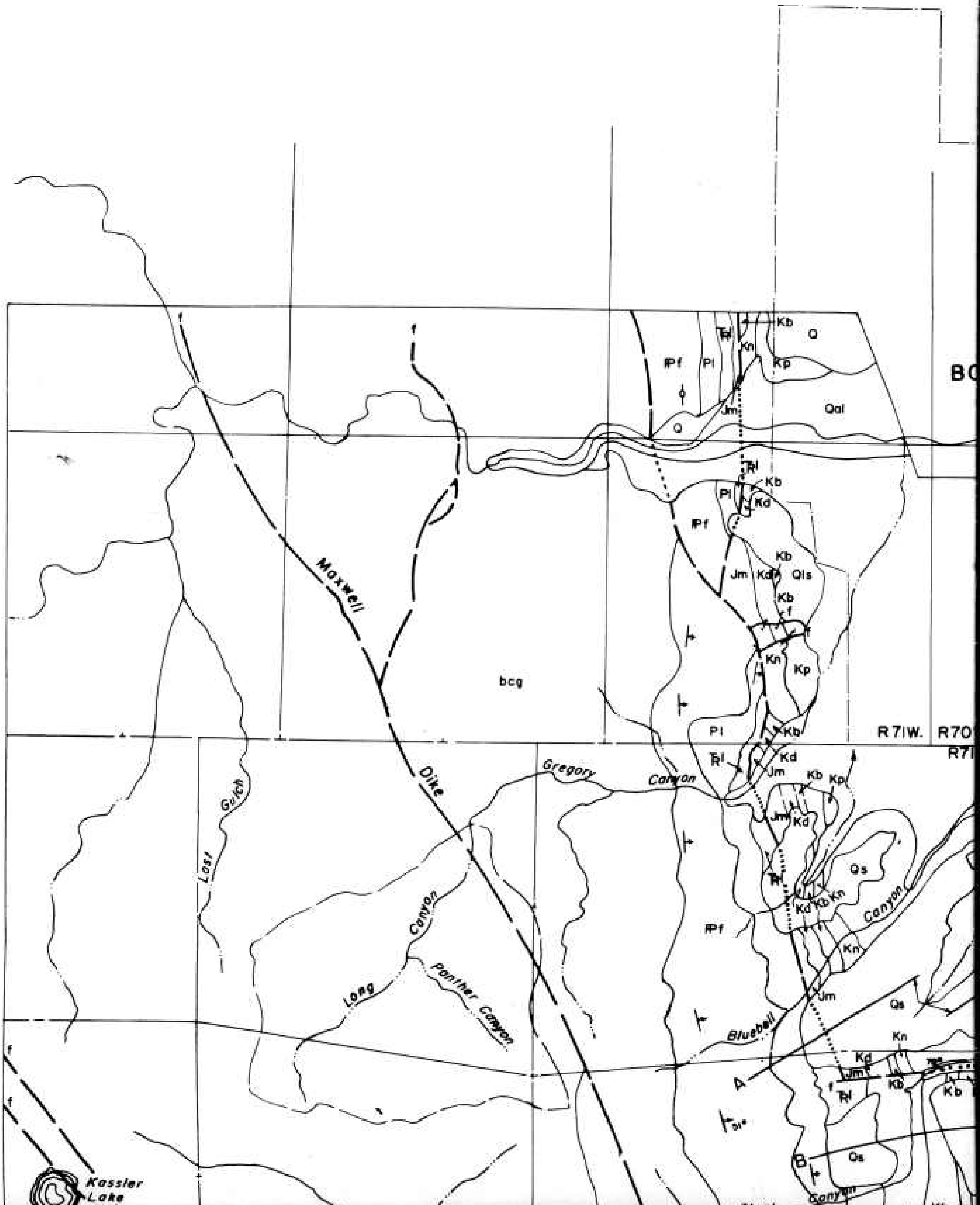
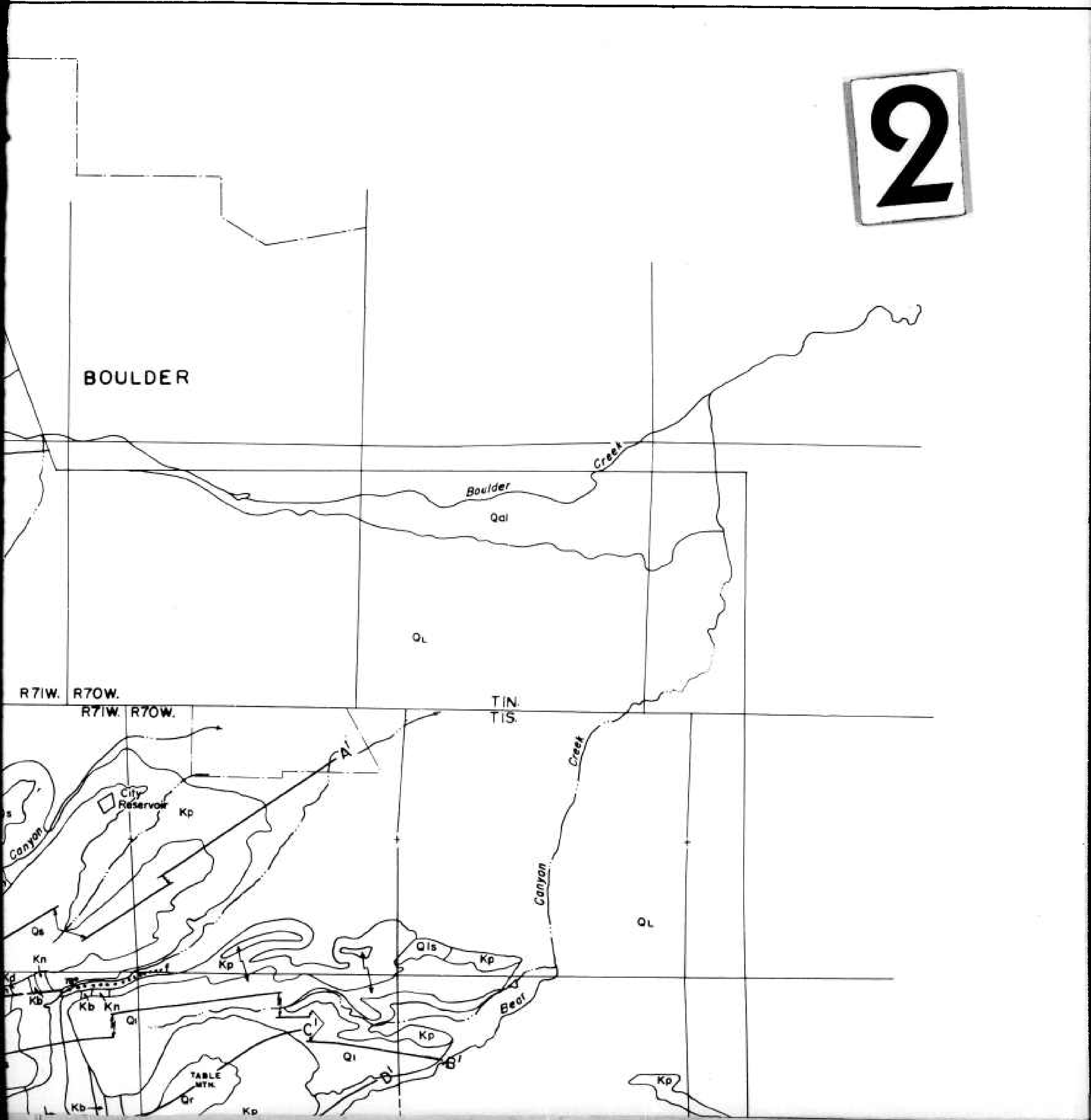

A
CHILENO CANYON
Composite profile
S = f(X + L_g)
Arithmetic plot
B
CHILENO CANYON
Composite profile
Logarithmic
S = f(1000 / (X + L_g))
H/L from Fig. 41
S = R̄ + L̄ in Fig. 41
C
CHILENO CANYON
Composite profile
log_10(S × 1000) = f(X + L_g)
Exponential plot
D
CHILENO CANYON
Composite profile
log_10(S × 1000) = f[log_10(X + L_g)]
Power (log-log) plot
S
(X + L_g)
(1000 / (X + L_g))
log_10(S × 1000)
log_10(X + L_g)

Fig. 45

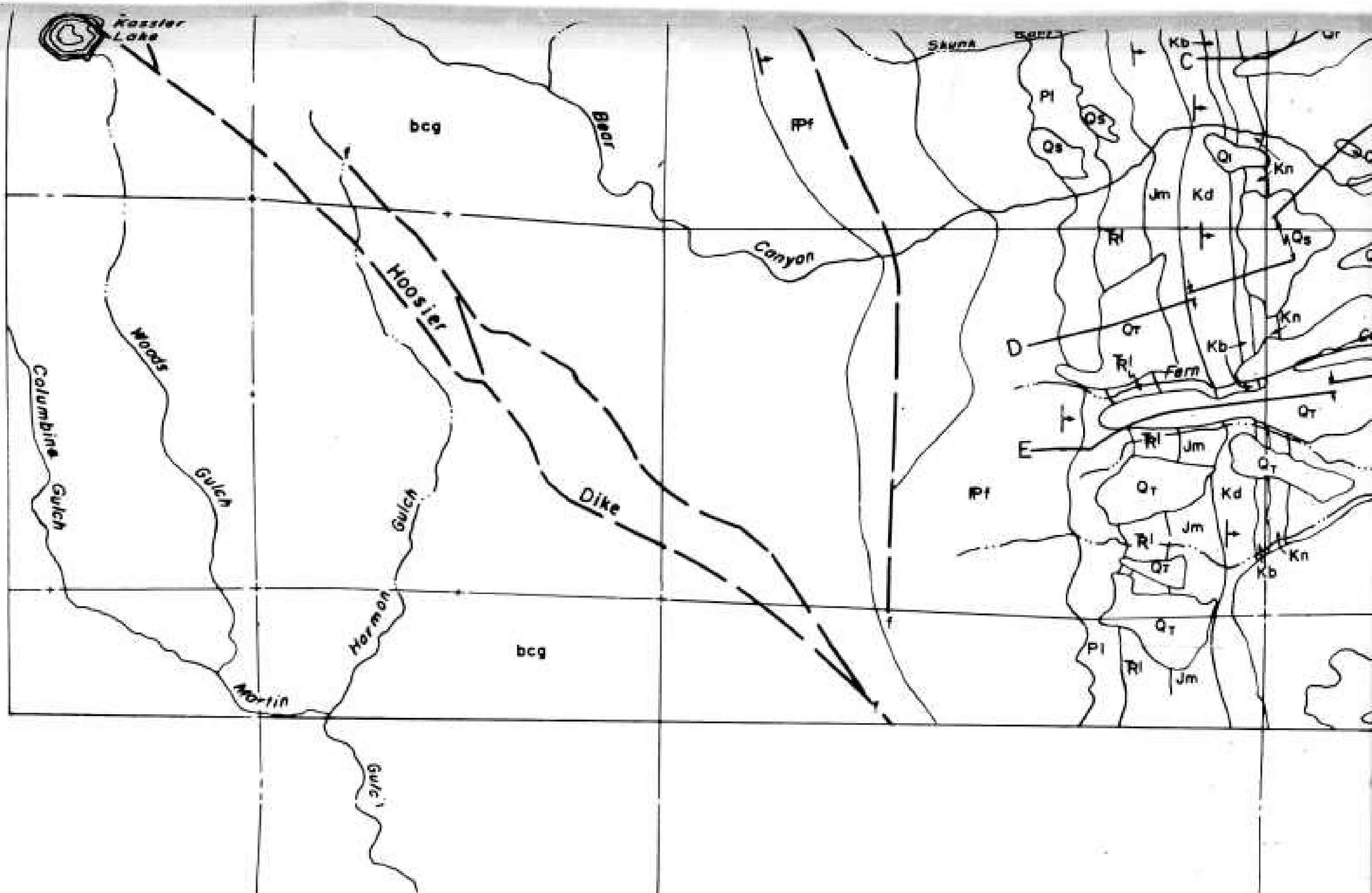
1



Maxwell
Dike
Gregory
Canyon
Lost Gulch
Long Canyon
Panther Canyon
Bluebell
Canyon
Skunk
Canyon
Kassler
Lake
bcg
Q
Qal
Qls
Qs
Kb
Kp
Kn
Kd
Jm
Pf
Pl
A
B
R 71W.
R70
BO



2
BOULDER
Boulder Creek
Qal
QL
R71W. R70W.
R71W. R70W.
T1N.
T1S.
Creek
Canyon
A'
City Reservoir
Kp
Canyon
Qs
Kn
Kd
Kb
Kb Kn
Ql
Qls
Kp
Bear
C'
B'
D'
TABLE MTN.
Qr
Kb
Kp
QL



LEGEND

QUATERNARY	Qal	Alluvium in active flood plains
	QT	Gravels of Table Mountain Pediment Surface
	QI	Gravels of Intermediate Pediment Surface
	QS	Gravels of Shanahan Hill Pediment Surface
	QL	Gravels of Lowest Pediment Surface
	Qls	Landslide debris
	Q	Undifferentiated terrace gravels
CRETACEOUS	Kp	Pierre formation
	Kn	Niobrara formation
	Kb	Benton formation
	Kd	Dakota formation
JURASSIC	Jm	Morrison formation
TRIASSIC AND PERMIAN	TRl	Lykins formation

3

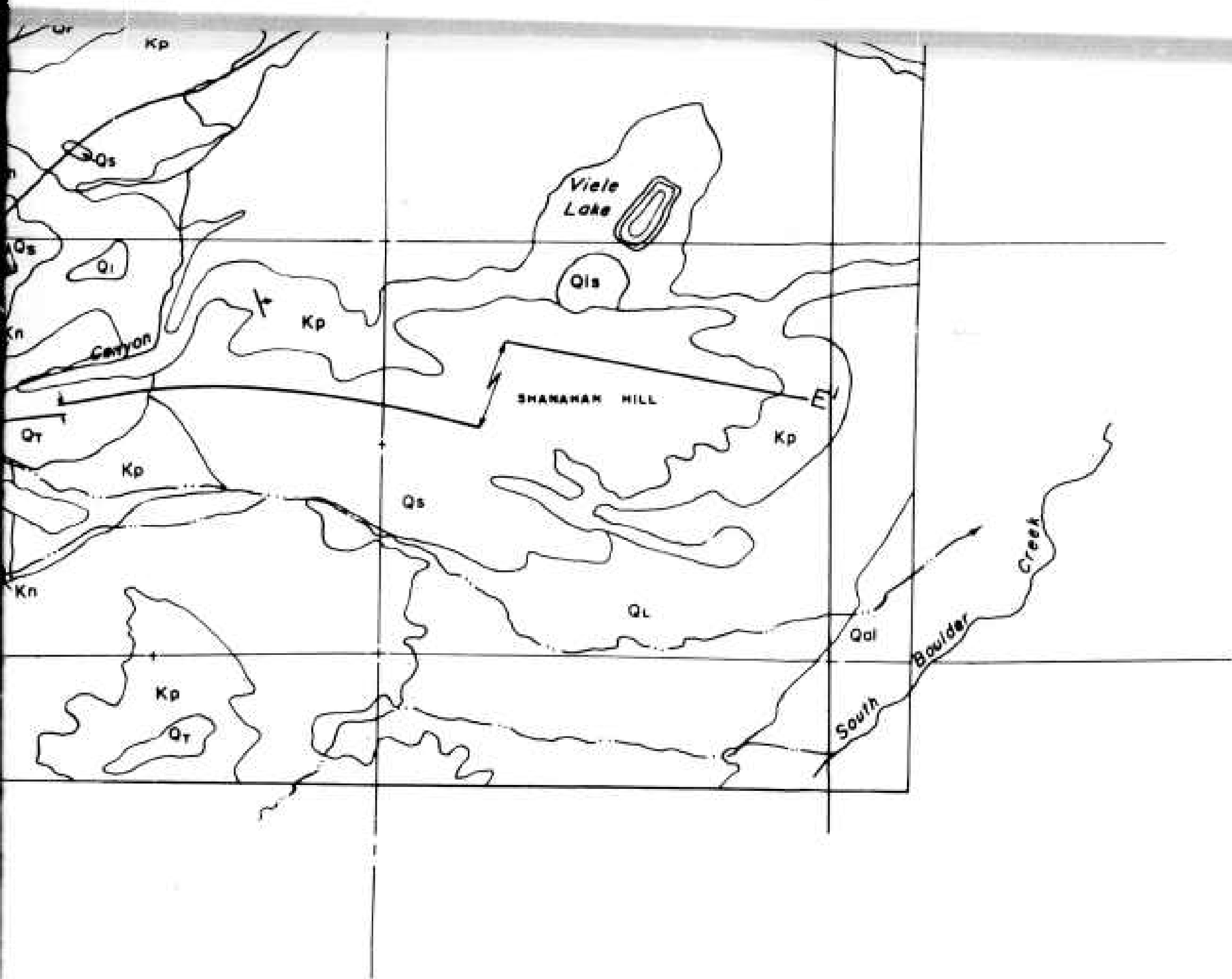
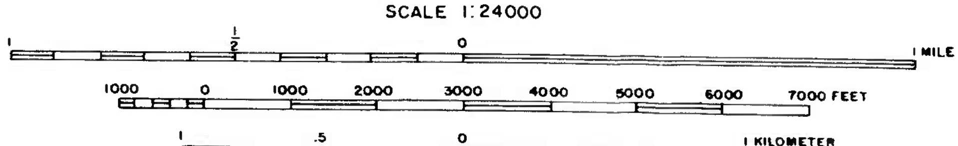


Plate 1

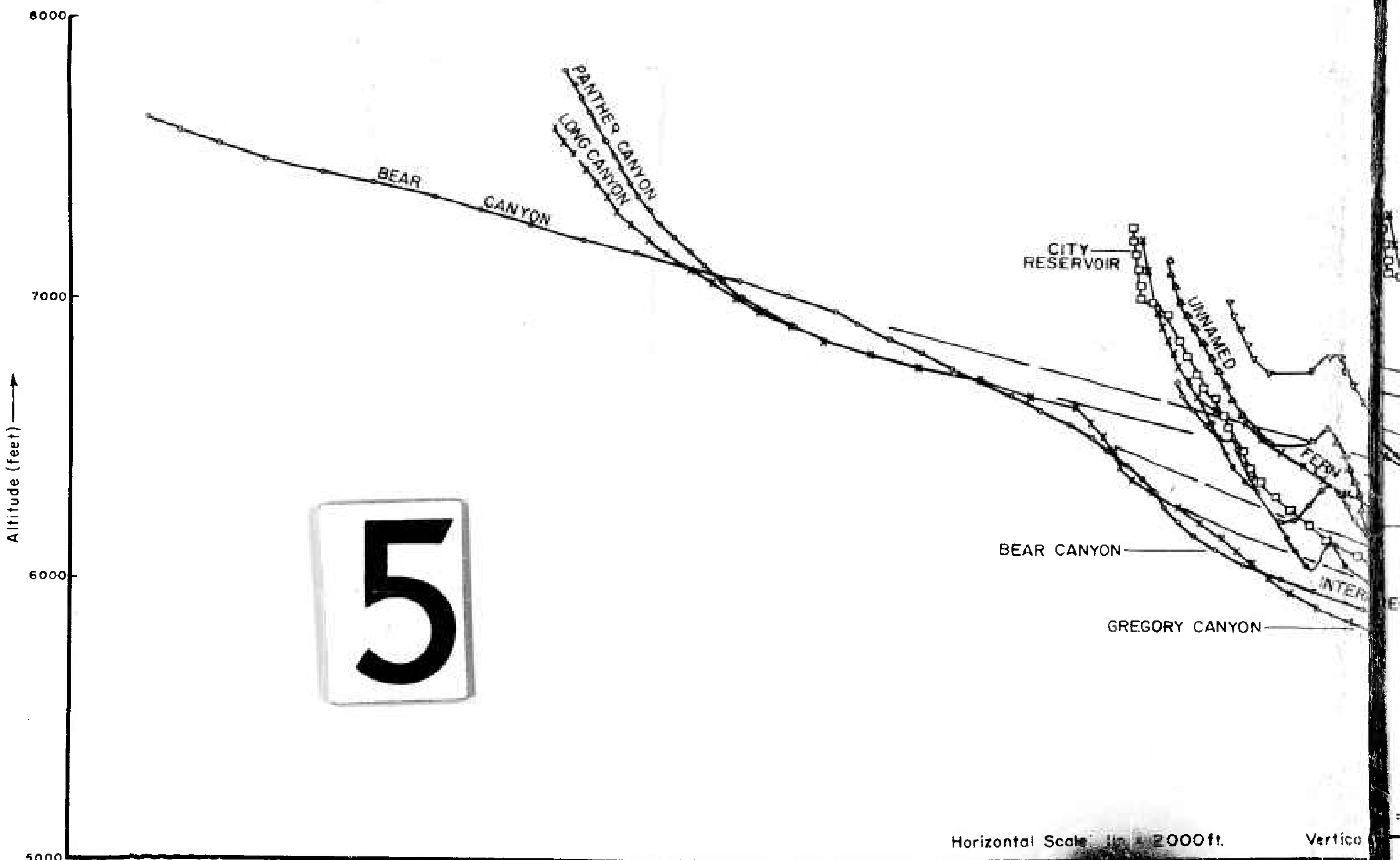
GEOLOGIC MAP
OF
LONG CANYON AREA,
SHOWING

location of basin studied in detail and of profiles AA' through EE'. See table 6 for summary of stratigraphy.

SCALE 1:24000



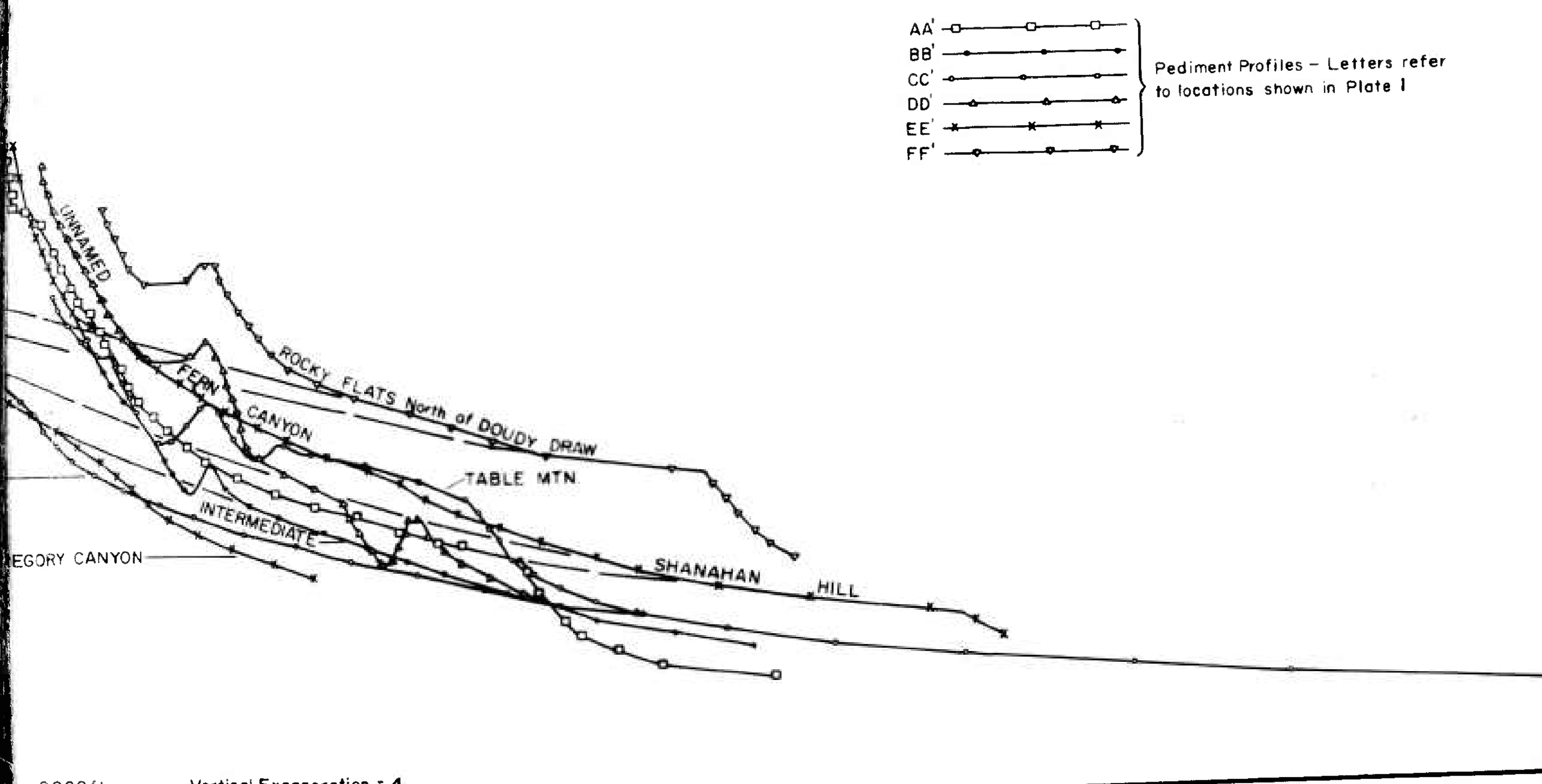
PERMIAN	Pl	Lyons sondstone
PENNSYLVANIAN	IPf	Fountain formation
PRECAMBRIAN	bcg	Boulder Creek Gronite



PROFILES OF SC

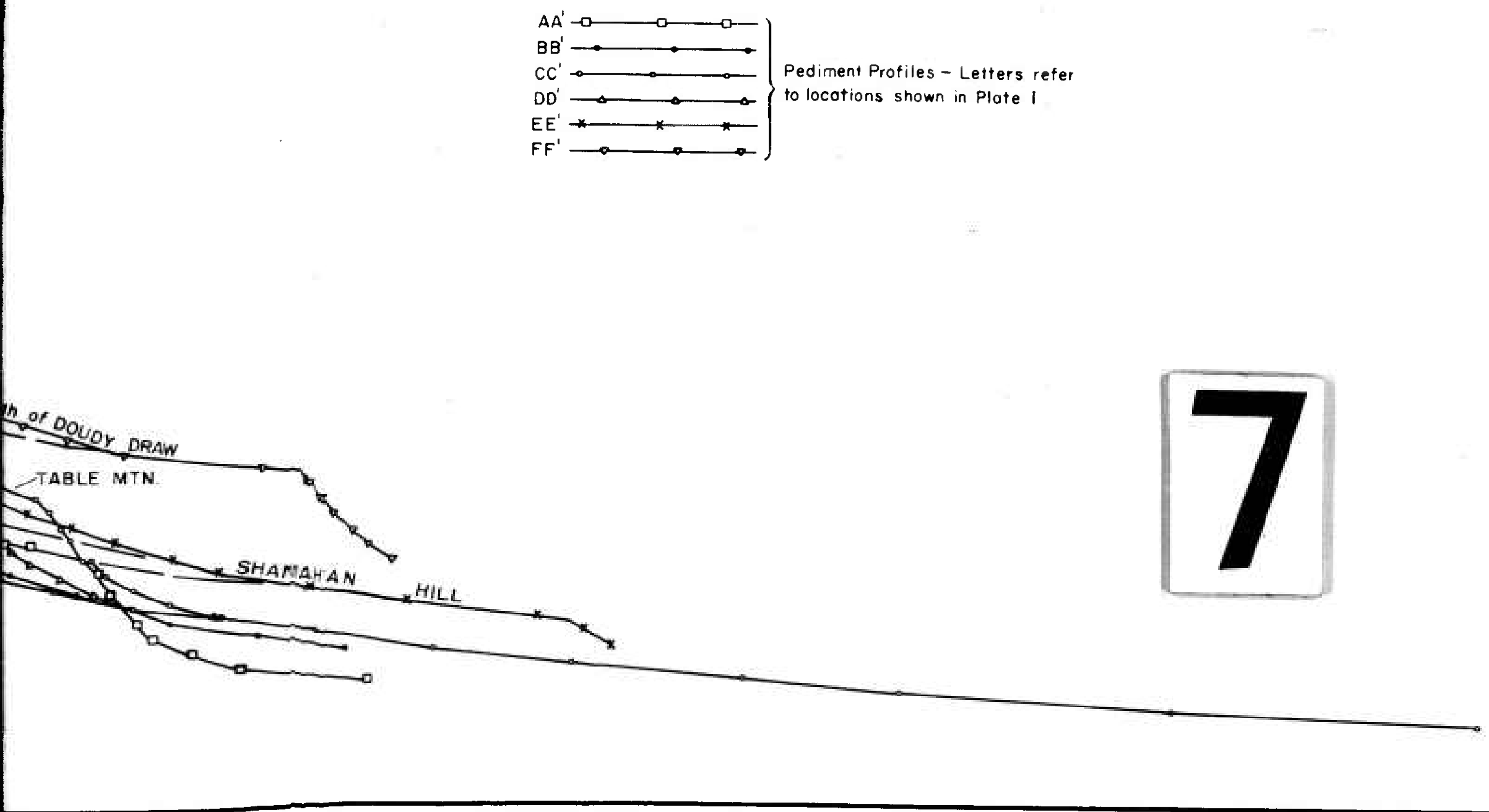
LON

6



FILES OF SOME STREAMS & PEDIMENTS

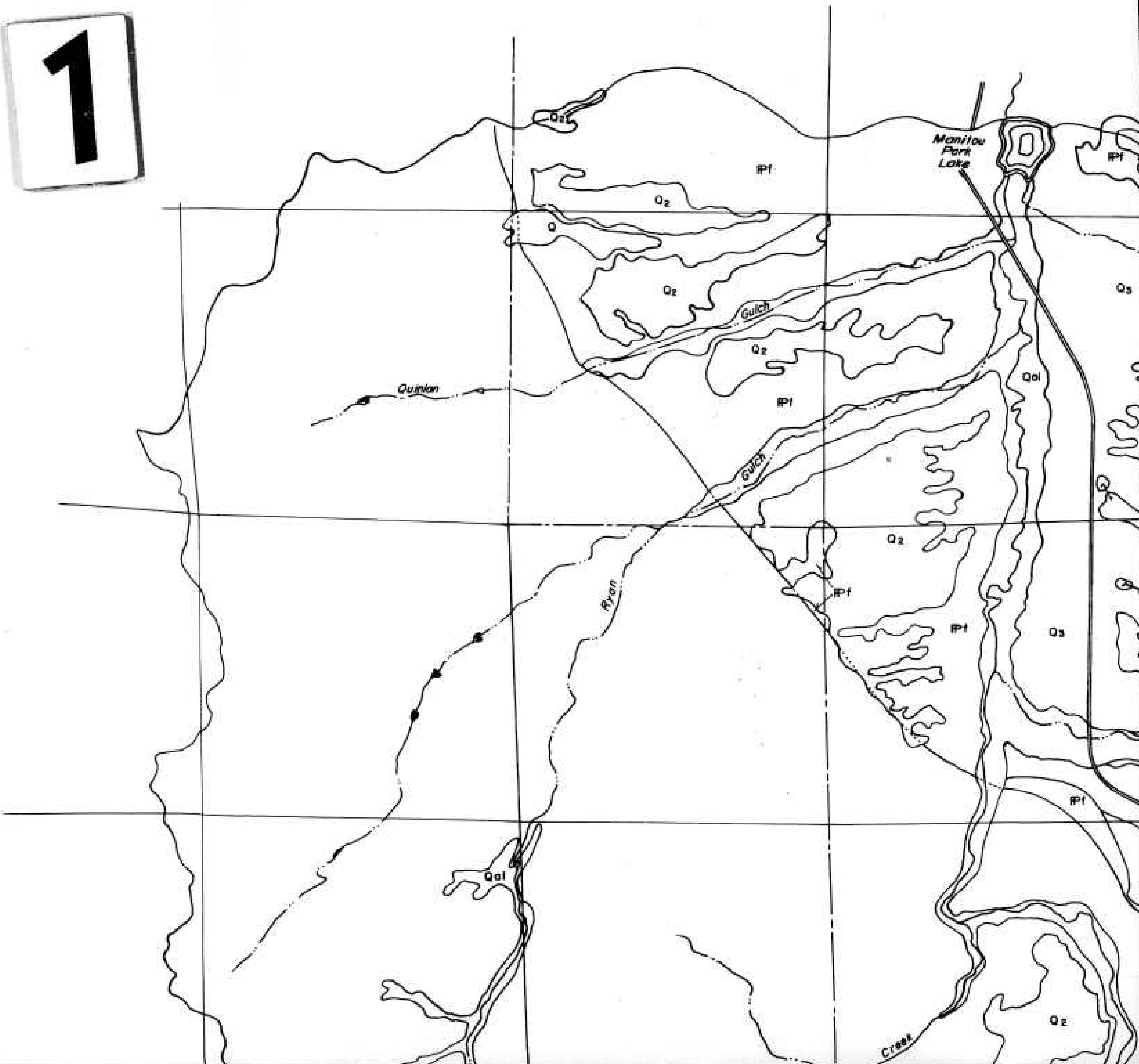
LONG CANYON AREA



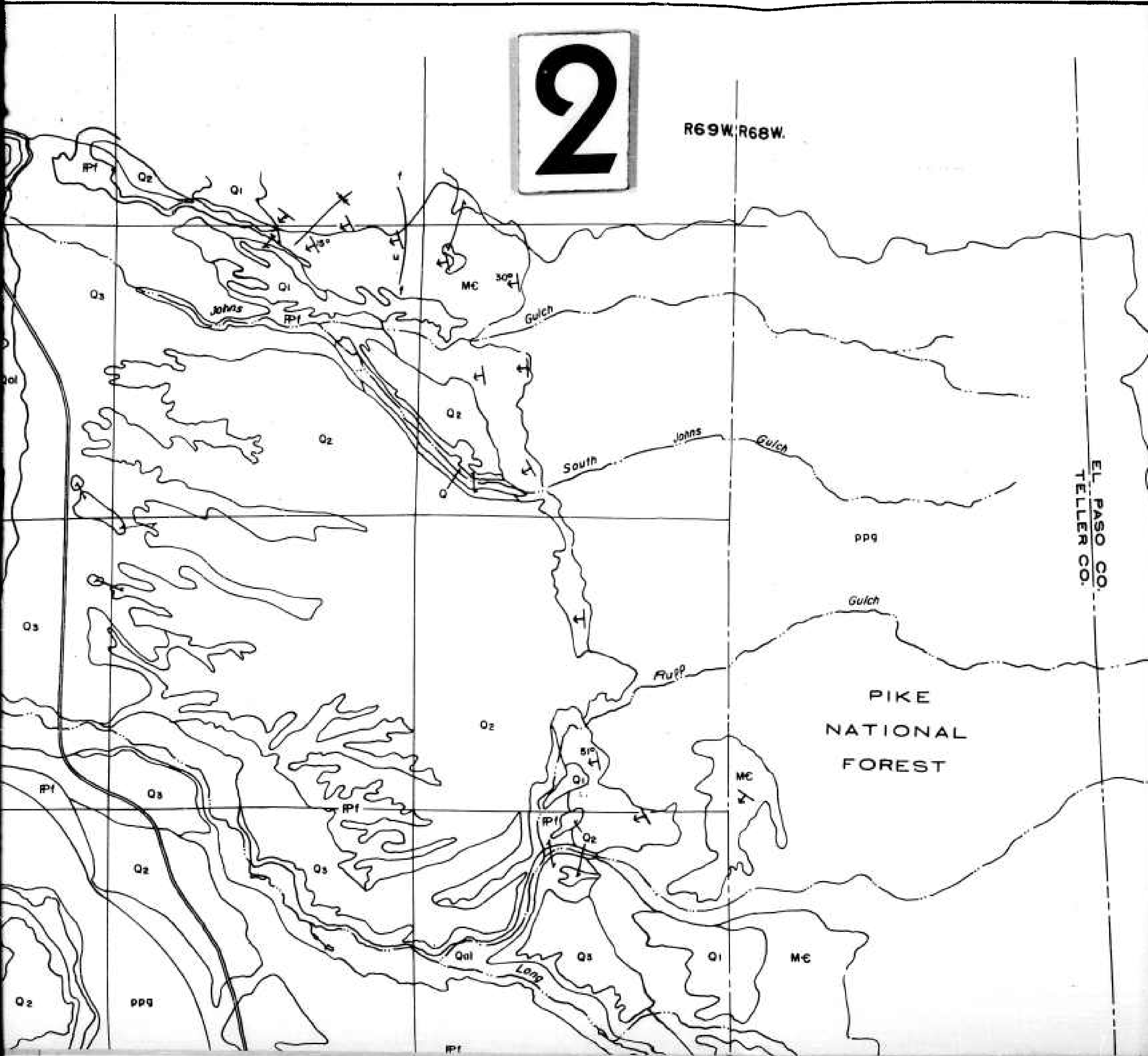
7

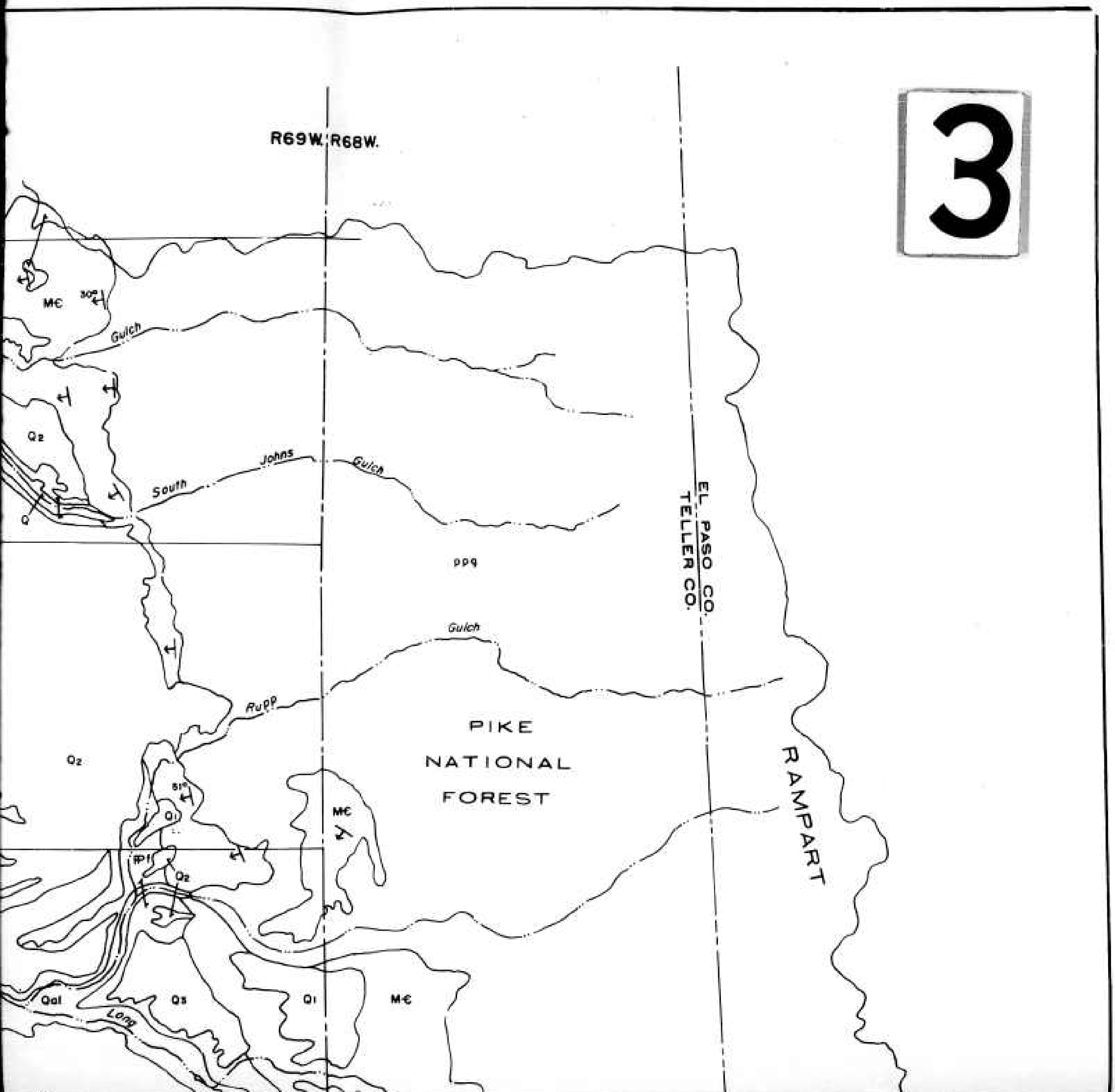
MS & PEDIMENTS
AREA

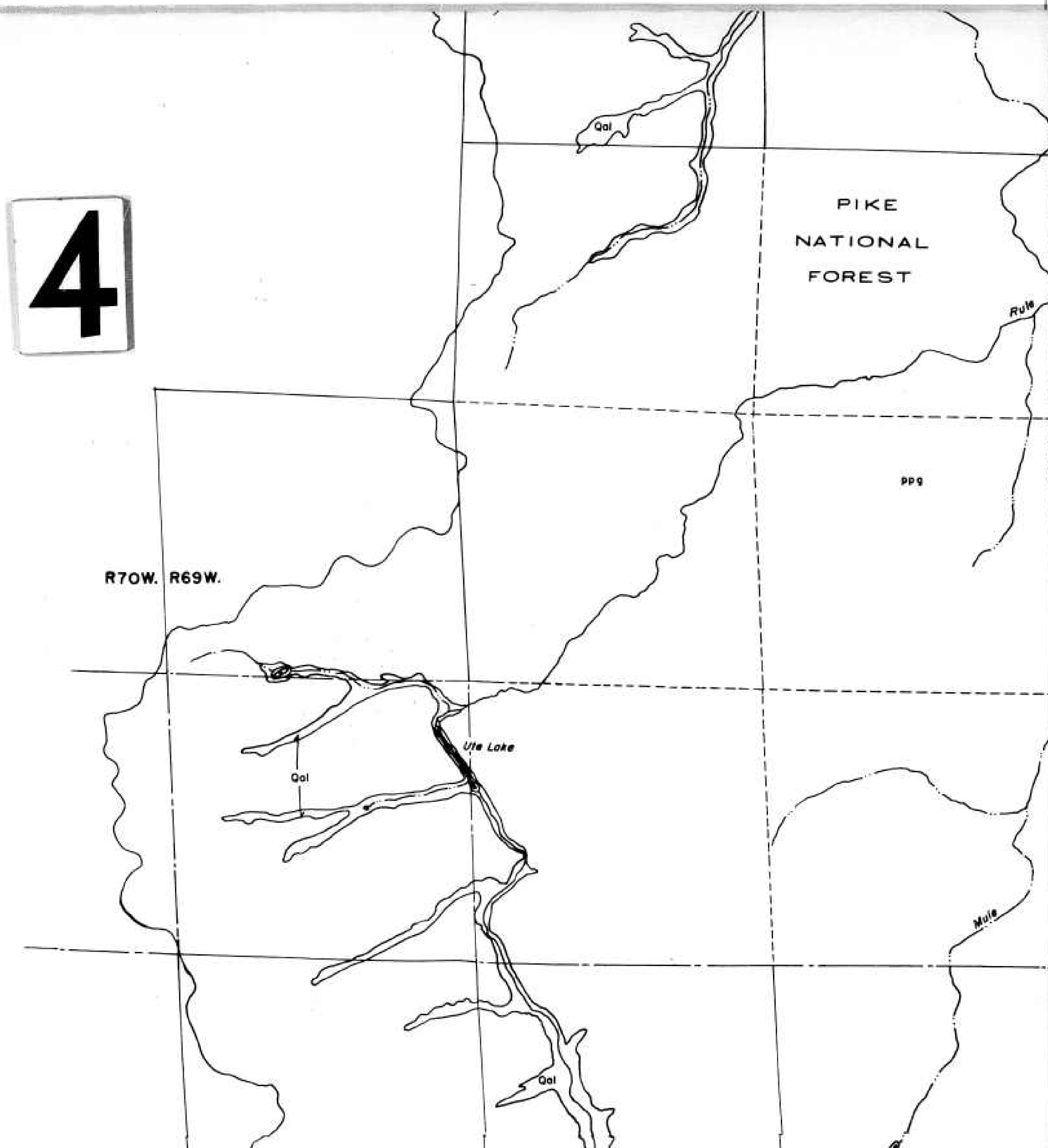
1

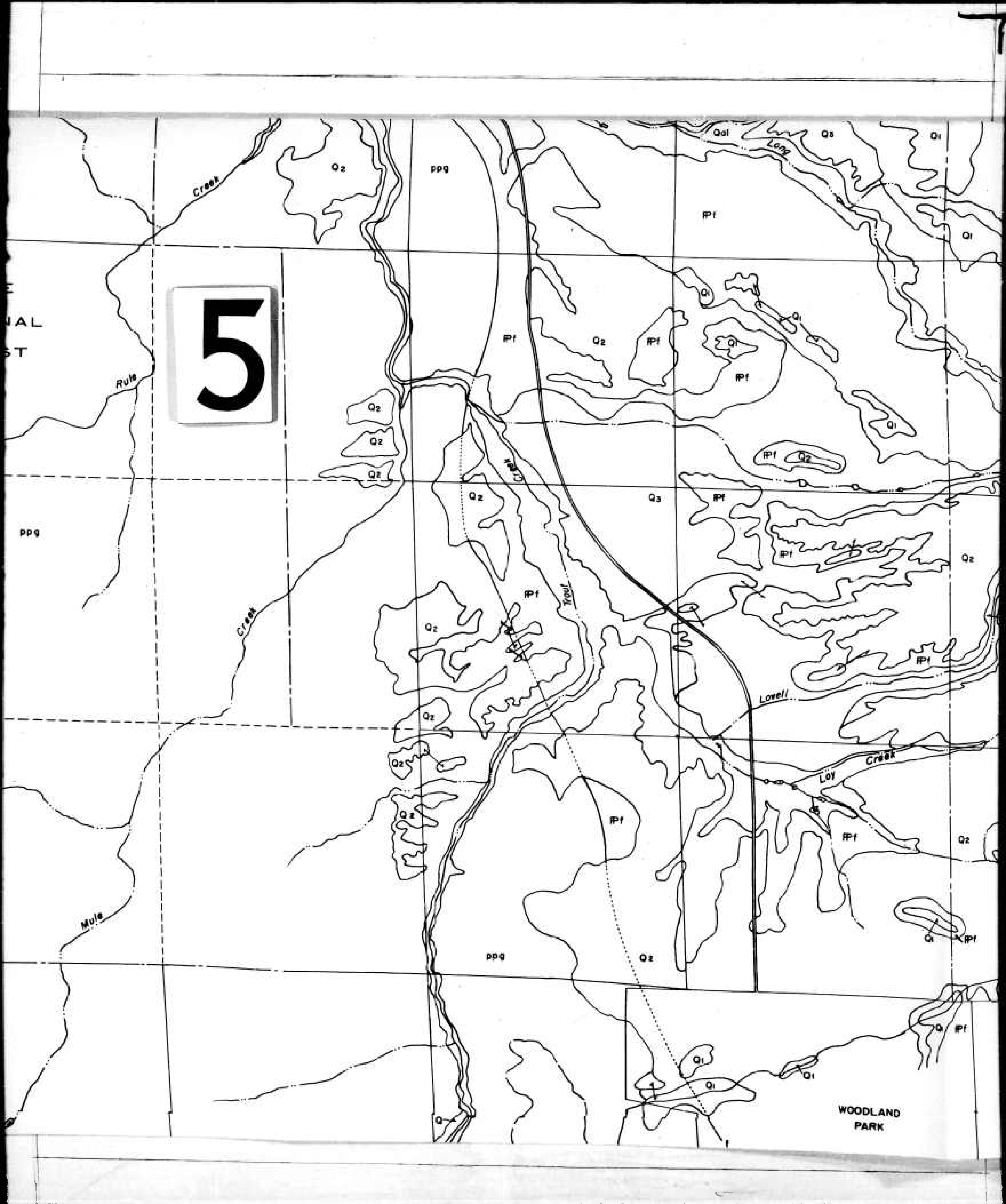


Q2
IPf
Manitou Park Lake
Q2
Q
Q2
Gulch
Q2
Q3
Qal
Quinlan
IPf
Gulch
Q2
IPf
IPf
Q3
Ryan
IPf
Qal
Q2
Creek

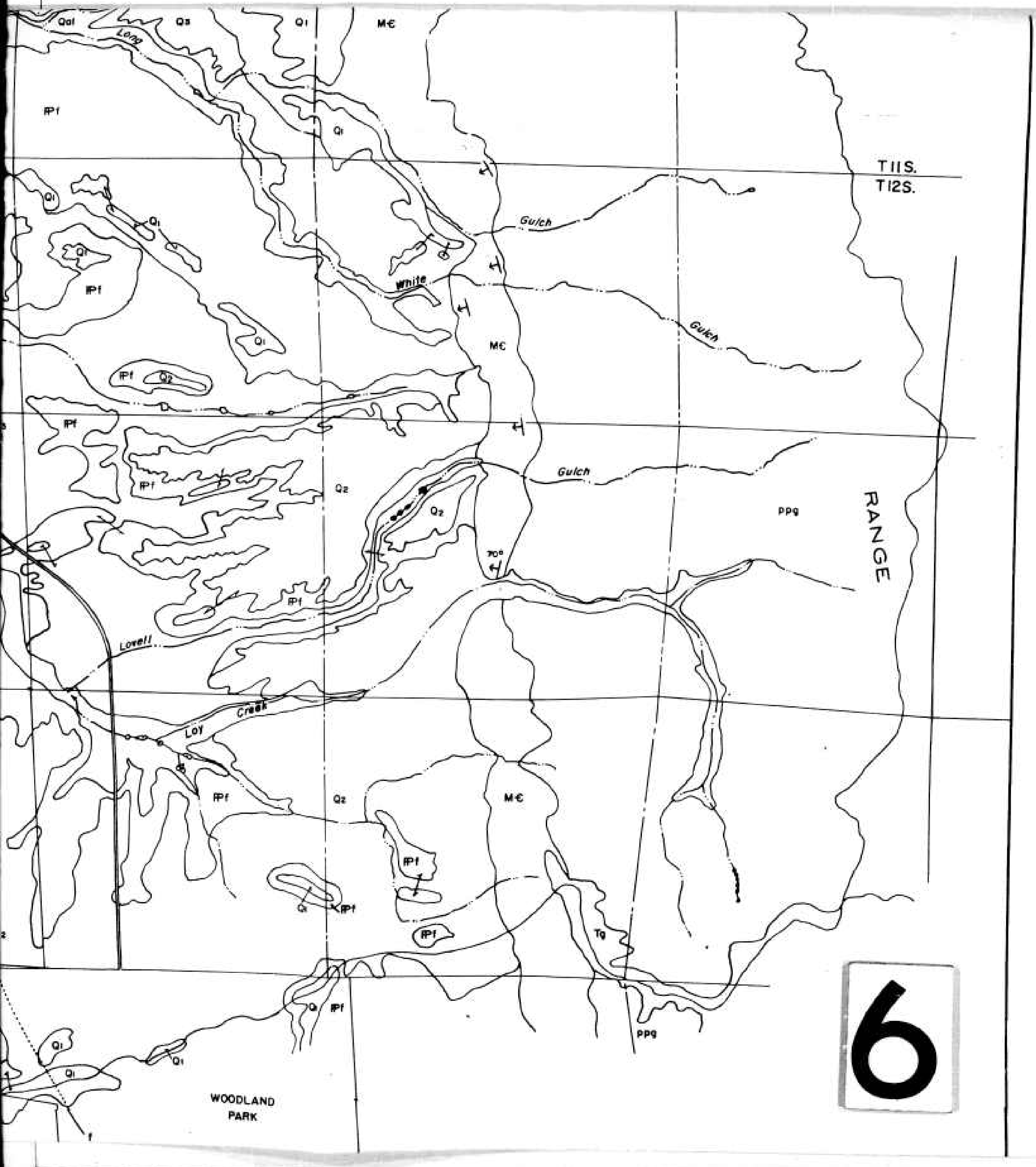

2
R69W. R68W.
Johns
Gulch
South
Johns
Gulch
Gulch
Rupp
Long
EL PASO CO.
TELLER CO.
PIKE
NATIONAL
FOREST
Q2
Q1
Q3
Qal
M€
ppg
Pf


3
R69W. R68W.
MЄ
Gulch
Q2
South
Johns
Gulch
ppq
Gulch
Rupp
PIKE
NATIONAL
FOREST
EL PASO CO.
TELLER CO.
RAMPART
Qal
Long
Q1

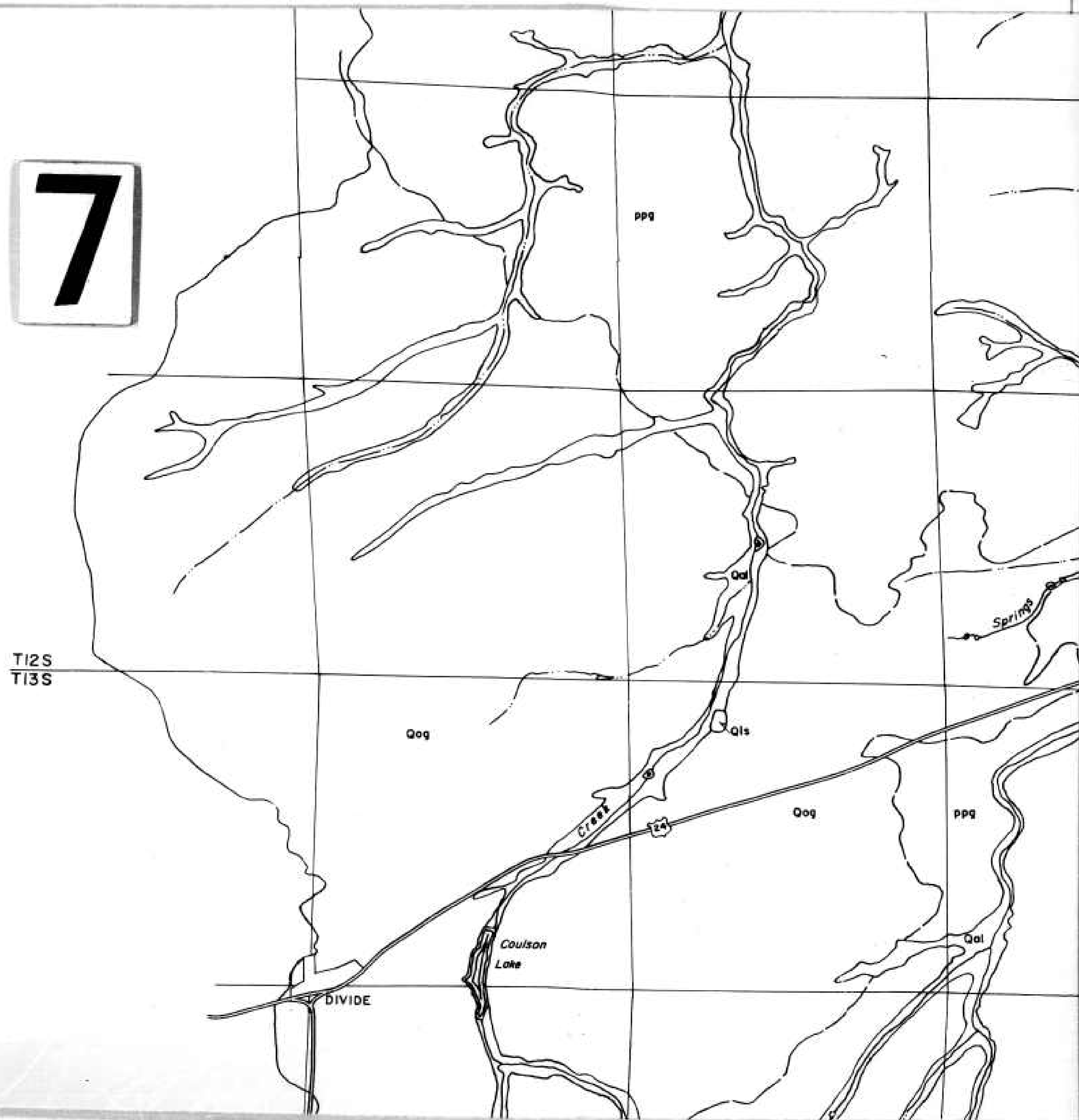

4
PIKE
NATIONAL
FOREST
Qal
Rule
ppg
R70W. R69W.
Ute Lake
Qal
Mule
Qal

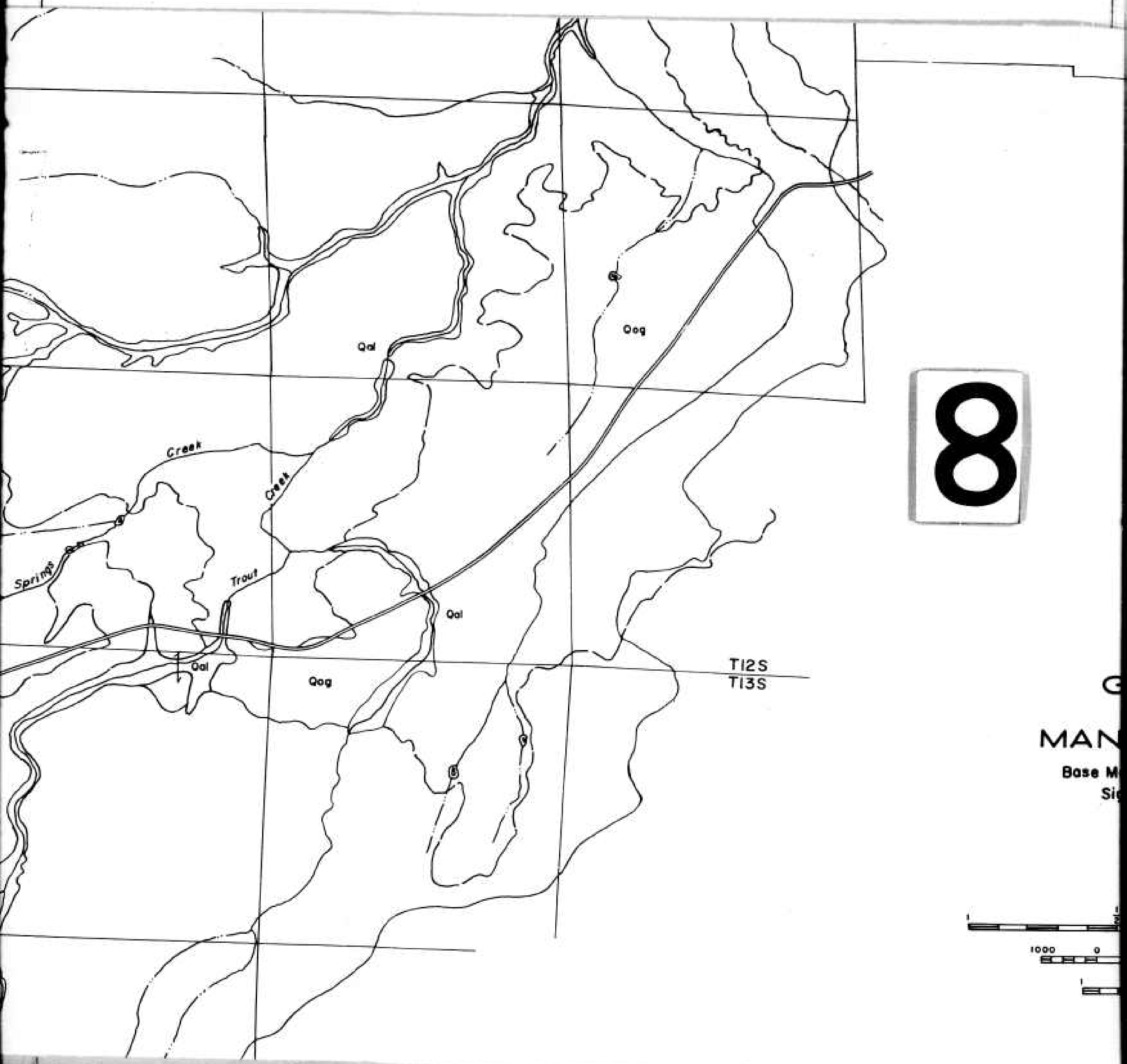


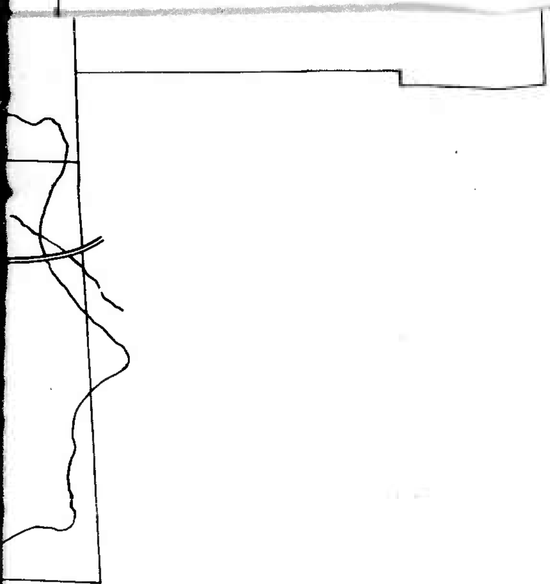
5
NAL
ST
Creek
Rule
Creek
Mule
ppg
Q2
Qal
Q3
Q1
Long
Trout
Creek
Lovell
Loy
Creek
Pf
WOODLAND
PARK


Qal
Qs
Q1
M€
Long
IPf
Q1
T11S.
T12S.
Gulch
White
Gulch
Q2
Gulch
ppg
RANGE
70°
Lovell
Loy
Creek
Q2
M€
Tg
ppg
WOODLAND
PARK
6

7


ppg
Qal
T12S
T13S
Qls
Qog
Creek
24
Qog
ppg
Springs
Coulson
Lake
DIVIDE
Qal


Qal
Qag
Creek
Creek
Springs
Trout
Qal
Qal
T12S
T13S
Qag
8
G
MAN
Base M
Si
1000
0



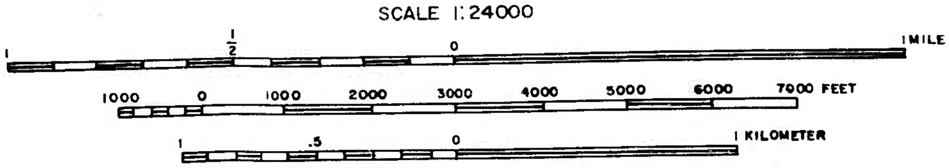
9

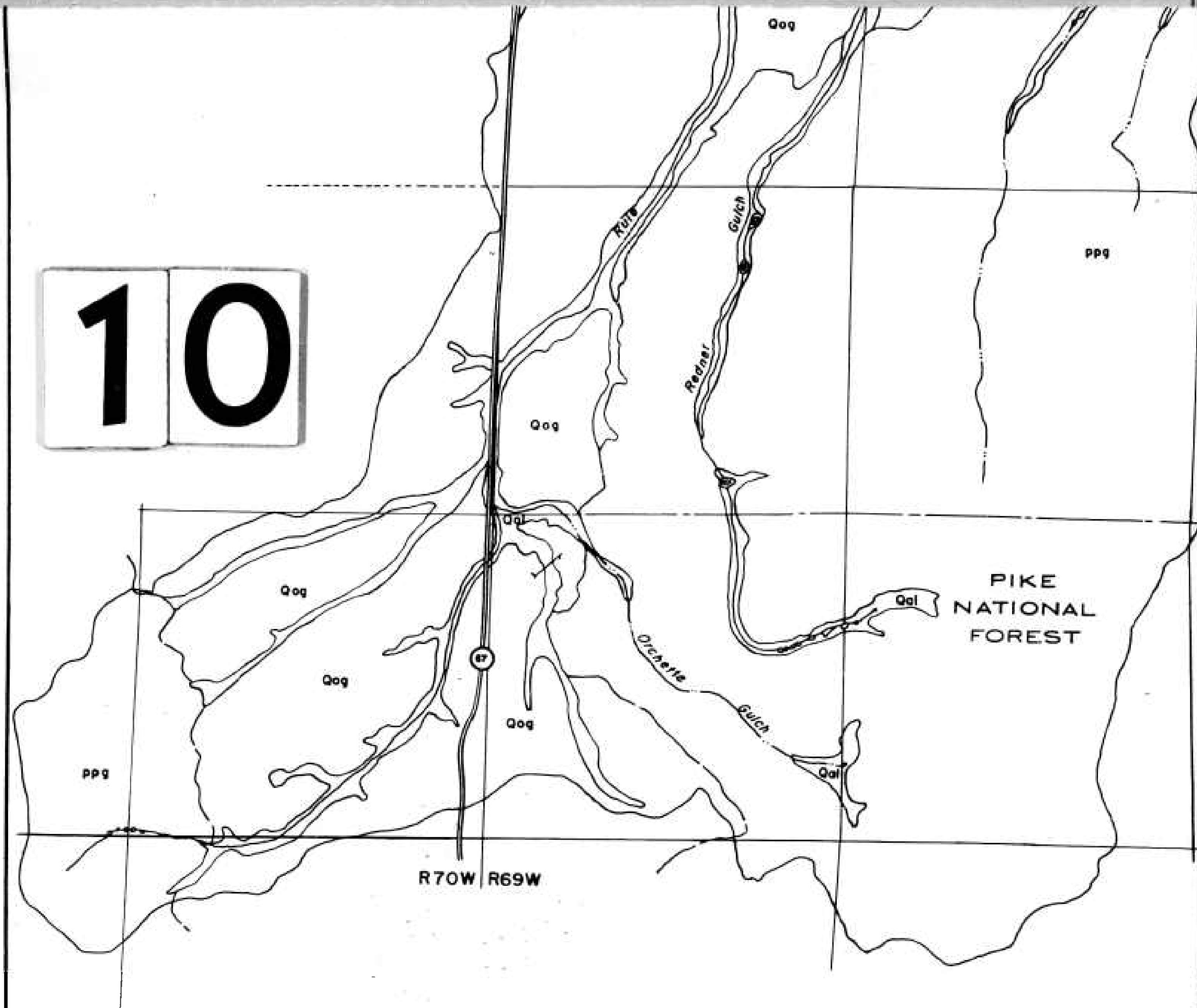
Plate 2

GEOLOGIC MAP
OF
MANITOU PARK AREA

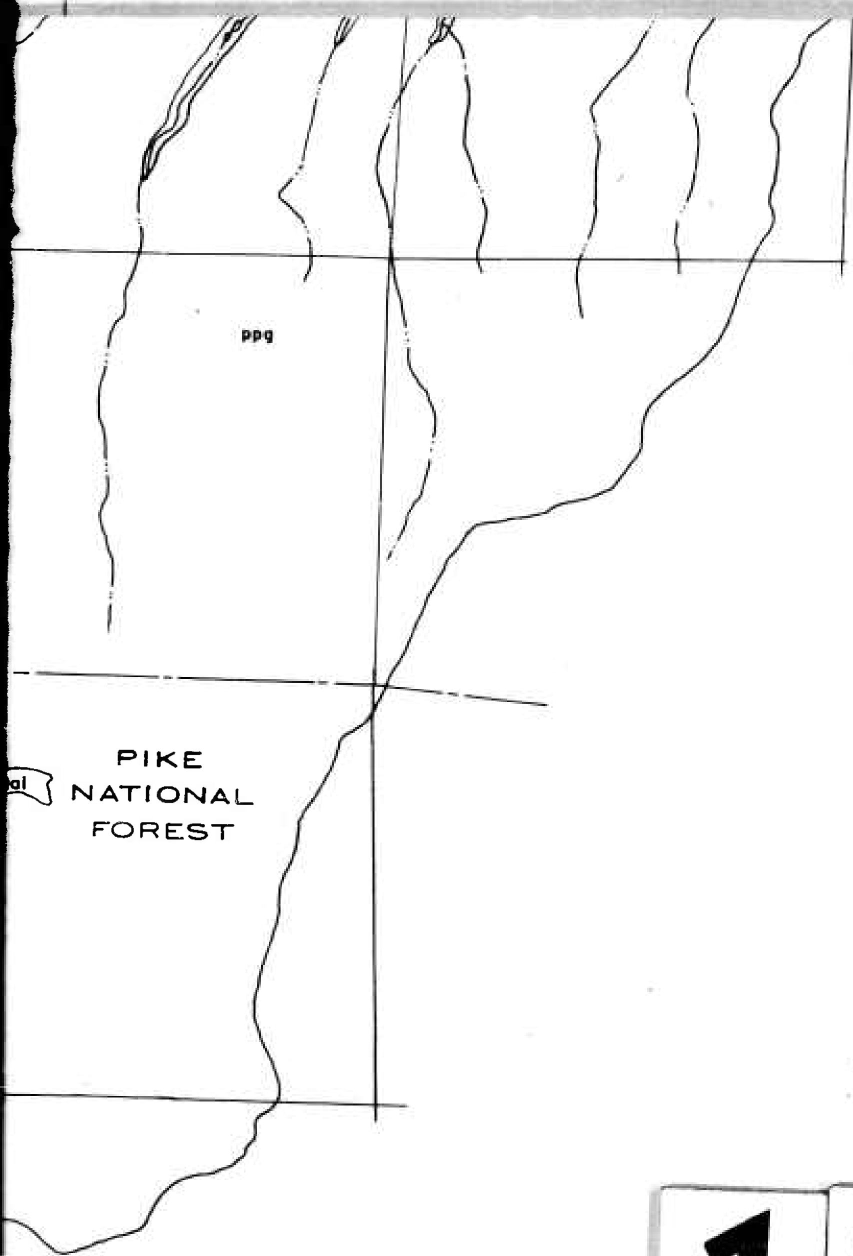
Base Map from Mount Deception, Woodland Park and Signal Butte Topographic Map Quadrangles

SCALE 1:24000





10
Qog
Rule
Gulch
Redner
ppg
Qog
Qal
Qog
Qog
Qog
ppg
Qal
PIKE
NATIONAL
FOREST
Orchette
Gulch
Qal
67
R70W
R69W



11

LEGEND

QUATERNARY	Qal	Alluvium
	Qls	Landslide Debris
	Q	Undifferentiated Alluvial Deposits
	Q_3	Youngest Pediment Deposits
	Q_2	Middle Pediment Deposits
	Q_1	Oldest Pediment Deposits
	Qog	Old Outwash Gravels
TERTIARY	Tg	Tertiary Gravels
PENNSYLVANIAN	IPf	Fountain Formation
MISSISSIPPIAN THROUGH CAMBRIAN	M€	Pre-Fountain Paleozoic Sediments
PRECAMBRIAN	ppg	Pikes Peak Granite

12