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Trend-Surface Analysis of the Basin and Range Province, and Some Geomorphic Implications

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By LAWRENCE K. LUSTIG

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A quantitative study of Basin and Range topography which provides a basis for considerations of the nature of a physiographic province, and of the relief age of ranges, the origin of pediments, and the development of mountain drainage systems in the Western United States

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TREND-SURFACE ANALYSIS OF THE BASIN AND RANGE PROVINCE AND SOME GEOMORPHIC IMPLICATIONS

By Lawrence K. Lustig

ABSTRACT

The literature on the Basin and Range province provides many qualitative assessments of the size, shape, and arrangement of mountain ranges in the region, and it is well known that the topography is nonuniform within the province. This report represents an attempt to examine quantitatively the existing regional topographic variations. Eleven topographic parameters are used for this purpose, namely (1) area of ranges to total area, (2) range length, (3) range width, (4) range height, (5) range relief, (6) range volume, (7) cumulative length of trends, (8) cumulative deviation of trends, (9) range width to length, (10) range width to height, and (11) range length to height. Measurements of these parameters were obtained from the 46 (mapped at 1:250,000 scale) topographic quadrangles that cover the Basin and Range province.

Four analytical methods of data treatment are described—manual contouring, relative-entropy function, Fourier analysis, and trend-surface analysis. The last method is used to analyze the topographic data, and trend-surface maps of first, second, and third degree are presented for each of the 11 parameters. The results show that each topographic parameter is not uniformly distributed throughout the region but varies widely with respect to range of value on a given surface of best fit. Average values of parameters on the surfaces of best fit range from 100 percent to 1,400 percent between the southern and the northern parts of the Basin and Range region.

The analytical results indicate that three areas in the Basin and Range province exhibit sufficient topographic distinctiveness to warrant delineation. These are southwestern Arizona and southeastern California, northwestern Nevada and adjacent parts of eastern California, and the eastern part of the entire region, which consists of southeastern Arizona, southwestern New Mexico, northeastern Nevada, and northwestern Utah.

This topographic distinction is the first of four geomorphic implications that are discussed. The writer concludes that the question of whether these areas should be designated as sections within the Basin and Range province or as separate provinces in their own right involves two additional questions. The first of these is the nature of hierarchical classification systems in general and the magnitude of internal variance associated with increasing rank in the system. The second is a more specific question; namely, the magnitudes of within-province variance and between-province variance that can be considered to be average values applicable to any physiographic province. Until these values and their respective ranges are assessed by quantitative means, it cannot be determined whether the within-province variance shown to exist in the Basin and Range province is normal or excessive for any province. Further work is indicated, but the results of this report suggest that any physiographic province, or finite area of the earth's surface, should be amenable to quantitative analysis by methods similar to those presented herein.

Whether the three areas within the Basin and Range region are actually sections or separate provinces, however, the magnitudes of variance of the topographic parameters are clearly sufficient to suggest three additional geomorphic implications of a regional nature.

The first of these, or second geomorphic implication, concerns the relief ages of ranges in the Basin and Range province. The variance of the regional topographic data that is indicated by the trend-surface maps implies that the topography reflects different erosional histories of ranges and, hence, different relief ages of ranges. Relief ages are not identical with radiometric dates because radiometric dates do not generally coincide precisely with dates of orogenic activity throughout the Basin and Range region. The available geological data suggest that substantial topographic differences probably existed by the end of the Tertiary and that the nonuniform distribution of Quaternary block faulting in the region served to emphasize many of the preexisting topographic distinctions. The present regional topographic variations coincide well with the known distribution of historic earthquake activity, with the Quaternary block faulting, and with the regional distribution of Precambrian and lower Paleozoic outcrops. The areas characterized by lower values of the area of ranges to total area ratio, range width, length, height, relief, and volume, and by higher values of cumulative deviation of range trend from north, are areas which by implication include ranges that have the greatest relief ages and longest erosional histories.

The known distributions of fans and pediments in the Western United States also accord well with the topographic distinctions that are made. In general, fans are more abundant in those areas characterized by large average values of range width, length, height, relief, volume, and area of ranges to total area, whereas pediments predominate in those areas where these values diminish. It is argued that the various hypotheses of pediment formation dependent upon processes that are operative on existing pediments are not relevant because they focus upon the wrong landform. Pediments are a natural and inevitable consequence of mountain mass reduction through time, and the only real "pediment problem" is the question of how this mass reduction is accomplished. The hypothesis offered in this report is that weathering predominates on the steep mountain fronts in interfluvial areas, which are probable loci of inselberg formation, whereas fluvial processes predominate in the drainage basins which are the loci of maximum mountain-mass reduction. According to this view, pediments are simply

a product of drainage-basin evolution in the mountains through time, as controlled by local base-level constraints.

Finally, it is suggested that regional drainage distinctions that are compatible with the topographic, relief age, and fan-pediment distinctions must also exist because each is a function of time. It is argued that the numbers of drainage systems and their order numbers are a function of the size, or mass, of a given range, in the absence of constraints of shape and lithology. As the range is reduced in mass through time, the average values of these variables should diminish. Drainage systems should accord with the steady state that is predicted by stochastic models and by hydraulic principles in the older and smaller ranges of greater tectonic stability, but may not yet have achieved this state within the younger and larger ranges characterized by more recent tectonic activity. The trend-surface maps of this report provide a basis for the future examination of such drainage distinctions within the Basin and Range province.

INTRODUCTION

The area discussed in this report is commonly called the Basin and Range province of the Western United States. It extends from the Sierra Nevada on the west to the Wasatch Range on the east, and from the Mexican border on the south to approximately lat. 42° N., which is the northern boundary of California, Nevada, and Utah. The boundary cannot be defined precisely, but that shown in figure 1 approximately delineates the Basin and Range province.

The term "Basin and Range province" has appeared in a legion of geologic, geographic, hydrologic, and other reports, and the general intent of any user is widely understood. Nevertheless, some contradictions exist between the standard definition of the Basin and Range province and the facts that have been set forth or surmised by many who have worked in the region. The "Glossary of Geology and Related Sciences" (American Geological Institute, 1957, p. 26) defines "Basin and range landscape" as "Landscape consisting of fault-block mountains and intervening basins." The supplement to this volume (American Geological Institute, 1960, p. 50) expands upon this by defining any physiographic province as a "Region of similar structure and climate that has had a unified geomorphic history." By combination of definitions, then, the Basin and Range province is a region of fault-block mountains and intervening basins within which the geologic structure, climate, and geomorphic history are nearly uniform.

The fact that Fenneman (1931) suggested nearly 40 years ago that the Basin and Range province be divided into five sections clearly indicates that the nonuniform characteristics of the region have long been known. In discussing various distinctions, for example, Fenneman (1931, p. 328) stated:

> The Great Basin lies north of latitude 35°30′. In this the space taken by the mountains is about half the total * * *. South of this, in California and southwestern Arizona * * * ranges are smaller and perhaps older occupying perhaps one-fifth of the space.

In a similar vein, Lobeck stated in his geomorphology text (1939, p. 557):

> In the southern part of the Basin and Range province, notably in southern California, southern Arizona, and New Mexico, the basin ranges have been almost annihilated by erosion. The presence of faults can only be inferred. The ranges are more or less symmetrical in shape and reveal none of the diagnostic features cited as topographic evidence of block faulting.

Finally, Eardley's work on the structural geology of North America includes the following summary remarks on the southern Arizona Rockies (1962 p. 425):

> A glance at the Geologic Map of the United States will show that the ranges of southern California and Arizona and southwestern New Mexico are smaller, more irregular in shape, less linear and parallel, and separated by relatively wider basins than those of western Utah and Nevada. Hence, the inclusion of the Sonoran Desert of Arizona in the Basin and Range province from a structural point of view must be made with reservations. The crisp boundaries imparted to ranges by block faulting are generally absent, and if the region is one of extensive block faulting, then the faults are older than those in Utah and Nevada, and erosion has beaten the fault scarps back considerable distances to form broad flanking pediments.

The essential burden of the foregoing statements is that substantial differences in topography and geologic structure are thought to exist between the southern and northern portions of the Basin and Range province and, by inference, that the erosional history is, likewise, nonuniform. In addition, it has been stated by many authors that although the rocks of the region range in age from Precambrian to Quaternary, Precambrian outcrops are far more abundant in the south than elsewhere. The facts, therefore, seem to be at variance with the definition of a province, and it might be asked whether the broad similarities within the Basin and Range region outweigh the differences that exist.

One purpose of this report is to examine the topographic differences that exist within the Basin and Range province in greater detail than previously attempted. It is noteworthy that the statements of the authors quoted above each contain some generalization or qualifying remarks that were necessary because of a lack of quantitative data at the time. Fenneman (1931) stated that the southern ranges occupy perhaps one-fifth of the total area; Lobeck (1939) stated that the southern ranges are more or less symmetrical in shape; and Eardley (1962) remarked that the size and shape and the degree of parallelism of these same ranges is also based on qualitative assessment to some extent. Each of these observations, however, is amenable to quantitative examination in terms of such questions as: How much smaller are the southern ranges? Are the

FIGURE 1.—Index map of the Western United States, showing the approximate boundary of the Basin and Range province and the distribution of Precambrian and lower Paleozoic (Cambrian and Ordovician) outcrops. The province area shown in central New Mexico and the westernmost part of Texas was omitted from this study. Note the correspondence of the outcrop areas to areas of greatest relief age discussed in text and to those exhibiting distinctive values of topographic parameters on the trend-surface maps (figs. 9–41).

The simplest presentation would consist of an orthogonal array of data values in which each particular horizontal or vertical line of points had the same value and was adjacent to another line of points of different value, the difference in value being equal to the selected contour interval. No interpolation between adjacent data points would be required, and the resulting contour map would consist solely of a series of equally spaced horizontal or vertical isopleths. The important point is that no subjectivity would be involved in the construction of the map; thus, maps produced by any number of investigators would necessarily be identical.

The hypothetical ideal cited above seldom, if ever, actually occurs, however. The topographic data from the study reported here reflect considerable variation of each parameter across the entire study region. The construction of isopleths from such data cannot be objective because the map produced by a given investigator is not precisely reproducible. In geophysical or other studies in which the location of specific high or low values is of importance, the tendency for an investigator to produce as many contour closures as possible is inherent. If, on the other hand, the basic goal of the investigation is to determine regional trends or gradients, the opposite tendency will exist, namely to produce the minimum number of closures from the same set of data. Subconsciously or otherwise, two investigators can easily produce startlingly different maps from the same set of data by manual-contouring methods.

The use of moving averages does not really eliminate this difficulty because it essentially represents an attempt to reduce one of the components of the total variance, namely local variance, and thus emphasizes regional trends or gradients. This is particularly true if successive moving averages are taken from the original data values. Regardless of the averaging scheme employed, the isopleth maps produced will always reflect some additional degree of subjectivity that is a function of map construction. For this reason, such maps were not constructed and employed for this study, despite the fact that discrimination of regional trends was an essential goal.

RELATIVE-ENTROPY FUNCTION

The mapping of variables by the manual-contouring method can be described as a univariate method because only the areal distribution of single variables, or perhaps some simple ratios, can be reflected by isopleth maps. In the study reported here, for example each of the 11 variables can be investigated on separate distribution maps of a given type; these would be classified as univariate maps. If, however, one wishes to treat the variables as parts of a multicomponent system, use of the relative-entropy function can, in certain problems, provide a quantitative and analytical technique.

In thermodynamics, the entropy of a system is a measure of the free-energy variation, and this concept has been applied in a general way to open and closed geomorphic systems by Chorley (1962). An alternative consideration of entropy in terms of the summation of the logarithms of probabilities of the states of a system has been used by Leopold and Langbein (1962). This usage, dervied from statistical mechanics, is very close to the significance of entropy in the relative-entropy function, but a better understanding can be derived from information theory.

As shown by Raisbeck (1963), if there is some information source, such as a transmitter or an experiment, which can yield n equally likely outcomes or messages, then the information associated with any given message, n, is log n. The reason for this can be seen if one considers a simple model (fig. 3) in which an information source, A, consists of two independent sources, B and C. If the possible outcomes or messages from B and C are n_B and n_C, and if these are equally likely, then the total number of possible outcomes, n_A, is equal to the product of n_B and n_C. The information transmitted by source A, however, must equal that transmitted by the sum of sources B and C. Therefore,

$$f(n_A)=f(n_B)+f(n_C), \text{ and} \tag{1}$$

$$n_A=n_B n_C. \tag{2}$$

One solution, then, is

$$f(n_A)=d \log n_A, \tag{3}$$

where d is some constant.

With this fact in mind, if one next considers a model in which the outcomes are not equally likely, the relationship of entropy to information content becomes clear. If an information source (fig. 4) generates n equally likely outcomes which can be segregated into two unequal groups, n_A *and* n_B, then if we ask whether a given output or message will be in group n_A or group

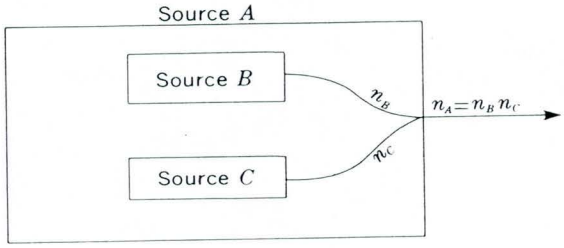

FIGURE 3.—Diagrammatic model of information source A that is composed of sources B and C, which yield equally likely outcomes n_B and n_C, respectively. (After Raisbeck, 1963, fig. 1.3.)

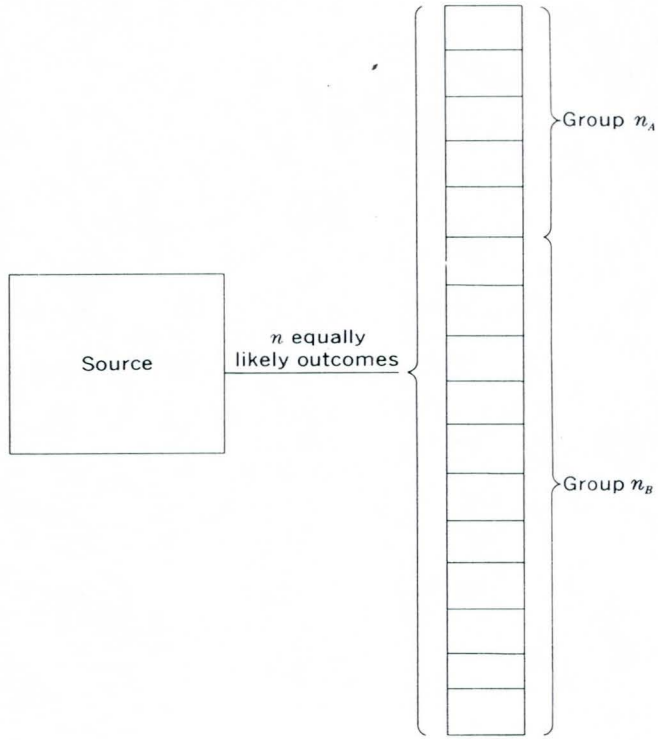

FIGURE 4.—Diagrammatic model of an information source that generates two groups of outcomes, n_A and n_B, which are not equally likely. (After Raisbeck, 1963, fig. 1.4.)

n_B, the probabilities of unequal outcomes must be investigated. The probability that a given message is within group n_A *is*

$$p_A=\frac{n_A}{n_A+n_B}, \tag{4}$$

and the probability that it is within group n_B is

$$p_B=\frac{n_B}{n_A+n_B}. \tag{5}$$

These expressions are simply statements of the fundamental definition of probability—that the probability of the occurrence of any given event is equal to the number of outcomes that will produce that event divided by the total number of possible outcomes. The information associated with any of the equally likely messages within group n_A is log n_A, and that associated with the messages within group n_B is log n_B. This information, however, can only be transmitted during a part of the total time n, namely during time n_A/n for a message in group n_A, and time n_B/n for a message in group n_B. Therefore, if information is defined as H, then

$$H=\log n-\frac{n_A}{n}\log n_A-\frac{n_B}{n}\log n_B. \tag{6}$$

Because n can be taken as unity, and because n_A/n and n_B/n are equal to the probabilities p_A and p_B, respectively,

$$H=-p_A \log p_A-p_B \log p_B, \tag{7}$$

or, in the most general form,

$$H=\sum_{i=1}^{N}-p_i \log p_i. \tag{8}$$

This expression, relating the information content of a source or system to the sum of the products of the probabilities and the logarithms of the probabilities of the components of that system, is essentially identical to the statistical definition of entropy and to the relative entropy function. The latter, as defined by Pelto (1954), is

$$100H_r=-\frac{100\sum p_i \log p_i}{H_m}, \tag{9}$$

where H_r is relative entropy, H_m is maximum entropy, and the constant 100 is simply inserted to obtain percentage results directly. For a system that consists of any finite number of components, one need only convert the values of each of these components to percentages and substitute these percentages for probabilities to obtain the $p_i \log p_i$ products in the numerator of the relative-entropy function. Maximum entropy, H_m, is a function of the number of components in the system and occurs when the probabilities $p_1, p_2, p_3, \ldots, p_n$ are equal. For a three-component system, for example,

$$H_m=-3(0.33 \log 0.33)=1.0986. \tag{10}$$

The applicability of the relative-entropy function to three-component facies mapping has been illustrated by Forgotson (1960) and a more general discussion has also been provided by Miller and Kahn (1962). The latter applied the relative-entropy function to mapping of an eight-component foraminiferal fauna and successfully revealed certain aspects of the areal distribution of facies that were not apparent from more conventional maps. Additional illustrations of the uses of entropy-function mapping are not abundant in the literature, and to the writer's knowledge no attempt has been made to apply the technique to geomorphic problems. Nevertheless, it represents a potentially useful mapping technique and was considered as such during the conduct of the study reported here.

If one wished to consider such topographic characteristics as the lengths, widths, and heights of ranges as components within systems of ranges, it would be entirely possible to convert the absolute values of these variables to percentages, compute relative-entropy val-

ues for individual ranges or topographic maps, and produce a relative-entropy map. It is noteworthy, however, that in the context of information theory, entropy refers to the degree of intermixing of the components of a given system. That is, maximum entropy is equivalent to minimum information, and this occurs either when the degree of intermixing of end members is greatest or when the probabilities associated with each of the components are equal. Conversely, maximum information is gained when entropy is a minimum, which occurs when all of the components or end members save one are equal to zero or are absent. Therefore, the relative-entropy function is a most efficient quantitative mapping tool when treating a set of components or variables, each of which ranges from 0 to 100 percent at some point within the system, or within the region studied. The components need not, of course, reflect the entire range from 0 to 100 percent, but a fairly wide range of values must be encompassed. Figure 5 shows the entropy distribution for a three-component system. High entropy values dominate the central part of this triangular representation of the relative-entropy distribution. For maximum information and low entropy values, two of the three components must tend toward zero; otherwise a corner of the total field will not be approached.

The topographic variables that are discussed in this report do not lend themselves to the most efficient usage because any combination of components tends to occupy high or moderate values of the relative-entropy distribution field. Like isopleth mapping, relative-entropy mapping was also considered and discarded in search of a means to extract the maximum information from the data by quantitative analytical techniques.

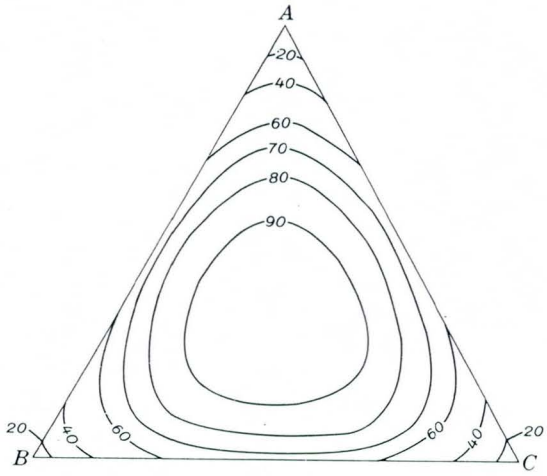

FIGURE 5.—Distribution of relative-entropy values for a three-component system. Minimum information is associated with maximum entropy values, at center of the field where the three components are equally abundant. Maximum information is associated with minimum entropy values at each of the three vertices.

FOURIER ANALYSIS

Fourier analysis is another potentially useful quantitative mapping technique which is most applicable to regional data containing oscillatory characteristics. This is most easily understood from consideration of the two-dimentional graph—that is, the graph of any function in an x, y coordinate system.

First, it should be recalled that specific functions can be approximated by expansion of terms in a Taylor or Maclaurin series. For example,

$$\frac{1}{1+x}=1-x+x^2-x^3 \ldots, \text{ or} \tag{11}$$

$$e^x=1+x+\frac{x^2}{2!}+\frac{x^3}{3!}+\ldots. \tag{12}$$

In general, if $y_1=a_0+a_1x$, $y_2=a_2x^2$, $y_3=a_3x^3$, and $y_n=a_nx^n$, then the Taylor expansion of $y(x)$ is

$$y(x)=y_1+y_2+y_3+\ldots+y_n. \tag{13}$$

This means that the graph of a function $y(x)$ can be approximated by the graphs of y_1, which is a straight line, y_2, which is a quadratic parabola, y_3, which is a cubic parabola, and other functions of successively higher order. The greater the number of terms that are considered the better the approximation to the original function, $y(x)$.

If the function is periodic, however, then it may best be approximated by a series of terms, each of which is also periodic. This was first shown by Fourier in 1807, who assumed that a function, $y=f(x)$, could be approximated by an expansion into sine and cosine terms, namely

$$f(x)=\frac{1}{2}a_0+a_1\cos x+a_2\cos 2x+a_3\cos 3x\ldots$$
$$+b_1\sin x+b_2\sin 2x+b_3\sin 3x+\ldots, \tag{14}$$

or that,

$$f(x)=\frac{1}{2}a_0+\sum_{n=1}^{\infty}a_n\cos nx+\sum_{n=1}^{\infty}b_n\sin nx. \tag{15}$$

The terms in this expansion of $f(x)$ therefore make n complete oscillations in the interval $-\pi$ to $+\pi$ and the problem involved is finding the values of a_0 and the coefficients $a_1, a_2, a_3, \ldots, a_n$, and $b_1, b_2, b_3, \ldots, b_n$. The problem is simplified by certain properties of the Fourier series which are termed "orthogonality conditions." These are—

$$\int_{-\pi}^{\pi}\cos mx\cos nx\,dx=\int_{-\pi}^{\pi}\sin mx\sin nx\,dx, \text{ which}$$
$$=0 \text{ (when } m\neq n),$$
$$=\pi \text{ (when } m=n), \text{ and} \tag{16}$$

Such province classification or boundary delineation, by methods akin to those described in this report, or others, must remain somewhat arbitrary. That is, some arbitrary choice of value for some parameter or combination of parameters must be made to fix any required boundary. The chief virtues of such procedure, however, are objectivity, reproducibility, and the facilitation of quantitative comparison of within-province variation and between-province variation.

Only within-province variation has been treated in this report. As previously stated, this writer would tend to define three physiographic provinces within the Basin and Range region on the basis of the quantitative data obtained. Others might prefer to term these three areas "sections," as did Fenneman (1931), who described five subdivisions in the Basin and Range province. The discrepancy in numbers of subdivisions is not at issue here; rather, the choice between the use of the terms "section" and "province."

The choice is not merely a matter of semantics but one that basically involves the very nature of classifications and of hierarchical systems in general. In any such system, the within-class variance will inevitably increase with an increase in order or rank. Therefore, the total internal variance at the highest levels, such as within the kingdom ranking of the zoologist, will be large indeed. But beyond some critical magnitude of total internal variance, the utility of a given classification may be destroyed.

To classify physiographic provinces and sections one basically needs to know the magnitudes of internal topographic variance allowable within each rank. The present writer has shown that average values of such parameters as range volume and the area of ranges to total area ratio exhibit a variation that is as much as 1,300 to 1,400 percent. The rest of the parameters exhibit a minimum variation of 100 percent. The question to be answered is whether such topographic variance is common to the province-level rank. If so, then the areas discussed in this report can be designated as "sections" in a hierarchical scheme. If this variance is excessive, however, the Basin and Range province as we know it should be subdivided into several provinces.

The answer to the question posed is beyond the scope of this report. There are no quantitative treatments of physiographic provinces that would enable one to state the average magnitude of topographic variance associated with the province rank and thereby to determine whether the known variance in the Basin and Range region is excessive. The writer recommends, therefore, that a province-by-province evaluation be undertaken to determine average values of within-province variation and between-province variation. In addition to the problem of proper subdivision of the Basin and Range region, several other questions of interest might be resolved.

To examine the degree of topographic similarity between the folded mountains of the Appalachian region, for example, and the Coast Ranges of California would be useful. Despite known differences in the geological histories of these two regions, the landform map of the National Atlas Series (U.S. Geological Survey, 1966) indicates that topographic similarity exists. Quantitative examination of these two areas might therefore lead to some assessment of the validity of the inference that similarity of topography implies similarity of geomorphic history. In another vein, the Basin and Range province of North America might be compared to its counterparts elsewhere in the world. The Dasht-e-Lut and Dasht-e-Kavir of Iran, or the basin and range regions of Afghanistan and West Pakistan, are among the more obvious choices for such an undertaking. This exercise would have more direct bearing upon the range of topographic values that exist within such areas.

In summary, further work is indicated, but the results of this report suggest that any physiographic province or finite area of the earth's surface is amenable to quantitative examination. One of the desirable goals of such efforts should be the establishment of quantitative standards of within-province and between-province variation, as well as the objective delineation of province boundaries.

AGE OF RANGES

The treatment of topographic data presented in this report supports the view of many workers that the ranges in the Basin and Range province are probably of different ages. This conclusion is indirectly implied by the topographic data, but it is supported by many other lines of evidence, some of which are discussed here. First, it should be recalled that the ranges in central and western Nevada and in part of eastern California are longer, wider, higher, and more closely spaced than are those of southwestern Arizona and southeastern California. An idealized cross section through a basin and two adjacent ranges in each of these two general categories of regions would resemble that shown in figure 42. The question is why this difference exists.

Among the possible explanations, three are most prominent. First, the difference in topographic relief and range spacing could be attributable to differences in depth of basin fill. Figure 42 shows that an increase in depth of basin fill would, for the larger ranges, produce topographic expression similar to that presently exhibited by the smaller ranges. Essentially, burial of

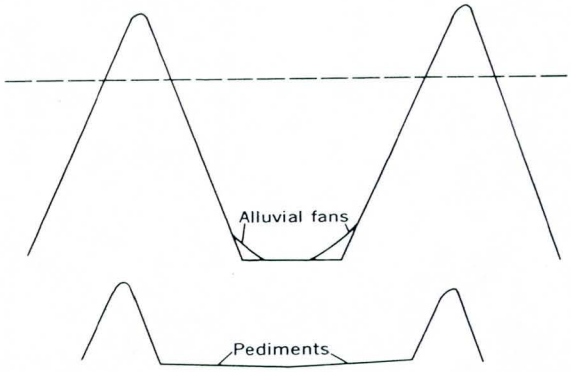

FIGURE 42.—Idealized cross section of two ranges and an intervening basin in two different parts of the Basin and Range region. Upper part of sketch shows ranges of large dimension and close spacing which occur in north-central and northwestern Nevada and eastern California, where alluvial fans predominate. Lower part of sketch shows ranges of small dimension and wide spacing which occur in southwestern Arizona and southeastern California, where pediments predominate. Dashed line in upper part of sketch illustrates how these topographic differences could be achieved by varying depths of basin fill. Area between ranges in lower part of sketch, however, is known to contain surface or near-surface pediments, and the depth-of-fill hypothesis is therefore untenable.

the larger ranges by alluvium would leave only their tops exposed, and the apparent range spacing and size would change accordingly. Aside from consideration of the range erosion necessary to accomplish this end, the basic question is whether the existing data on depths of fill in the Basin and Range area will support such an interpretation. Such data are very sparse, as indicated by the recent basement map of North America (American Association of Petroleum Geologist and United States Geological Survey, 1967), which is largely blank over the part of the Western United States considered here. The various geophysical surveys that have been made in the northern and southern parts of the Basin and Range area, however, will certainly not sustain the idea that depths of fill differ drastically. Moreover, as is well known, the southern basins have a history of through-flowing drainage, whereas the northern basins do not, and this has permitted the transportation of sediment out of the southern basins at various times. This also mitigates against the suggestion that the smaller and more widely spaced ranges are a consequence of greater depths of basin fill. The depth-of-fill explanation seems therefore to be untenable on a regional basis and may be disregarded.

A second possibility is that the differences in topographic attributes are related to basic structural differences. Specifically, the spacing of faults and the magnitudes of uplift differed in the several parts of the Basin and Range area to such an extent that the topographic differences are directly related to structural conditions. The rather voluminous geological literature on the Basin and Range area clearly suggests that this hypothesis is equally improbable. In general, faults and fault scarps are more commonly observed in the northern part of the region, and they are in zones that are reasonably close to the mountain blocks. This is not true of the southern part of the region, where broad bedrock pediments are far more common, and evidence of faulting is obscure. The argument would require the existence of fault planes between the pediments and the ranges which they abut; faults in such locations have not been observed. If this second hypothesis is disregarded, the remaining alternative is that the ages of the ranges generally differ in the Basin and Range area.

Reference to the "age" of ranges in the context of this discussion means relief age or the time span since topographic expression was achieved. Clearly, a given relief age need not be coincident with the radiometric age that may exist for the plutonic or volcanic rocks in a given range. In fact, in this context a radiometric age can only serve as a limiting value for the relief age of a range. That is, the radiometric age must be greater, for it represents either the time of crystallization of a specific part of a given magma or the time of extrusion of a given lava. Damon and Mauger (1966) and Damon (1967) have discussed the chronology of events in the Basin and Range province in such a way that the question of the relief ages of ranges is somewhat obscured. Some discussion of this point is therefore warranted.

Basically, these authors presented potassium-argon dates for volcanic and hypabyssal plutonic rocks that have a bimodal distribution in time. One peak of the distribution occurs 60–70 million years ago and this represents Late Cretaceous or Laramide time. The second peak occurs 20–30 million years ago, in Oligocene to Miocene, or late Eogene to early Neogene time. They generally concluded that these radiometric-age peaks are coincident with times of orogeny throughout the Basin and Range province and related the two time peaks to the classical pulse-of-the-earth hypothesis, which demands synchroneity of magmatism and orogeny. Whether such synchroneity exists depends upon the scale of events that is considered and upon whether the equation of magmatism with orogenic activity is actually justified.

Related to the first of these factors, the scale of events, each of the radiometric age-distribution peaks is associated with a chronological range of values of considerable magnitude. Thus, the Laramide magmatism (Damon and Mauger, 1966; Damon, 1967) occurred between 50 and 90 million years ago, and the Tertiary episode occurred between 5 and 45 million years ago. The bimodal distribution of ages is not questioned here, but the range of values about each mode—namely 40

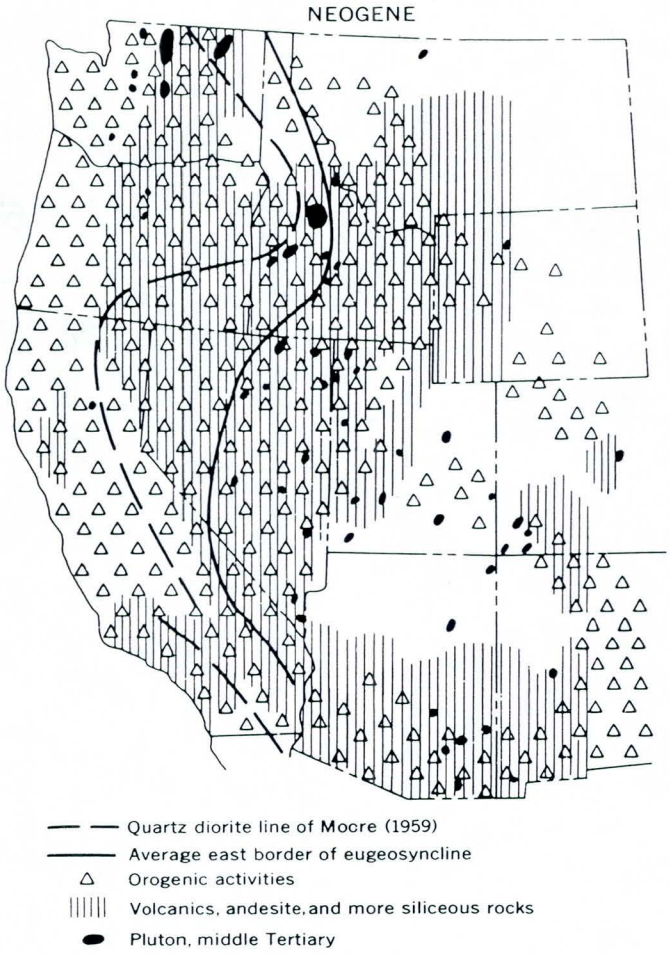

FIGURE 44.—Volcanism, tectonism, and plutonism during the Neogene in the Western United States. (After Gilluly, 1965, fig. 7.)

and in western Utah and New Mexico. The quantitative topographic data and trend-surface maps (figs. 9–41) presented in this report also coincide notably well with these regional structural patterns.

As a final point bearing upon the relief age of ranges in the Basin and Range area, figure 1 is instructive. Although highly generalized and locally inaccurate because of the small scale of the compilation (1:7,500,000), this map (fig. 1) clearly shows that the distribution of Precambrian and lower Paleozoic rocks in the Basin and Range area is nonuniform. It can be seen that outcrops of rocks of these ages occur primarily in the southern part of the region and in eastern Nevada and western Utah. These are precisely the areas which correspond to minimal recorded earthquake activity (fig. 45) and Quaternary block faulting, and the logic of Occam's razor would suggest that the relief ages of ranges in these areas are greatest. That is, these stable regions have been subjected to the longest time spans of erosion; hence, the oldest rocks are exposed within the ranges that exist.

In summary, the geomorphic implication that can most reasonably be drawn from the trend-surface maps of Basin and Range topography is that the relief ages of ranges in the region are different. Differing time spans of erosion is the simplest explanation for the variance of length, width, height, area, volume, relief, and trend of ranges that was noted previously, and this explanation accords well with the known geological history of the region. Because durations of topographic expression and of consequent erosional periods have varied within the region, a third inference can be drawn from the topographic data. This concerns the origin and distribution of pediments, which are discussed below.

ORIGIN OF PEDIMENTS

The subject of pediments and theories of their origin occupies a vast number of papers in the literature on the Basin and Range area and other parts of the world. Most of these papers have been cited elsewhere (Lustig, 1967) and will not be specifically discussed here, but a recent review of the pediment literature by Hadley (1967), which appeared after the text of this report was written, is worthy of note. Several of the better-known theories of pediment formation are probably incorrect. As an example of this generalization, consider the often-cited claims that sheetflooding is the process responsible for pediment production. Such claims are based solely on two or three reports of early vintage which described wagons overtaken by vast "walls of water" in the Western United States. The wagons in question were all traversing roads that bordered the lower reaches of a pediment surface, in low areas where the effect of channelized flows on the pediment surface combined to produce high water. This writer has never observed an unconfined "wall of water" on a gently sloping desert surface and is unacquainted with any who have observed such a phenomenon. Moreover, to attribute the origin of bedrock surfaces to sheetflows is to confuse cause and effect, even supposing that the shallower channels on these surfaces are occasionally overtopped during intense runoff events. The surfaces must necessarily predate the runoff events in question.

Lateral erosion is another frequently offered explanation. This hypothesis primarily treats the migration of channels that exist on pediment surfaces. No doubt, channels will migrate with time on these surfaces, and some erosion will therefore be accomplished, but the part of any pediment that abuts the mountain front cannot be explained in this manner. The hypothesis virtually requires that streams emerge from a given mountain range and, on occasion, turn sharply to one side or the other to "trim back" the mountain front in interfluvial areas. Such stream paths, nearly perpendic-

ular to a sloping surface, would defy the laws of gravity and have not been observed except those in areas where drastic tilting has occurred. This is not surprising, because knowlege of the triangle of probabilities (fig. 46) suggests that the least probable path in a two-dimensional consideration is precisely the right-angle path required of a stream emerging from a given range. This triangle can be constructed by moving a marker to either the left or the right of any given origin in successive steps. Each given probability is equal to one-half the sum of the two numbers above it, and the probability at any point can be computed from the following general formula:

$$Z_n k = \tfrac{1}{2}\,[Z_{n-1}(k-1) + Z_{n-1}(k+1)], \qquad (68)$$

where $Z_n k$ is the probability that the marker will be at point k after n trials. Thus the path of greatest probability coincides with the central portion of the triangle (fig. 46). In the absence of constraints the three-dimensional natural condition would most assuredly be best represented by a stream that emerges from the mountains and flows downslope to the basin floor, or pediment margin, with minimum deviation from a central path. Hence, lateral planation undoubtedly occurs on pediment surfaces, although quantitative data indicating the effects of the process are lacking, but it cannot account for the existence of pediments as such.

It has also been proposed that pediments result from parallel slope retreat of the mountain front. Slope retreat of this type is itself a topic that occupies much literature, and the more ardent champions of this process argue for parallel retreat of cliffs on a continental scale. The writer's observations in several deserts of the world suggest that few, if any, escarpments are not dissected by prominent drainage systems. This is true even in the driest regions, such as the Namib Desert in South West Africa or the Tuwaiq escarpment of central Arabia. The precipitation is about 2 inches per year in both areas. The existence of drainage basins in the mountain ranges is of central importance to the various pediment arguments. These basins are the loci of the most effective erosional processes that operate on mountain ranges in the Basin and Range region or elsewhere. The mountain fronts may well retain some characteristic slope angle that reflects rock strength, structure, weathering characteristics, and other variables, and they may retreat at this angle. This does not prove, however, that ranges are primarily reduced by parallel retreat of escarpments. This point will be pursued later.

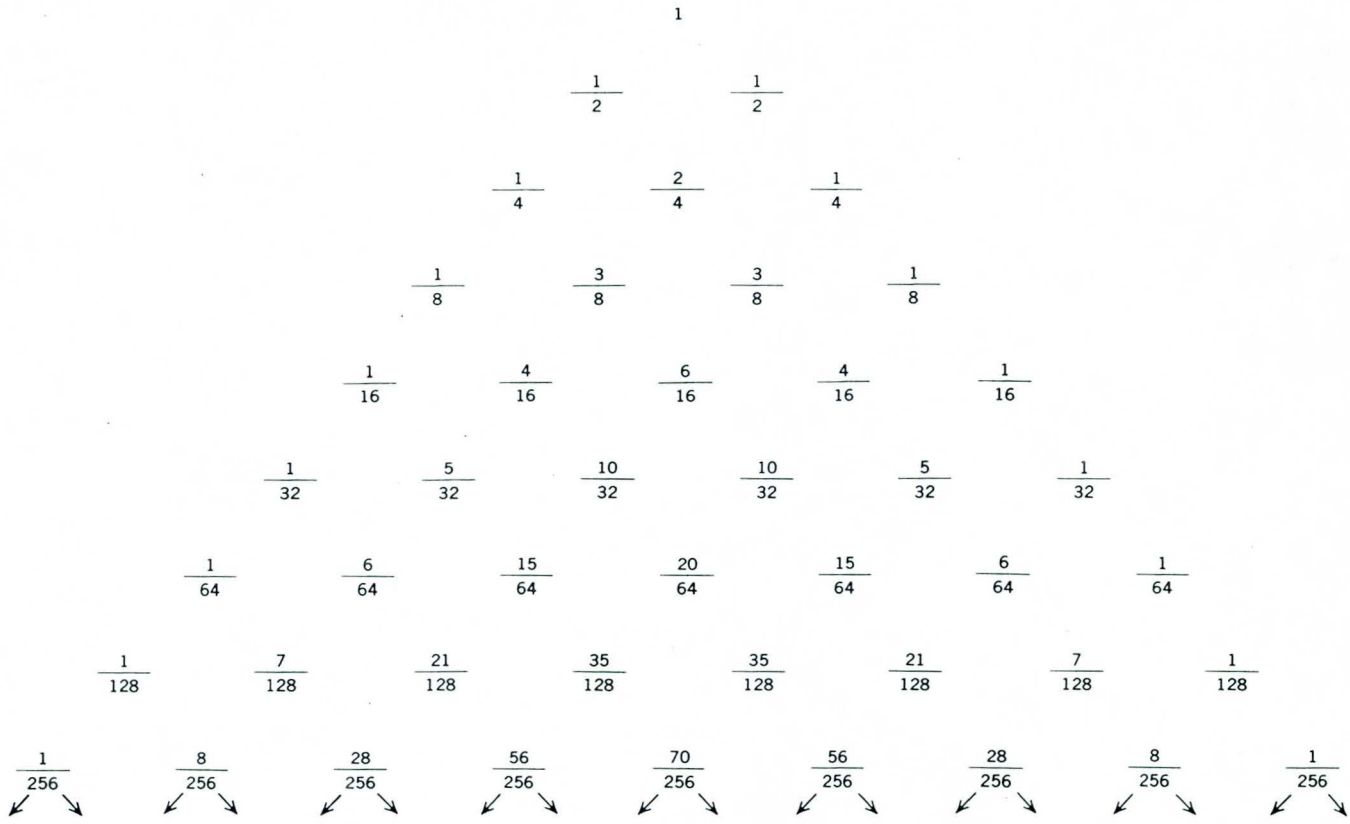

FIGURE 46.—The triangle of probabilities, showing the probability associated with any point on a two-dimensional random walk. The origin is represented by the apex of the triangle, which has a probability of 1.

Although additional arguments presented in literature concern the origin of pediments, the above examples will suffice here. The many discussions of pediment surfaces have focused upon the wrong landform in the writer's opinion. There is no question that processes of subaerial and suballuvial weathering occur on pediments today, nor that fluvial erosion also occurs. A pediment must exist prior to the onset of these processes, however, and in this sense the origin of pediments resides in the adjacent mountain mass and its reduction through time. Even if quantitative data on the rates and intensities of processes that act upon pediments were obtained, these would have little bearing upon the origin of bedrock surfaces.

To say that pediments result from the reduction of adjacent mountains through time is to give voice to a seemingly obvious and intuitive argument. But this point has often been insufficiently stressed in the past. Each range has some local base level in an adjacent basin, and it cannot be eroded to an elevation below this level. Given stability for a sufficient period of time, the consequences of mountain reduction must inevitably include the production of a pediment, whether in arid or nonarid regions. The nature of the surface produced may vary, and it may be mantled by, or free of, alluvium. However, it simply represents an area that was formerly occupied by a mountain or other bedrock topographic high. The only real "pediment problem" is how the reduction or elimination of mountain mass occurs. This question will be considered here, admittedly in a deductive manner, and the relationship of the topographic data to the pediment question will subsequently be discussed.

First, it is significant to note that the "sharp break in slope" between the pediment surface and the mountain front, which has always been emphasized in the literature, exists only in interfluvial areas. Observation shows that the course of any master stream channel from a given drainage basin in the mountains onto the pediment surface and thence to the basin floor below has no sharp break in slope. In the absence of constraints, such as recent structural disturbances, any such stream channel will exhibit a relatively smooth, concave upward, longitudinal profile that accords with the local hydraulic geometry. There are no hydraulic anomalies in nature, and none exists at the "mountain front." The interfluvial areas, however, generally do exhibit a marked change in slope, at least within a narrow zone parallel to the mountain front. The reason for the existence of such a zone is precisely that it is an interfluvial area; the dominant process that operates on the mountain front is not fluvial.

Qualitatively, it can be argued that two basic processes are operative on a given mountain mass. The steep slopes of the mountain front are interfluvial areas that are subject to weathering. Runoff on these steeply sloping surfaces is of short duration and is not concentrated. The runoff serves largely to remove the finer weathered debris that is transportable. Larger particles generally remain in place until they are reduced in size by weathering. The rates of mountain-front retreat are basically unknown, but by any reasonable assessment they are slow in relation to rates of processes that are operative in drainage basins. This is clearly true because the headwater region of any given drainage basin also consists of steep walls that are virtually indentical to those of the mountain front in interfluvial areas. In these headwater regions the same processes of weathering and of removal of debris occur. Hence, the rates of retreat of the bounding walls in the headwaters of drainage basins must be at least as great as the rate of retreat of the mountain front in the interfluvial areas. Also, however, the drainage basins represent the only parts of any mountain range that are subjected to concentration of flow and to its erosional effects, and these basins must therefore be the principal loci of mountain-mass reduction.

The entire argument may be summarized by stating that two processes are operative on mountain ranges, namely "A" and "B," and that process "B" is rapid relative to "A." If "A" operates on the mountain front, whereas both "A" and "B" operate in drainage basins then the bulk of range reduction must occur in the latter areas. Moreover, it is logical to further infer, as a corollary, that the interfluvial areas, or parts of the mountain front proper, must be "left behind" with the passage of time. These areas, which are often described as "triangular facets" in the literature, are possible loci of inselberg production. The latter landforms are mountain residuals which are left on the pediment surfaces, as these surfaces are produced by drainage-basin evolution through time.

The foregoing hypothesis appears to have the support of logic, but because quantitative data are lacking it can be considered no more than this, namely a hypothesis. Nevertheless, some tests of its merit are possible, and in this sense the topographic trend-surface data of this report are related to the pediment question.

If, as has been argued here, the origin of pediments is a direct consequence of mountain-mass reduction, the average mountain mass should be significantly smaller in certain areas that are characterized by the existence of pediments. The trend-surface results of this report have clearly indicated that regional differences do exist with respect to each of the 11 topographic parameters

used. The lengths, widths, heights, relief, areas, and volumes of ranges (figs. 9–41) are, on the average, much smaller in southwestern Arizona and southeastern California than in the north-central and northwestern parts of the Basin and Range area; western New Mexico, northwestern Utah, and northeastern Nevada occupy an intermediate status with respect to most of these characteristics. As discussed in the section "Age of Ranges," the areas occupied by smaller ranges are believed to be those where the ranges are of greatest relief age and, hence, where the ranges have longer erosional histories. It is also well known that the areas occupied by significantly smaller ranges, as delineated by the trend-surface maps, are indeed those areas within the Basin and Range region which are characterized by the existence of pediments. In those areas in which the larger ranges occur, alluvial fans are far more characteristic. The generalized cross section of an ideal basin and two adjacent ranges (fig. 42) indicates why this is true. Reduction of the larger ranges, shown in the upper part of the figure, to the dimensions of the smaller ranges, shown below, must be accompanied by the production of a residual surface surrounding the ranges, the elevation and nature of which is primarily a function of local base level. This should not be construed as an argument that no pediments exist in the northwestern part of the Basin and Range region nor that no alluvial fans exist in the southwestern part of the region. As indicated for the several topographic parameters, some part of the total variance always arises from local components. But there is a significant regional variation in topography, and this coincides with the regional variation in the distribution of fans and pediments.

This coincidence does not necessarily prove that the hypothesis for pediment formation offered here is correct. It simply shows that mountain-range reduction and the occurrence of pediments go hand in hand. If pediment production is accomplished by drainage basin evolution through time, however, some regional drainage distinctions may exist within the Basin and Range province. The question of whether such distinctions exist and their nature constitutes a final geomorphic implication.

DRAINAGE DISTINCTIONS

A considerable body of literature supports the idea that drainage evolution, in the absence of constraints, accords with stochastic processes. The several random-walk models of Leopold and Langbein (1962), Schenk (1963), and Scheidegger (1967), among others, and the mathematical analysis of aspects of Horton's laws (1945) by Shreve (1966), and by Woldenberg (1966) clearly suggest that in areas of homogeneous rock type and structural stability, the drainage pattern that will develop is dendritic and, moreover, that this is the most probable pattern in nature. Combined with the far greater amount of information on the hydraulic geometry of river channels, which includes data on the profiles of drainage systems as well as their areal pattern, the status of knowledge of drainage basins and their contained drainage networks is known to be at least one order of magnitude in advance of the period when drainage was characterized as "youthful," "mature," and "old." The present writer believes, however, that so much effort has been devoted to establishing the concept that drainage systems reflect the most probable steady-state conditions that insufficient attention has been given to the study of the effects of time and whether these effects produce measurable drainage distinctions.

The drainage patterns that occur in the mountain ranges of the Basin and Range region have not been imposed by hydrologic input upon fullblown mountain blocks with planar sides, as so often depicted in older geomorphology texts and in the block diagrams of random-walk papers. Although the rates of orogeny are probably greater than the rates of denudation in the region since the Tertiary (Schumm, 1963), the existing drainage patterns must have begun to evolve at the very outset of the development of topographic relief. This means that complete equilibrium between the drainage systems and their respective host ranges may not yet be achieved in the more recently uplifted ranges, although these systems may be closer to mean steady-state conditions than might be suspected. In those ranges which have undergone long periods of stability, the drainage systems should be well adjusted and should reflect all of the attributes that are predicted by the stochastic models and by the hydraulic-geometry relations. Some measurable drainage distinctions should exist on this basis alone, however. That is, those parts of the Basin and Range region which are characterized by larger area of ranges to total area ratios, and by greater average widths, lengths, heights, volumes, and relief of ranges, might be predicted to be areas that are also characterized by some degree of departure from steady-state drainage systems.

Aside from this possibility, however, the effects of time may influence drainage systems in another way. Given a mountain block of finite size and homogeneous lithology, under specified hydrologic conditions there will be some finite number of drainage systems that can develop. Although the number of drainage systems that can coexist has never been specified, it clearly must be a function of mountain mass or the size and shape of a

given range. W. B. Langbein (written commun., 1966) used random-walk models to investigate the drainage systems that will develop in square and rectangular areas in the absence of contraints. For a square area the largest stream system drained 21 percent of the total area, whereas the largest stream drained only 17 percent of the total area of a rectangle with a 2:1 side ratio. These results suggest that the problem is also amenable to testing by simple counts of the number of drainage systems in ranges of similar size, shape, lithology, and erosional history. The important question is, however, if this is true, then what effect has the passage of time on the numbers and the nature of drainage systems in a given range?

The writer has stated previously that mountain reduction is basically accomplished by the enlargement of drainage systems through time and that this results in pediment formation. But if the number of drainage systems is a function of the size of a range, this number must diminish as the mass of the range is reduced through time. Again, it might be predicted that those parts of the Basin and Range region characterized by different values of the 11 topographic parameters discussed will also be characterized by different values of mean number of drainage systems.

Finally, as the mass of a given range is reduced beyond some critical value, the nature of these drainage systems, as well as their number may be altered in some discernable manner. Clearly, the order numbers of the drainages must diminish, but, in addition, in a region characterized to some extent by orographic controls on precipitation, the hydrologic input will necessarily diminish, and weathering—rather than fluvial processes—will attain the dominant role in final mass reduction. Qualitative observation of many long-stable, residual ranges in southern Arizona and southeastern California supports this view; the lack of any prominent drainage network on the slopes of these low, narrow, and commonly linear ridges is characteristic. Thus, although this writer dislikes the use of the word "cycle," because of the many unsound or incorrect implications associated with it in geomorphology, the evolution of drainage systems in the Basin and Range region may well be termed "cyclic" in a restricted sense. Although there is undeniably an adjustment of process and form through time, predictable on the basis of the laws of probability and hydraulics, the evolution of drainage systems is intimately related to mountain mass and its ultimate reduction. The number of drainage systems and their order must diminish through time, and the relative roles of fluvial erosion and weathering must be reversed as the drainage systems diminish through time.

A search for quantitative regional drainage distinctions is therefore worthy of future efforts in the Basin and Range province. The writer suggests that these distinctions will probably coincide with the distribution of fans and pediments and with the regional topographic differences discussed in this report.

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