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GEOMORPHOLOGICAL SYSTEMS—EQUILIBRIUM AND DYNAMICS

ALAN D. HOWARD
118 Ridgewood Street, Davenport, Iowa

ABSTRACT. The historical record contained within landforms and the tendency of landforms toward equilibrium with the processes acting upon them are not, as it might seem, contradictory; both facets may be encompassed within the systems approach to geomorphology. Landform features may be considered as open systems of complex behavior. Equilibria in geomorphology may arise in several types of system-environment relationships, and all adjustments of landforms to changes in the environment may be regarded as tending toward an equilibrium state. The influence of a past process having acted upon a geomorphic system is proportional to the intensity and duration of its action but inversely proportional to the elapsed time since its action. That is to say, the amount of information within landforms about their historical changes decreases the more remote the past. Some landform features reflect only recent changes of environment, whereas others yield a certain amount of information about the more distant past.

Tectonic movements largely control the intensity of erosion but are not reflected in a simple manner through individual slopes and gradients of the landforms. Many slope relationships and terrace features previously ascribed to tectonic action actually result from geologic controls or climatic change. An areal uniformity of landform parameters is characteristic of regions of the same tectonic unit, homogeneous geology, and equivalent climate. Conversely, in areas of the same climatic and tectonic history, contrasts of landforms usually reflect areal variations of stratigraphy and structure, and certain landforms are characteristic of the boundary between different lithologies and structures.

A search for logically simple explanations of landform evolution has led many geomorphologists into one of two positions regarding the nature of erosional processes (Chorley, 1962).

The first of these schools, because of a preoccupation with the changes through time of landforms, postulates that landforms are essentially *historical*, or additive, such that every erosional process leaves a largely indelible imprint upon surface forms and deposits. Thus with the proper "spectacles" one may read back through an indefinite period into the past. The "cyclical" schools of Davis and Penck have largely embraced these assumptions, interpreting the landscape in terms of an assemblage of largely independent form elements of different ages.

Contrasting with the above position is the concept of *equilibrium* landforms. Hack (1960) argues for a "dynamic equilibrium" in present landforms where all topographic elements are eroding vertically at an equal rate with no change through time of slopes or areal arrangement of the topography. Such equilibrium landforms would be completely adjusted to the processes presently acting upon them.

While perhaps few geomorphologists would subscribe to either position in the extreme formulation given above, many conclusions and working assumptions in geomorphology fall squarely into one of the two schools of thought as will be demonstrated throughout this paper. I shall argue that both the historical content of landforms and the tendency of surface features toward adjustment to processes acting upon them (Langbein and Leopold, 1964) may be encompassed within the discipline of system study first applied explicitly to geomorphology by Strahler (1952) and Chorley (1962).

The most general model for natural phenomena is the *system.* A system is composed of elements (objects), their instantaneous state and interrelationships, and is subject to modification through time (Cowan, 1963). Broadly speaking, any subject of investigation showing unity and a strong interdependence of constituents can be profitably treated by the systems approach. In geomorphology useful defined systems include a drainage basin, a stream segment or longitudinal profile, a hillslope, et cetera. Geomorphic systems, inasmuch as they exchange both mass and energy with their surroundings, are *open* systems (Foster, Rapoport, and Trucko, 1957; Chorley, 1962).

The state of a system is characterized by its composition, organization, and flow of energy and mass. The state is measured by system parameters, or variables, of which an infinite number may be defined. However, one is usually concerned with those variables that are most easily measured and that most critically define the state of the system. Representative parameters in geomorphology are drainage density, discharge, slope angle, et cetera.

Those factors not within the defined system, which control the flow of mass and energy through the system, are the *external* variables. Geomorphic systems are essentially *passive,* that is, they change only through change of the surroundings. This can be true only if all sources of mass and energy ultimately derive from and are lost to the surroundings (Foster, Rapoport, and Trucko, 1957). Similarly, it is necessary to consider geomorphic systems in a determinate manner, that is, any non-random change of a system in time or space must be ultimately attributable to the action of an external variable.[1] A complication to the passive concept arises where the system partially controls its environment, that is, the control of microclimate by topographic form (Geiger, 1959), and conversely, the effect of microclimate differences on slopes of different orientation upon slope values, drainage density, et cetera (Hack and Goodlett, 1960). In a similar vein are the interactions of landforms and vegetation, also treated by Hack and Goodlett (1960). Often, however, these may be considered second-order effects in geomorphology, either by selecting internal parameters which mask small-scale interactions (for example, slope values averaged over all slope orientations) or by neglecting this "feedback" when quantification of landform parameters rather than causal explanation is desired (for example, considering discharge and sediment load to be independent factors in stream regimen studies, as discussed by Leopold and Maddock, 1953).

A change of one external variable usually causes readjustment of all system parameters (Hall and Fagen, 1956). Thus geomorphic systems should respond as an organic whole to changes of environment. However, the historical faction has postulated a large degree of independence between the various components of landforms. According to the theories of Penck, each slope element, once formed at the stream-slope junction, migrates backward at a constant rate and slope regardless of further changes of stream erosion, geologic substratum, or climate. Davis's school of thought considers the stream network

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[1] Erosional processes involving "thresholds", such as landslides, which act discontinuously, tend to be distributed randomly in time of occurrence and location in the absence of change of external variables.

to be the principal determinate of the course of erosion; slopes are therefore a derivative feature, less capable of vertical erosion (Schumm, 1963), and lag behind changes of stream regimen. Furthermore, in areas assumed to bear a multicyclic imprint, the portions of slopes and streams belonging to each cyclic stage are considered to be physically separate from each other; adjustments of topography to a rejuvenation of erosion are thought to proceed by progressive horizontal encroachment of knickpoints and escarpments rather than through a distributed internal modification. Evidence for such a marginal encroachment during an intensification of erosion is given by Schumm (1956) and Carter and Chorley (1961) for areas where drainage systems are becoming progressively established on originally constructional surfaces. In areas having established drainage nets, a rejuvenation of erosional activity would probably be rapidly transmitted to the lowest-order drainage basins (Weber, 1958).

On the other hand, quantitative studies have shown the excellence of correlation (and hence inter-adjustment) between all parts of the landscape. Stream discharge, sediment load, slope, width, depth, et cetera are clearly interrelated (Leopold and Maddock, 1953); the gradient, width and length of streams, drainage area, discharge, and drainage basin shape and relief observe consistent relationships among themselves and with stream order within the same drainage complex (Leopold and Miller, 1956; Morisawa, 1962; Lubowe, 1964). Furthermore, a close relationship between slope and divide morphology on one hand and with stream parameters on the other hand is indicated by the grading of most streams for removal of supplied sediment load (Mackin, 1937; Leopold and Maddock, 1953; Hack, 1957; Wolman, 1955). Further evidence of interrelationship between various aspects of the topography is indicated by a tendency of slopes, divides, hollows, and ephemeral stream channels to intergrade (Hack and Goodlett, 1960). Studies by Hack (1957) and Hack and Goodlett (1960) show the significance of slope and divide erosion. Although most historical studies have underestimated the unity of the landscape, quantitative studies, by concentrating upon well-established and stable drainage systems, have been biased against observing sequential and migrating landform changes.

Systems may be dominated in their response by one type of external variable (Von Bertalanffy, 1950). In geomorphology dominance by tectonics has been a characteristic interpretation. However, the recent trend has been toward recognition of multivariate control in geomorphic systems (Weber, 1958). So great has been the preoccupation with the role of tectonics in the figuring of landforms that structural benches (Thwaites, 1960; Forsyth, 1962), concordent, rounded divides on homogeneous rock (Shaler, 1899; Hack, 1957), and stream terraces of climatic origin have been too widely used in reconstructions of past tectonic movements. Among both historical and equilibrium schools there has been a widespread tendency to consider the effects of stratigraphy and structure upon landforms to be a secondary and even temporary influence. The widely-held opinion that geologically-controlled profile irregularities are eventually erased in a graded river is criticized by Wolman (1955). Morisawa (1964) regards geologic irregularities in a drainage basin as exerting a delaying effect upon the attainment of a steady state. More reasonable is the expectation that all variations of stratigraphy and structure will find continuous expression through form and process variations in the landscape (Thornbury, 1954, p. 18; Weber, 1958). Many studies have shown the adaption of stream, slope, and drainage pattern to structure and lithology (Wolman, 1955; Hack, 1957; Hely and Olmsted, 1963; Flint, 1963). Similarly climatic and microclimatic variations in time (Leopold and Miller. 1954) and space (Hack and Goodlett, 1960) should require corresponding adjustments of landform parameters.

The concept of *equilibrium* is quite basic to system theory and is considered here to imply a complete adjustment of the internal variables to external conditions. The degree of approach of system variables to equilibrium may be measured by two methods: (a) if the external variable remains constant through time, then the parameters of a system in equilibrium should also remain constant (however, the sensitivity of specific internal variables to changes of the external variables is indeterminate by this method); (b) if the value of an external variable changes through time or space, a correlation of low variance between the value of the external variable and that of the system property indicates a close approach to equilibrium whereas a high correlation coefficient indicates a high sensitivity of the system property to changes of the external variable. Each combination of external variables defines a unique system equilibrium state. Langbein and Leopold (1964) propose that the equilibrium state represents a balance between a tendency toward equal areal distribution of energy expenditure and a tendency toward minimum total work expended upon the landforms. Thus an equilibrium state would exhibit maximum efficiency of erosion under the given external conditions.

Crucial to the study of equilibrium and dynamics of a system is the concept of the resistance to change (*inertia*) of a system variable (Chorley, 1962; Langbein and Leopold, 1964). Following a change of external variable the system will tend to adjust to the new regime. In the case of a system that is manifesting no secondary responses (discussed below) and that is changing from one equilibrium state to another, the internal parameters in many natural systems tend to approach the new equilibrium at a rate proportional to their distance from the equilibrium value (for example, Strahler, 1952, and Schumm, 1963, propose a rate of erosion proportional to the average elevation above base level). Such an exponential approach implies a time-constant characteristic of the system and of the type of change of external variable. Although a system may never achieve exact equilibrium, it will within a finite period reach any desired approximation to equilibrium.

The rate of change of an external variable compared to the capacity for adjustment of the system determines the behavior of the system. The significance of this ratio should become clear in the following discussion of the important external factors which control the dynamics of landforms.

Stratigraphy and structure act passively upon landforms, exerting influence through constraints upon the system and, in the case of stratigraphy, as a source of mass for the system. In areas where lithology and structure are of constant composition or only slowly varying in the vertical direction, a complete adjustment between landforms and geology is to be expected, and such a case is indicated by the well-defined correlation between stream and slope parameters and the parental material in areas of steep regional dip or locally homogeneous lithology (Flint, 1963; Hely and Olmsted, 1963; Hack, 1957; Wolman, 1955). On the other hand, when the lithology and structure are heterogeneous in the vertical direction, landforms must adjust as erosion exposes new parent rock and structure. For example, exposure of a more resistant layer should occasion a steepening of landform gradients and an increase of local relief for more efficient erosion. In general, items such as slope values, drainage densities, drainage basin configurations will all require adjustment to changes of geology during erosion. Associated with vertical successions of stratigraphy and structure will be transitional or non-equilibrium landforms, for example, the escarpment separating landforms on an upper resistant unit from those on a lower, weaker stratum. These transitional landforms will be zones of maximum rate of change in time and space of landform parameters, and in areas of minutely inhomogeneous geology all landforms would be transitional.

Several variables act upon the topography with great effect, but over such a geologically short time period that no equilibrium state is to be expected. Such variables are usually rare and unpredictable in time and place of action. Volcanic eruptions, glaciation, major floods, tectonics (discussed separately below), and most activities of man fall in this category. Each action of such a variable must be individually considered as an "event" in the history of the landforms. Glaciation, volcanic eruptions, and some types of tectonic movement result in landscapes that may be considered as *constructional* as opposed to erosional. The resulting landform, whether it be drumlin, volcano, or fault block, has an initial form essentially independent of erosional processes. However, when such intensive variables cease to operate, erosional landforms become superimposed upon the original structure and initial conditions become less determinate of the landforms as time proceeds. Thus in the western United States what were originally valley volcanic flows often become resistant ridges, and long-inactive faults find topographic expression only through superposition of unlike strata or through their weakness to erosion caused by fracturing. When a variable such as volcanic activity or tectonic uplift occurs intermittently, no landforms that are completely constructional will be formed and the landscape will show aspects of both.

Perhaps the greatest debate in geomorphology has been over the role of tectonics in shaping surface features. Davis constructed a theory of landform evolution around the assumption of uplift movements essentially instantaneous compared to the resulting rate of erosion, whereas Penck conceived of slowly varying uplift rates of the same magnitude as the rate of erosion. Modern studies indicate that a variety of uplift movements may occur and may be more local in extent than is commonly supposed (Chorley, 1963; Weber, 1958). Equilibrium between landforms and tectonic movement implies an equivalence of the rate of erosion to the rate of uplift, but this is probably very seldom, if ever, the case because of the slow response of landforms to tectonic movement (Schumm, 1963). Schumm (1963) and Davis, however, went a step further and proposed that no equilibrium landforms could develop in association with a uniform and long-continued uplift, although Thornbury (1954, p. 21) argued for "perpetual youth" in such cases. Davis maintained that continued uplift must produce a constant increase in relief, whereas Schumm envisions a constant extension of drainage in such a circumstance. Both authors cite the inefficiency of slope and divide erosion as causes for this disequilibrium; this position has been disputed earlier in this paper. Schumm's scheme implies either extension of some drainage basins at the expense of others (thus indirectly challenging the proposal of a tendency toward equal areal distribution of erosional intensity, advanced by Shaler, 1899, and Langbein and Leopold, 1964) or a continual increase of drainage density. Both Davis's and Schumm's viewpoints imply that landforms do not tend toward equilibrium and that geomorphic systems tend to be non-conservative. In view of the numerous manifestations of close adjustment between form and process in other aspects of geomorphic systems (for example, stream regimens), the present author allows for the possibility that the rate of uplift and the rate of erosion could be equal, even though this would rarely occur because of fluctuations in and the possible episodic nature of tectonic movement. In the case of a stable land-sea level, the only equilibrium in keeping with inactive tectonics would be peneplanation.

The external variables loosely grouped under the term *climate* are active factors of less intensity than those of volcanism, glaication, et cetera but which act with more regularity. Although we usually receive weather reports in daily lump sums, true *weather* is only the instantaneous value of temperature, precipitation, et cetera, whereas climate represents weather averaged (integrated) over an arbitrary finite time interval. Weather can have no effect upon geomorphic systems; only extended action of the external variables, expressed as climate, can be correlated with action upon the system. In illustration, an intense rainfall (severe instantaneous weather) will have little effect upon landforms if continued for only a few seconds but will have a large effect if continued for several hours (as reflected in the climatic variables of precipitation duration and average intensity). The type of climatic factor considered is arbitrary—one may define such variables as hourly precipitation averages, annual temperature, and humidity averages for a certain month. Those climatic factors to which the landforms are most sensitive are of greatest interest. Certain other definable factors exhibit the characteristics of the climatic type and are usually indirect effects of climate; in stream studies supplied load and discharge are essentially climatic in action upon stream and channel characteristics.

Because of inertia in natural systems, external factors which fluctuate rapidly (in comparison to the adjustive capacity of corresponding system parameters) influence the parameters only as their average; the rapid fluctuations are "filtered out" in system response. For example, weather acts in this manner upon many geomorphic features. The external variable to which the system parameter is most sensitive would be a climatic factor measured by weather averages for periods of the same order of magnitude as the response-time constant of the system parameter. If these climatic averages in turn maintain a consistent value over a period of time, the system parameter will attain equilibrium.

Secondary responses to changes of external variables add another dimension of complexity to equilibrium. Because of the sensitive relationship of system components, the rate and path of adjustment may not be a simple asymtotic function but may have secondary (or tertiary, et cetera) effects which may enter into or dominate the adjustment. For example, in response to a sustained increase of average precipitation, the cross-sectional channel parameters of most streams will quickly adjust in a primary response to the increase of discharge and sediment load. But over a longer interval, further landform changes occasioned by the climatic modification may alter the discharge characteristics, amount and quality of supplied load, and stream slope, causing in turn secondary adjustments of the cross-sectional characteristics. System variables showing pronounced primary adjustments are, in general, closely related to the mass and energy exchange between system and surroundings, whereas secondary effects often result from adjustment of the grossest structural features of the system (Bradley and Calvin, 1956).

In certain cases the response of a system to a change of external variable may involve a *threshold*, or discontinuity, which separates two rather different system economies. In many areas of the western United States having a clay or shale bedrock, it is common to see within the same immediate area severely dissected badlands topography on bare rock coexisting with smoother topography with a grass cover. Overgrazing and increased aridity seem to favor transition to the badlands regime, and the continuing existence of the two strikingly different topographic forms suggests that the external and internal variables are close to the value at which the abrupt transition takes place. Changes of external factors which require system parameters to cross a threshold may allow a metastable disequilibrium state to continue because of the great change required to initiate an equilibrium regime.

In the preceding discussion it was assumed that only one external factor was changing at a time, but in nature this is rarely the case—tectonic movements, climatic changes, and vertical successions of geologic strata occur simultaneously. Reference to equilibrium in natural systems must be directed to specific external variables. Thus the slope of a hill may be shown to be consistently related to the geologic substratum but increasing or decreasing in slope, length, or convexity in response to climatic change of tectonic movement. Even if it is demonstrated that a system or system parameter is not in equilibrium with an external parameter, the existence of a theoretical equilibrium state retains its significance as it defines the direction of system response.

The extent to which the past action of an external variable influences a present system parameter is a positive function of its relative intensity of action upon the system and of the length of time over which it acts. This is the "frequency and magnitude" concept of Wolman and Miller (1960). However, the influence of past values of the external variables decreases with time at a rate that is a function of the ability of system variables to adjust to changes in external conditions (Chorley, 1962; Weber, 1958). Single low intensity rainstorms are soon overshadowed in their effects upon landforms by later storms, but a high-intensity event like a major earthquake or glaciation leave discernable effects upon landforms for hundreds or thousands of years. A variable that acts with low frequency but high intensity may have equal or greater effect than those acting less strongly but more constantly, for example, the importance in erosion and sediment transport of the infrequent thunderstorm (Wolman and Miller, 1960; Hack and Goodlett, 1960; Hack, 1957).

The decreasing influence with time of past actions of the environment upon the system means conversely that the remoter the past, the less may be inferred about past conditions of the system and the external variables (Ashby, 1958; Chorley, 1962; Weber, 1958). Consequently the present state of a system may have been reached through any of an infinity of previous states, with a wider range of past states theoretically possible as the time considered is more remote; this is equivalent to the principle of *equifinality* (Von Bertalanffy, 1956). Similarly, for a system variable in equilibrium with an external factor, the constancy through time of the external factor becomes less certain in the further past. Some authors have maintained that initial conditions, especially amount of tectonic uplift, may have a lasting effect upon the texture of landforms (Schumm, 1956; Thornbury, 1954, p. 127-129). This historically oriented viewpoint is in conflict with numerous studies of equilibrium tendencies in landforms and especially with observations of Flint (1963), who shows that the original configuration of the fall zone surface has little influence on the present topography of New England in those areas where the fall zone surface has been completely dissected. The close adjustment of topographic parameters to stratigraphy and structure (Hely and Olmsted, 1963; Flint, 1963) leaves little possibility for enduring textural inheritances from the distant past. The ability of topographic form to adjust rapidly to vertical successions of lithology in areas of horizontal structure gives further evidence of the decreasing influence through time of past conditions. It seems therefore reasonable to expect that areas of similar climate and geology which are experiencing the same rate of erosion should have similar landforms regardless of past tectonic history. Erring in the opposite direction are those working from the equilibrium viewpoint who underestimate the historical record in landforms.

Different geomorphic system parameters and sub-systems have unequal response times to changes in the same external factors; therefore some elements of the landscape will carry a longer-term historical record than others. Cross-sectional parameters and sediment load in high-order streams are most responsive to rapid fluctuations of supplied load and discharge, and therefore seasonal and year to year climatic fluctuations would be reflected most clearly in these system variables. The longitudinal profile of major streams takes several tens or several hundreds of years to respond fully to a climatic change, variation of drainage basin base level, or other disturbance to stream regimen (Leopold and Maddock, 1953; Daniels, 1960), and thus evidences in the building and dissection of alluvial terraces would be informative about regimen changes extending over such intervals of time. The general shape of drainage basins and slope relations require a greater time to respond to changes of climate or base level, and they would reflect only long-term changes of environment. As secondary geomorphic responses, the coarser features of landforms may be completely in equilibrium with geologic controls and long-term climatic averages while the primary landform responses, such as stream cross-sectional parameters, vary with short-term climatic fluctuations. On the other hand, the nice adjustment ("quasi-equilibrium") of stream parameters to small-scale variations of climate (Leopold and Maddock, 1953; Wolman, 1955) does not imply that the coarser features are at equilibrium.

CONCLUSIONS

High relief areas and headwater areas of large drainage basins are little affected by small-scale changes of land-sea relative levels (Thornbury, 1954, p. 106) and hence should carry little evidence of individual tectonic movements. However, areas of low relief on non-resistant rocks bordering on major streams and rivers will be affected in terms of available relief by a land-sea level change on the order of a hundred feet. Such areas may carry unmistakable evidence of a stagnation or rejuvenation of erosion. Schumm (1956) and Carter and Chorley (1961) considered erosion of the small-scale landforms of poorly consolidated rocks and show that a lowering of base level on originally muted topography results in an intensification of erosion which is progressively propagated through the area concerned in a manner similar to the initial stages of landform evolution as proposed by Davis. The main drainage channels first adjust to the lower base level, and the areas bordering the main channel because of steep gradient develop steep slopes, while smaller and more distant drainage channels incise less and the slopes are little steepened. In areas of rejuvenation of erosion, the intensification would not be reflected so much in slope profiles as in an areal variation of slope values (Strahler, 1950). Some evidence of such a pattern of drainage development may be seen in the Midwest, where postglacial drainage patterns are forming on glacial deposits; areas near main streams have rolling topography, while drainage divides remain largely flat. Areas in the eastern United States bordering on major rivers appear also to show the effects of a base-level lowering.

On the other hand, a raising of sealevel relative to the land or a prolonged period of land-sea stability would have the effect of a general decrease of relief first expressed along the main drainage channels and least affecting the headwater areas.

Despite the importance of tectonic movement and sealevel changes, their importance has been overemphasized. In many cases changes of erosional regime previously ascribed to tectonic factors must be accounted for by geologic effects upon the landforms or by climatic changes. More and more episodes of aggradation and intrenchment in the western United States are being recognized as effects of climatic change. Such would be the case especially in areas of high relief or those far removed from major drainage.

Studies in areas of homogeneous lithology show that parameters like stream and hill slopes, slope profiles, height of drainage divides, drainage density and drainage basin shape remain equal, in a statistical sense, from drainage basin to drainage basin in areas of the same tectonic unit and climatic environment. This implies that for such uniform areas an equi-partition of erosive areas is the most stable state (Langbein and Leopold, 1964; Shaler, 1899). Each type of lithology gives rise to unique landforms—limestone in humid climates supports subdued, rounded topography, while sandstone is characterized by coarse topography and straight slopes associated with a high degree of physical weathering (Hack, 1957). Likewise, areas of intense erosion on the same type of rock and in similar climates might be differentiated from areas that have received less recent uplift by coarser landforms, steeper gradients, and more predominate physical weathering. Schumm (1963) notes a correlation of intense erosion with a high ratio of basin relief to basin length. Similarly, changes of climate will call forth variations in landforms.

Conversely, lateral and vertical variations in quality of landforms in areas of the same tectonic unit and similar climate should be attributable to changes of stratigraphy or structure. For example, lateral and vertical changes of topographic parameters in areas of nearly horizontal, heterogeneous rock clearly correlate with geologic changes (Thwaites, 1960). Landforms in areas of heterogeneous rock, especially in areas of low-dipping strata, have a historical aspect not found in areas of uniform geology. In response to vertical changes of geology divides may migrate, streams may be captured, and in general slopes, drainage densities, et cetera, will change through time. In the past these geologically-induced topographic changes have often been mistaken for tectonic movement.

Because of the interrelated nature of geomorphic systems, landforms on one type of rock will be influenced by the character of the surrounding strata. Hack (1957) shows the pronounced effect of bedload transported from upstream upon stream regimen in downstream areas of differing geology. These interrelationships between rock units are most conspicuous in the transitional landforms in areas of low-dipping rocks; a resistant rock may act as a perched base level to an overlying weak unit, and conversely, escarpment retreat and overly-steep slopes on a non-resistant unit may be caused by an overlying resistant rock. Hack (1960) demonstrates that lateral planation in the eastern Appalachians is most pronounced where areas underlain by resistant rock discharge onto weaker strata, and Howard (1963) has proposed that cavern development may ultimately depend upon an inhomogeneity of geology.

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