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INTERPRETATION OF EROSIONAL TOPOGRAPHY IN HUMID TEMPERATE REGIONS*

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ABSTRACT. Since the period 1890 to 1900 the theory of the geographic cycle of erosion has dominated the science of geomorphology and strongly influenced the theoretical skeleton of geology as a whole. Some of the principal assumptions in the theory are unrealistic. The concepts of the graded stream and of lateral planation, although based on reality, are misapplied in an evolutionary development, and it is unlikely that a landscape could evolve as indicated by the theory of the geographic cycle.

The concept of dynamic equilibrium provides a more reasonable basis for the interpretation of topographic forms in an erosionally graded landscape. According to this concept every slope and every channel in an erosional system is adjusted to every other. When the topography is in equilibrium and erosional energy remains the same all elements of the topography are downwasting at the same rate. Differences in relief and form may be explained in terms of spatial relations rather than in terms of an evolutionary development through time. It is recognized however that erosional energy changes in space as well as time, and that topographic forms evolve as energy changes.

Large areas of erosionally graded topography in humid regions have been considered to be "maturely dissected peneplains." According to the equilibrium theory, this topography is what we should expect as the result of long continued erosion. Its explanation does not necessarily involve changes in base level. Pediments in humid regions and some terraces are also equilibrium forms and commonly occur on a lowland area at the border of an adjacent highland.

INTRODUCTION

The part of geologic theory that deals with the interpretation of landforms and the history of landscape development has been dominated for several generations by the ideas of William Morris Davis and his followers. Davis' theory of landscape evolution was first fully presented in his essay, "The Rivers and Valleys of Pennsylvania" (Davis, 1889).[1] The important concepts that he introduced include the geographic cycle, the peneplain, and the formation of mountains by a succession of interrupted erosion cycles. Davis' theories became immensely popular among geologists in Europe as well as in America, though there were dissenters, including, for example, Tarr (1898) and Shaler (1899). His theory of the evolution of mountains as topographic features through the mechanism of multiple erosion cycles was especially influential and came to have a great influence on the theoretical skeleton of the whole science of geology. Its impact is still felt. Many of our ideas relating to the history of mountains, the internal constitution of the earth and the origin of some ore deposits are closely related to this theory. The idea that mountain ranges are vertically uplifted after they have been folded was conceived in order to explain the widespread existence of dissected peneplains (Daly, 1926). Another example is the theory of origin of bauxite and of manganese ores and other residual concentrates in the Appalachian Highlands, that are thought by some to have formed on a Tertiary peneplain surface (Hewett, 1916; Stose and Miser, 1922, p. 52-55; Bridge, 1950, p. 196.)

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[1] Davis' major papers dealing with the sculpture of landscapes by streams (Davis, 1889, 1890, 1896a, 1896b, 1899a, 1899b, 1902a, 1902b, 1903, 1905a, 1905b) as well as others of his papers were collected in one volume published as "Geographical Essays" (Davis, 1909) and reprinted in 1954 (Davis, 1954). The 1954 edition of "Geographical Essays" has the same page numbers as the 1909 edition.

In the last 20 years, however, Davis' ideas have become less popular and the small but ever-present number of geologists who were skeptical of his theories has increased. Though many geologists have been dissatisfied with it, the theory of the geographic cycle and its application to the study of landforms has not generally been replaced by any other concept. Several alternative theories have been proposed, including the theory of Penck (1924, 1953) which relates the form of slopes to changes in the rate of uplift relative to the rate of erosion, and the "pediplain" theory of L. C. King (1953), an elaboration and expansion of Penck's concept of slope retreat. Both of these theories, however, are also cyclic concepts and hold that the landscape develops in stages that are closely dependent on the rate of change of position of baselevel.

During the course of my work in the Central Appalachians which began in 1952, seeking a different approach to geomorphic problems, a conscious effort was made to abandon the cyclic theory as an explanation for landforms. Instead, the assumption was made that the landforms observed and mapped in the region could be explained on the basis of processes that are acting today through the study of the relations between phenomena as they are distributed in space. The concept of dynamic equilibrium forms a philosophical basis for this kind of analysis. The landscape and the processes molding it are considered a part of an open system in a steady state of balance in which every slope and every form is adjusted to every other. Changes in topographic form take place as equilibrium conditions change, but it is not necessary to assume that the kind of evolutionary changes envisaged by Davis ever occur. The consequences and results of this kind of analysis in most cases differ from conclusions arrived at through the use of the cyclic concepts of Davis.

On rereading some of the classic American literature in geomorphology I realized that G. K. Gilbert used essentially this approach and that I have followed a way of thinking inherited either directly from him or from some of his colleagues. Even though Davis and Gilbert were contemporaries and friends, Gilbert makes little use of and few references to the theory of the geographic cycle or any of its collateral ideas. This omission is so conspicuous that it is difficult to believe Gilbert ever wholeheartedly accepted the idea. It seems to me that Gilbert's famous paper, "Geology of the Henry Mountains" (Gilbert, 1877, p. 99-150) outlines a wholly satisfactory basis for the study of landscape that does not foreshadow the developments in geomorphology that followed in the next 50 years.

In the pages that follow some concepts inherent in the theory of the geographic cycle that seem to me unsound are briefly discussed. The alternative approach to landscape studies based on spatial relations in a system in equilibrium is briefly presented. Very few of the ideas are original and most of them have been published in one form or another in the works of other geologists. In addition I wish to acknowledge the considerable assistance obtained in stimulating discussions with my friends and colleagues, especially C. S. Denny, J. C. Goodlett, C. B. Hunt, L. B. Leopold, C. C. Nikiforoff, and M. G. Wolman with whom I have been associated at various times during the formulation of these ideas. The manuscript has been read and criticized by R. P. Sharp of the California Institute of Technology, Sheldon Judson of Princeton University.

C. C. Nikiforoff (formerly of the Department of Agriculture) as well as by some generous colleagues in the U. S. Geological Survey.

THE GEOGRAPHIC CYCLE AND THE PENEPLAIN CONCEPT

The theory of the geographic cycle rests on the assumption that there is a base level toward which every area erodes and to which the streams become graded. After an initial uplift or rise of a part of the earth's crust, erosion proceeds through successive stages of youth, maturity, and old age; from a time in which stream grades are irregular, through a time when they become smooth, to a stage of low relief when the entire landscape is reduced close to base level. An important stage in the cycle is reached when the slopes of the larger streams are so reduced that they are able to transport just the amount of debris supplied from upstream and no more. At this point the stream is said to be graded and the stage of maturity begins. The trunk streams, unable to erode their beds, shift laterally, forming floodplains and meanders. The debris-covered area on the valley floor expands laterally as the interstream divides are lowered. At the final stage of old age the landscape is one in which the streams meander across broad plains covered by a sheet of waste. The divide areas are graded to the streams and are covered by a waste mantle transported by creep. They rise only slightly above the shallow valleys (Davis 1909. p. 254-272; 1899, p. 485-499). Davis envisaged that there must be interruptions of the ideal cycle of erosion and in fact that an ideal cycle is rarely completed. Alternate periods of uplift and stability of base level result in successive incomplete cycles during which the uplifted peneplains are dissected and new ones form along the streams. Hilly areas in which the hilltops rise to roughly the same height above the streams, like the Piedmont region of the central Atlantic States, are peneplains that have been uplifted and dissected by stream erosion until a stage of maturity has been reached (Davis, 1909, p. 272-274; 1899, p. 499-501).

The concept of planation.—The concept of *planation* or *lateral planation* is lucidly presented in the Henry Mountain report (Gilbert, 1877, p. 127). Gilbert described the process of planation in connection with the formation of smoothly graded, gravel-covered surfaces, cut on soft Mesozoic rocks at the foot of the Henry Mountains. Surfaces like these have come to be known as *pediments* and have been restudied in the Henry Mountains by Hunt, Averitt, and Miller (1953). It was recognized by Gilbert that the planation in this region occurs on soft rocks, such as weak sandstones and shales where slopes or declivities are small in comparison with the trachyte mountains in which the streams originate. Gilbert thought that lateral shifting of the streams is dependent on the fact that the bed load transported by the stream is more resistant than the rock through which it flows so that the stream cuts laterally against the soft bank. Where one of these streams cuts again through hard rock lateral planation ceases (Gilbert, 1877, p. 130) and canyons are formed. The process is dependent on the geology of the drainage basin of the laterally shifting stream, and on a contrast in rock resistance and slope between the upper and lower parts of the basin.

Davis applied the erosion cycle concept to the idea of lateral planation. In his theory a stream always has a tendency to erode laterally against its banks.

As the landscape passes through the evolutionary stages of the erosion cycle, first the larger streams and later the tributaries approach the base level of erosion. As they do so their ability to cut downward diminishes. They migrate laterally eroding the valley walls, producing a floodplain or surface of planation.

It is interesting to note the contrast between the planation observed and described by Gilbert and the planation envisaged by Davis. Gilbert's explanation of lateral planation involves a dynamic equilibrium of forces existing at the present time in actual drainage basins and the relation of these forces to the rocks. Davis' theory on the other hand assumes that lateral planation occurs in any drainage basin with the passage of time, regardless of its geology. In fitting the concept of planation into the framework of the geographical cycle Davis attempted to rationalize relations between things that change through time and hence cannot be observed or measured. In the transfer from a scheme of ideas that involves space to a scheme that involves time Davis ignored the spatial relations cited by Gilbert that make the concept valid.

Surfaces of planation are produced by streams under certain circumstances, but there is no reason to believe that such surfaces enlarge through time as relief is lowered, merely as a consequence of a reduction in slope. On the contrary it is likely that as gradation proceeds, the efficiency of the stream system in removing the waste of its drainage basin may increase.

The graded stream.—One of the key ideas in the theory of the geographic cycle is the concept of the graded stream. The word "grade" was used by Gilbert (1877, p. 112) in discussing the stable slope of the stream channel in the same sense that an engineer uses it to describe the slope of a railroad or highway. Davis borrowed the term at Gilbert's suggestion and used it in a more special sense to designate a certain stage in the evolution of stream profiles when the stream's ability to transport the load supplied to it from above is just balanced by the load that it has to carry (Davis, 1909, p. 392; 1902, p. 89).

This concept of grade has probably received more discussion among geomorphologists than any other aspect of the geographic cycle (for example Kesseli, 1941, Mackin, 1948, Woodford, 1951, Rubey, 1952, Leopold and Maddock, 1953, Wolman, 1955). As suggested by Kesseli, the concept as outlined by Davis seems rather elusive, so that it is difficult to identify a graded stream in nature. Mackin, however, in his study of the graded stream, clarifies some of the ideas and suggestions of Davis. The examples of graded streams cited by him are migrating laterally, depositing on the floodplain an amount of material equal to what they erode by lateral cutting. The graded stream is not actively cutting vertically downward and its longitudinal profile is being changed only very slowly as the relief or other conditions in the drainage basin change. Since it is cutting laterally, the channel of the graded stream is bordered by a floodplain underlain by thin river deposits and by terraces whose composition is entirely material carried from upstream and different from the underlying rock (Mackin, 1948, p. 472).

Leopold and Maddock (1953) considered the graded stream in relation to the hydraulic geometry of the channel. Their study of stream gaging and cross section data indicates just as consistent a pattern in the relationships between the variables width, depth, velocity, and sediment load in ungraded as in graded streams. They conclude that Mackin's concept of grade cannot be demonstrated by consideration of stream gaging data and they use the term "quasi-equilibrium" in reference to the equilibrium in stream channels observed by them in all the streams studied. They recognize that this equilibrium is distinct from the equilibrium implied by Davis and Mackin in the concept of the graded stream.

In Davis' concept of grade, high velocity of flow and a high capacity are associated with a steep channel slope. As slope diminishes during the evolution of the landscape through the erosion cycle, velocity diminishes as well as the capacity to transport debris (Davis, 1909, p. 397-398; 1902, p. 95-96). This idea may have seemed reasonable to Davis because he shared with many others the belief that mountain streams with steep channels have higher velocities of flow and therefore greater capacity than do large streams with lower slopes in lowland areas. This observation is not necessarily true. Actual measurements in many natural streams demonstrate that for equivalent frequencies of discharge average velocities tend to increase downstream rather than decrease (Leopold, 1953). Studies of some Appalachian streams, furthermore, indicate that the size of material a stream has on its bed and banks is not related directly to slope, but is related also to discharge and other variables in such a way that in many streams the competence (or size of material that a stream can transport) increases downstream as slope diminishes (Hack, 1958). These facts make it appear doubtful that streams reach a balanced condition through any evolutionary sequence involving a gradual reduction in slope. Probably the balance that exists in most streams is the quasi-equilibrium described by Leopold and Maddock (1953, p. 51). This is a balance among at least seven variables. It is so complex and there are so many alternative adjustments possible that equilibrium can be achieved under many conditions and is arrived at very quickly, almost immediately, in the development of a valley. The uniform, or regular concave-upward longitudinal profile that is characteristic of many streams and has been called "the profile of equilibrium" results not from the attainment of a certain stage in the evolution of a valley, but merely from the regular change downstream in some of the many variables involved in channel equilibrium. Most important of these is probably discharge that increases downstream as a consequence of a regular enlargement of the drainage area.

The streams cited by Mackin (1948) as examples of graded streams represent special cases that are exceptional rather than general. Like Gilbert's streams in the Henry Mountains, such streams head in hard rock areas of high slope and altitude. Their lower courses are in soft rocks and as a consequence have a low slope relative to the increased discharge. They migrate laterally and have a diminishing competence only because of the geologic pattern of the terrain they traverse. They represent a class of streams intermediate between those whose competence with respect to the load derived from upstream is increasing in a downstream direction or remains the same, and those whose competence decreases downstream so abruptly that they aggrade actively enough to build fans. They are no more in a state of equilibrium or disequilibrium than a mountain torrent that is engaged in cutting a gorge. The torrent also has a bed load and lag deposit or floodplain along the bank composed of material too coarse for the stream to move in the ordinary flood, but in this case the lag deposit is locally derived by washing or sliding down the adjacent slope or by plucking from the bed.

The stage of old age and the maturely dissected peneplain.—In the concept of the geographic cycle the appearance of the land surface in the stage of old age is dependent on the process of lateral planation. The ideal surface is a plain partly graded by planation and covered by a veneer of waste. Divide areas with convex upward slopes exist, but are relatively smaller in area than in earlier stages. Such graded surfaces, as stated above, do not now exist in nature. The extensive plainlands of the earth are either depositional surfaces like alluvial plains, deltas, drift plains, and coastal plains, or if they are erosion surfaces in humid areas, they are hilly with rounded divides and steep-walled valleys that have generally come to be described as "maturely dissected peneplains." Exceptions are pediments and terraces, that in humid regions occupy relatively small areas. Excellent examples of maturely dissected landscapes in America are found in the Piedmont region of eastern North America, or in the Central United States where the so-called Ozark peneplain has been "dissected and uplifted." Large areas of the Canadian shield have been said to be a dissected peneplain whose drainage has been disrupted by glaciation. The great limestone valley of the Appalachians, similarly, has been said to be a dissected peneplain as is the plateau area to the west of the Appalachians. Thus land surfaces that are worn down to the stage of old age, as conceived by Davis, are virtually nonexistent; on the other hand former old age surfaces that have been dissected to Davis' stage of maturity are ubiquitous in the older terrains of the earth, especially in humid regions. Indeed this kind of topography is so universal it suggests that the end product or end surface toward which erosion proceeds resembles the "maturely dissected" surface rather than the "old age" surface or peneplain. Such an end surface is one whose forms are graded for the efficient removal of waste rather than one on which the waste products accumulate and stagnate.

THE PRINCIPLE OF DYNAMIC EQUILIBRIUM IN LANDSCAPE INTERPRETATION

An alternative approach to landscape interpretation is through the application of the principle of dynamic equilibrium to spatial relations within the drainage system. It is assumed that within a single erosional system all elements of the topography are mutually adjusted so that they are downwasting at the same rate. The forms and processes are in a steady state of balance and may be considered as time independent. Differences and characteristics of form are therefore explainable in terms of spatial relations in which geologic patterns are the primary consideration rather than in terms of a particular theoretical evolutionary development such as Davis envisaged.

The principle of dynamic equilibrium was applied to the study of landforms both by Gilbert (1877, p. 123) and by Davis (1909, p. 257-261, 389-400; 1899, p. 488-491; 1902, p. 86-98). Recently Strahler has outlined the principle in more modern terms as it might be applied to landscapes (Strahler, 1950, p. 676). The concept requires a state of balance between opposing forces such that they operate at equal rates and their effects cancel each other to produce a steady state, in which energy is continually entering and leaving the system. The opposing forces might be of various kinds. For example, an alluvial fan would be in dynamic equilibrium if the debris shed from the mountain behind it were deposited on the fan at exactly the same rate as it was removed by erosion from the surface of the fan itself. Similarly a slope would be in equilibrium if the material washed down the face and removed from its summit were exactly balanced by erosion at the foot.

In the erosion cycle concept of Davis, equilibrium is achieved in some part of the drainage system when there is a balance between the waste supplied to a stream from the headwaters and the ability of the stream to move it, or in other words, when the slope of the channel is reduced just enough so that the stream can transport the material from above with the available discharge. As argued on page 9 this kind of equilibrium probably is achieved in a stream almost immediately and is not related to a particular stage in its evolution. Davis' concept would imply that some parts of a drainage system would be in equilibrium whereas at the same time other parts would not, and that the condition of equilibrium is in time gradually extended from the downstream portion to the entire drainage system.

Rather than a concept of balance between the load of a stream and the ability of the stream to move it, it is more useful in the analysis of topographic forms to consider the equilibrium of a particular landscape to involve a balance between the processes of erosion and the resistance of the rocks as they are uplifted or tilted by diastrophism. This concept is similar to Penck's concept of exogenous and endogenous forces (1924, 1953). Suppose that an area is undergoing uplift at a constant rate. If the rate of uplift is relatively rapid, the relief must be high because a greater potential energy is required in order to provide enough erosional energy to balance the uplift. The topography is in a steady state and will remain unchanged in form as long as the rates of uplift and erosion are unchanged and as long as similar rocks are exposed at the surface. If the relative rates of erosion and uplift change, however, then the state of balance or equilibrium constant must change. The topography then undergoes an evolution from one form to another. Such an evolution might occur if diastrophic forces ceased to exert their influence, in which case the relief would gradually lower; it might occur if diastrophic forces became more active, in which case the relief would increase; or it might occur if rocks of different resistance became exposed to erosion. Nevertheless as long as diastrophic forces operate gradually enough so that a balance can be maintained by erosive processes, then the topography will remain in a state of balance even though it may be evolving from one form to another. If, however, sudden diastrophic movements occur, relict landforms may be preserved in the topography until a new steady state is achieved.

The area in which a given state of balance exists and that may be considered a single dynamic system may be conceived as very small or very large. In the Appalachian region, it may be that large areas are essentially in the same state of balance. In the West, however, in an active diastrophic belt, a single dynamic system may constitute only a small area such as a single mountain range or a small part of a mountain range. Furthermore, because of sudden dislocations of the crust relict forms may be preserved in the landscape that reflect equilibrium conditions that no longer exist.

The crust of the earth is of course not isotropic and within a single erosional system, no matter how small, there is a considerable variation in the composition and structure of the crust. These variations are reflected by variations in the topography. Consider, for example, an area composed partly of quartzite and partly of shale. To comminute and transport quartzite at the same rate as shale, greater energy is required; and since the rates of removal of the two must be the same in order to preserve the balance of energy, greater relief and steeper slopes are required in the quartzite area. Similarly geometric forms differ on different rock types. An area that is underlain by mica schist or other igneous or metamorphic rock subject to rapid chemical decay, has more rounded divides than an area underlain by qaurtzite, if both are in equilibrium in the same dynamic system, for the schist is comminuted by weathering to silt and clay particles that are rapidly removed from hill tops on low slopes. On the other hand to remove quartzite from a divide at the same rate, steeper slopes and sharper ridges are required because the rock must be moved in the form of larger fragments.

The analysis of topography in terms of spatial or time-independent relations provides a workable basis for the interpretation of landscape. This kind of analysis is uniformitarian in its approach, for it attempts to explain landscapes in terms of processes and rates that are in existence today and therefore observable. It recognizes that processes and rates change both in space and time, and, by clarifying the relation between forms and processes, it provides a means by which the changes can be analyzed.

THE RELATION OF SOIL TO TOPOGRAPHY

Cyclic concepts of soil evolution have developed in a manner parallel to the erosion cycle concept of geomorphology. The idea of a cyclic evolution of soil through a stage of maturity to senility in which the profile becomes intensified and thickened through time is dependent on the concept of a topography that is stable, such as might exist on a peneplain or on a remnant of a dissected peneplain. Naturally enough, this idea lends support to the cyclic concept of landscape evolution.

An alternative theory of soil evolution based on dynamic equilibrium has been forcefully presented by C. C. Nikiforoff (1942, 1949, 1955, and 1959, p. 188) and parallels the concept of equilibrium in landscape evolution. As explained by Nikiforoff, nearly all soils achieve a state of dynamic equilibrium if they are exposed to the surface for a sufficient time. Factors in the equilibrium include climate, slope, rate of erosion, composition of the parent material, vegetation, and others. The horizons of the soil become diversified and owe their existence to an equilibrium among processes that tend to accumulate certain substances at certain depths, and those that tend to remove them. Take the clayey "B" horizon as an example:

The cyclic viewpoint holds that the clay in the "B" horizon accumulates through leaching of the "A" horizon above it. The concentration of clay increases through time, though at a slower and slower rate until further accumulation is impossible. At this point the soil is mature and remains in this state until removed by erosion.

In terms of dynamic equilibrium, on the other hand, the amount of clay present in any horizon of the soil is the result of a balance at that place between the rate of clay accumulation and clay removal. These rates differ in different horizons and subhorizons and the balance between them determines the amount of clay present. Similar balance between rates of removal and of accumulation and the interactions between them determine the composition of all the horizons.

From the point of view of landscape interpretation this view of the soil has many advantages. It permits the lowering of the hilltop by erosion at a more or less constant rate, at the same time maintaining the equilibrium of the soil. In fact the soil profile is dependent on erosion as one of the factors in the equilibrium.

Compare a hilltop underlain by pure limestone or by clayey or silty limestone with a hilltop nearby underlain by cherty limestone containing massive beds of chert (fig. 1). The hilltop underlain by silty limestone does not accumulate weathering products because they are removed by erosion as soon as they are freed from the rock by solution of the carbonate that binds them. On the other hill, underlain by cherty rocks, though solution goes on at the same rate, a debris of chert fragments is produced in addition to fine silt. These are too coarse to be removed by sheet erosion on slopes as gentle as those of the first hill. The chert accumulates forming a protective armor that prevents finer insoluble residues, also present, from being eroded. Accumulation of this deposit continues until the slopes are steep enough for the chert to be removed. The topography is now in equilibrium. One hill is covered with saprolite or

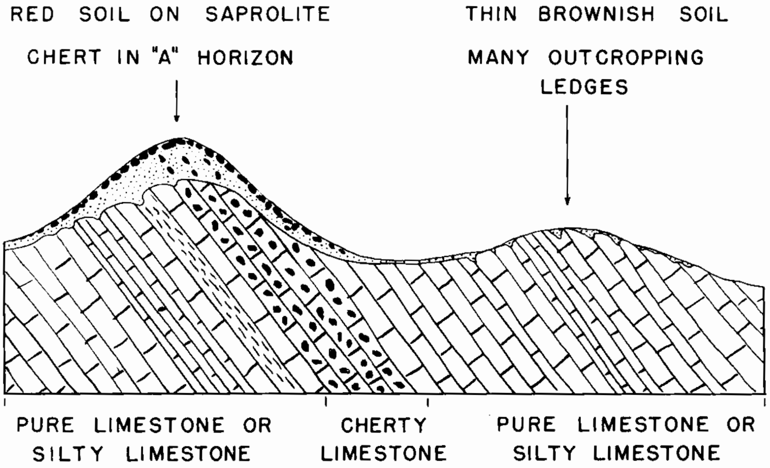

Fig. 1. Hypothetical cross section through two hills in a limestone region showing the relation of the bedrock and topography to the residual soils.

residuum and the other is not, but the saprolite-covered hill has steeper slopes and rises higher above the streams than the other (Hack, 1958b). It might be said that the residual material is "stored" on top of the hill as its covering armor is comminuted to sizes that can be removed by creep and wash. During the period of "storage" the material becomes oxidized and reddened and a profile develops. The time of storage may be very long, even thousands of years, and may be long enough for the soil to have survived major changes in climate and to owe some of its characteristics to irreversible reactions that took place in the past (Nikiforoff, 1955, p. 48).

EXAMPLES OF EROSIONALLY GRADED OR EQUILIBRIUM TOPOGRAPHY

As an area is graded by erosional processes the differences in the bedrock from one place to another cause a differentiation of the forms on them. Landscapes that develop on intricate and actively rising fault blocks may bear a closer relation to major structural features than to the underlying rock, but in a landscape like that of the Appalachian region in which large areas are mutually adjusted, the diversity of form is largely the result of differential erosion of rocks that yield to weathering in different ways. Such topography may be referred to as erosionally graded.

Ridge and ravine topography.—Many of the erosionally graded landscapes in humid temperate regions belong to the almost ubiquitous type that is commonly known as the "maturely dissected peneplain". Preferring a term that has no genetic connotation a more descriptive one such as *ridge and ravine* topography is suggested. This term refers to the monotonous network of branching valleys and intervening low ridges that make up the landscape of large areas. This topography may be concisely explained in terms of dynamic equilibrium in the words used by Gilbert (1909) in his discussion of rounded hilltops. He conceived that the important elements of the topography could be divided into two domains. The first, a domain of stream sculpture represented by channels in which the slopes are concave upward, because, as he says (Gilbert, 1909, p. 344), the transporting power of a stream per unit of volume increases with the volume; the transporting power also increases with the slope; and a stream automatically adjusts slope to volume in such a way as to equalize its work of transportation in different parts. The other domain is that of creep, represented by the slopes between the channels. In this domain slopes are mostly convex. Gilbert states (1909, p. 345) that:

> This is because the force impelling movement of material is gravity which depends for its effectiveness on slope. On a mature or adjusted profile the slope is everywhere just sufficient to produce the proper velocity. It is greatest where the velocity is greatest and therefore increases progressively with distance from the summit.

The forms of well-graded ridge and ravine landscapes vary within wide limits. Typical examples, both in areas of high relief, have been described by Strahler (1950) and by Hack and Goodlett (in press, 1960). Somewhat gentler topography of the same type is widespread in the Piedmont Province. An example of such an area is shown in figure 2. This is in a drainage basin tributary to the Patapsco River in Carroll County, Maryland. The bedrock is phyllite that is cut by veins of quartz. The interstream divides are convex upward

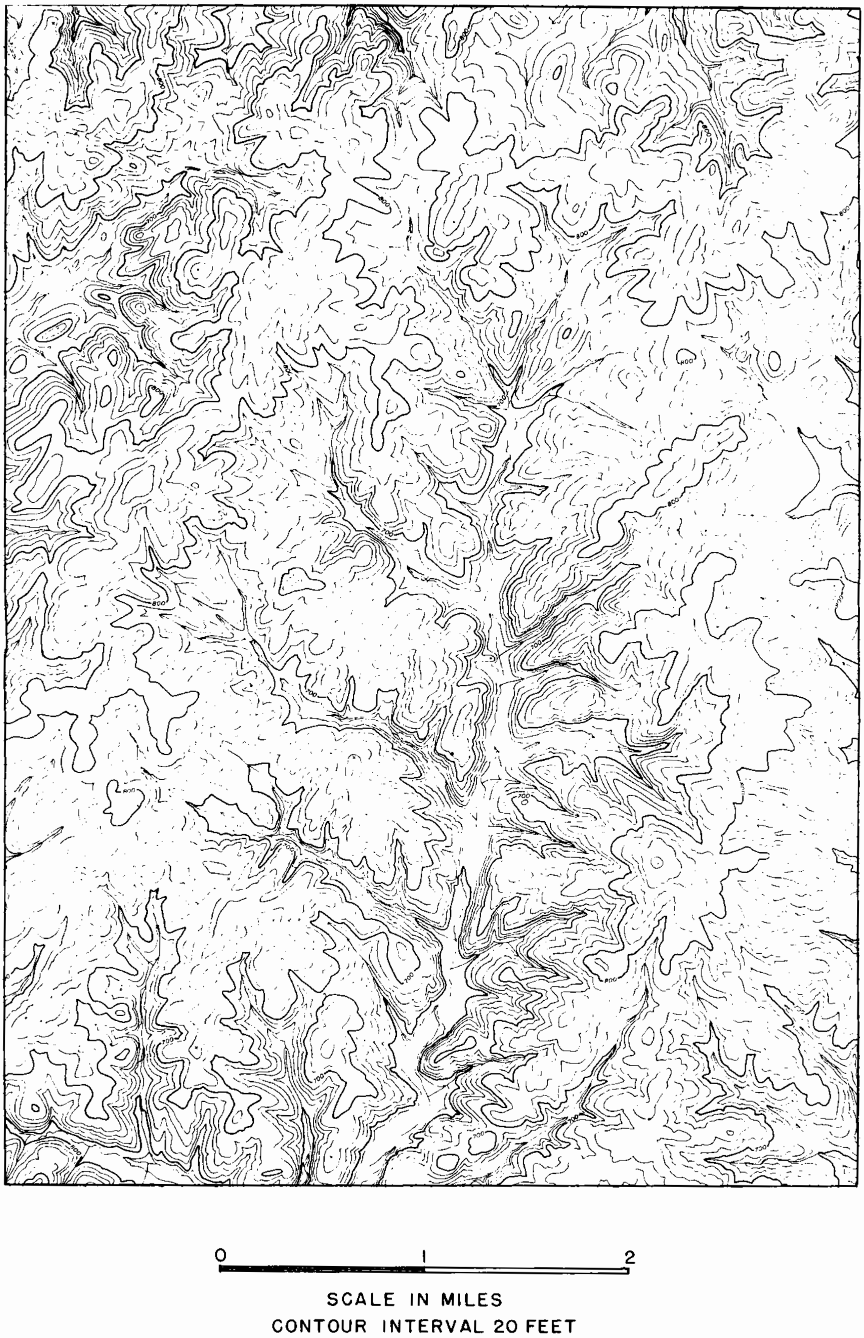

Fig. 2. Topographic map of area in the Piedmont Province of Maryland, showing typical ridge and ravine landscape (1950, U. S. Geol. Survey Winfield Quadrangle, Maryland).

and if measured on a coordinate system in which the origin, or zero point. is the top of the hill or ridge, they have the form of a parabolic curve like the one shown in fig. 3. They intersect the stream bottoms in steep slopes and sharp angles. though in places the foot of the slope is concave upward. especially in slopes that intersect the floodplain of a stream at a point opposite the channel. The regularity of the landscape and the rather uniform height of the hills owe their origin to the regularity of the drainage pattern that has developed over long periods. by the erosion of rocks of uniform texture and structure.

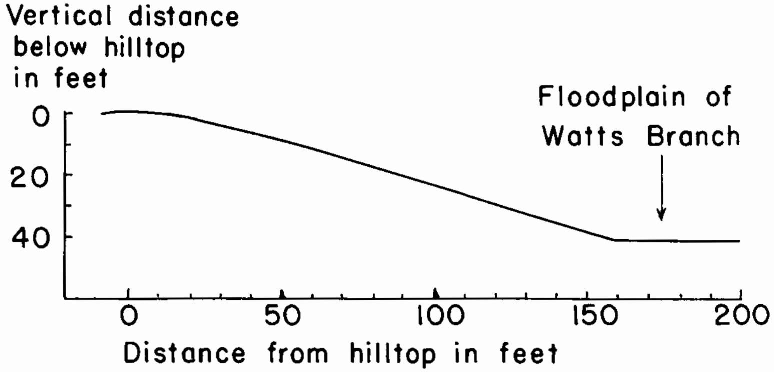

Fig. 3. Profile of hill slope near Rockville, Maryland, on fine-grained mica schist.

Differences in form from one area to another. including the relief. form of the stream profiile. valley cross sections. width of floodplain. shape of hill tops and other form elements are explainable in terms of differences in the bedrock and the manner in which it breaks up into different components as it is handled on the slopes and in the streams.

Pediments.—Where differences in rock resistance in graded landscapes are slight or confined to narrow or small areas, the differences in topography are small. Where. however. two large areas. one of resistant rock and the other of much softer rock. are juxtaposed. the differences are not only pronounced but there is a zone of transitional forms on the less resistant rock. In both areas ridge and ravine landscapes are developed. but as the more resistant area has greater relief. steeper slopes. and sharper divides. debris is shed from the higher to the lower area. This kind of situation is a common one in the Appalachian Highlands where many valley or lowland areas are underlain by limestone and shale and are bordered by ridges or series of ridges underlain by sandstone and quartzite. The transitional forms are broadly fan-shaped gravel-covered and dissected surfaces cut by streams on bedrock that closely resemble typical pediments in many western areas. They are called pediments because of this resemblance. but it is recognized that similar surfaces may be produced by different processes.

An example of a pediment area in the headwaters of the South Fork, Shenandoah River. Augusta and Rockingham Counties, Va., may clarify the equilibrium relations involved. As shown in figure 4, Dry River. Briery Branch.

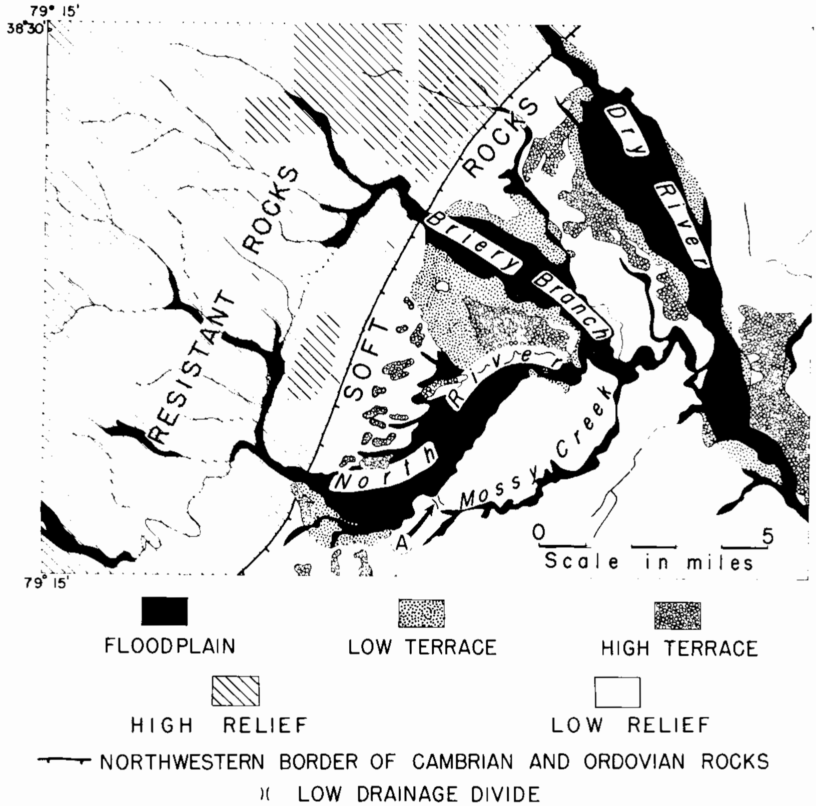

Fig. 4. Simplified map showing bottomlands and terraces on the northwest side of the Shenandoah Valley, Va., to illustrate the formation of pediments by lateral planation and piracy.

and the North River have their headwaters in an area of resistant rock of Silurian. Devonian and Mississippian age consisting mostly of sandstone, quartzite, and shale. The relief in this area averages 1,500 to 2,000 feet and ridges rise to altitudes as high as 4,400 feet. The soft rock area into which the three streams flow is underlain by Cambrian and Ordovician carbonate rocks and shale and has an average relief of only a few hundred feet. Most of it is less than 1800 feet in altitude. On entering the carbonate rocks each of the three streams is bordered by a broad floodplain and terraces composed of cobbles and sand derived from the mountains upstream. The low hilly plain at the foot of the mountains is an extensive complex of dissected terrace remnants that resembles, and in fact is similar to the dissected pediments common at the foot of mountain ranges in the western United States.

Mossy Creek, a tributary of the North River, does not head in the sandstone mountains, but in the limestone area. It has a flatter gradient than the North River even though a smaller stream and at locality A (fig. 4) where the two streams are separated by a low divide, Mossy Creek is about 60 feet below the elevation of the North River floodplain. In 1949 during a severe flood, water actually spilled over the divide into Mossy Creek. This is therefore an example of a stream piracy in progress.

In the resistant rock area the relief is high because the bedrock is removed largely through mechanical processes. Slopes are steep, divides sharp and there are many rock slides. Stream slopes throughout are adjusted for any given drainage area and discharge to transport rock fragments of large size. In the soft rock, or carbonate area, on the other hand, chemical weathering is more important and although the surface is being lowered at the same rate as in the resistant rock area the graded slopes are much gentler and the relief lower. Where the North River leaves the resistant rock area it moves a large load of sandstone cobbles on its bed. They are carried out onto the soft rock area where the channels are adjusted for the transportation of much finer debris. As a consequence the stream shifts laterally and deposits cobbles on the banks, forming a floodplain. Being more resistant to weathering than the carbonate rocks on which they have been deposited, the cobbles persist in the landscape for long periods and as the river continues to erode they form terraces and eventually cap divides.

Mossy Creek will continue to erode its channel and since it is not required to move a load of cobbles, momentarily cuts faster than the North River. Eventually piracy will occur and Mossy Creek Valley will be aggraded by cobbles brought in by the North River. The North River floodplain below locality A will then be abandoned and will become a dissected terrace. Captures similar to this one have already occurred at other places. Note for example in figure 4 the low terraces that connect Briery Branch with the North River.

In this explanation it has been assumed that the resistant and soft rock areas are in the same erosional system and that the average rate of erosion in the two parts is the same. The pediment area exists because cobbles are shed from one part to the other, thus introducing and maintaining a belt of resistant cobbles at the margin of the soft rock area. The pediment area is of course itself in equilibrium in the same system. Its size and the amount of relief are determined by the rate at which cobbles are carried into the soft rock area (a function of size of drainage basin) and by the rate at which they are weathered and broken into pebbles that can be moved out in the streams draining the soft rock area. Hunt, Averitt, and Miller (1953, p. 189) applied the same kind of explanation to the pediments in the Henry Mountains. In that area, however, because the climate is semi-arid the processes are not quite the same, for there is a loss of discharge involved as the streams leave the more humid mountain area.

In the Valley and Ridge Province of the Appalachian Highlands there are many extensive surfaces produced by the processes just described. Many valleys are floored by shale and bordered by relatively high sandstone ridges. The gravels shed by the ridges are too coarse to be carried off by the master stream flowing in shale, and so are stored in floodplains, terraces, and dissected terraces, that because of their resistance to erosion form high benches on either side of the master streams. Eventually the cobbles and gravels in these benches are reduced by weathering and reworking in the laterally shifting streams to sizes that can be carried off down the main valley. Such extensive pediment-like landscapes have long been mistaken for a former gravel-covered broad valley stage or peneplain that is now dissected. Actually such gravelly surfaces testify to the contrast in resistance between the rocks of the mountains and the rocks of the valley and they are part of the equilibrium between the two.

Terraces.—Some stream terraces may have their origin as equilibrium forms. Mapping of surficial deposits in the Shenandoah Valley, Va.. indicated that terraces are most common in soft rock areas along streams that originate in hard rock areas. This coincidence suggests that the terraces are preserved essentially because they contain components more resistant than the underlying rock. Terraces composed of chert cobbles are common in areas of cherty limestone. They are not common, however, in areas of homogeneous rocks of any kind that do not provide a possibility for a contrast in resistance between the stream load and the rock through which it moves.

THE RETREATING ESCARPMENT AND PARALLEL RETREAT OF SLOPES

According to cyclic theories elaborated by Penck (1953) and King (1953) the evolution of topographic forms involves parallel retreat of slopes. As the hill or mountain slope retreats away from the main stream a pediment or network of interconnected pediments forms at the foot of the retreating slope and is extended as erosion continues. The Badlands area of South Dakota provides an example (Smith, 1958). Such forms are. however. far from universal. The retreating escarpment appears to be characteristic of gently dipping stratified rocks in which some beds are more resistant to erosion than others. Pediments and foot slopes may or may not be associated with them. The Highland Rim of Tennessee is an example of an escarpment that may be retreating but is without pediments at its foot. The Badlands of South Dakota. on the other hand, have in front of them a broad network of miniature pediments.

Retreating escarpments and associated pediments appear to be especially characteristic of dry climates, a relationship pointed out by Frye (1959). They are certainly less common features, however, in the Appalachian Highlands and in the Piedmont of the eastern United States where not only is the climate humid but horizontally bedded rocks are rare. In these areas the escarpments are fixed in space by geologic contacts. There may, however, be exceptions. The Blue Ridge escarpment of Virginia and the Carolinas appears to divide rock areas that are in some places identical. This scarp may indicate a condition of disequilibrium between two areas (Davis. 1903; White, 1950; Dietrich, 1958).

EVOLUTION OF TOPOGRAPHIC FORMS THROUGH TIME

The theory of dynamic equilibrium explains topographic forms and the differences between them in a manner that may be said to be independent of time. The theory is concerned with the relations between rocks and processes as they exist in space. The forms can change only as the energy applied to the system changes. It is obvious, however, that erosional energy changes through time and hence forms must change. It is of interest. therefore, to speculate on the effect of a gradual reduction in relief of a well-graded landscape such as we assume occurs through long periods of geologic time as diastrophic forces cease to exert their influence and an isostatic balance is approached.

In a typical ridge and ravine landscape the general character of the topography is probably maintained as the relief is lowered. There is no reason to believe that the efficiency of the forms for the shedding of waste becomes any less. The forms in which the waste is removed may change, however, and the rate of removal may diminish. In an area of high relief the waste may be largely in the form of boulders and cobbles that are removed mechanically. As relief is lowered in the same area, perhaps chemical weathering becomes relatively more important. In a high relief area, the divides are sharp and slopes steep. As relief is lowered in the same area the slopes in interstream areas become more rounded, and the divides more blunt.

Speculating on the evolution of pediment landscapes that occur in soft-rock areas adjacent to hard-rock areas it is evident that if relief becomes lower the difference in the energy potential between the two areas will become less marked. It can be expected therefore that the pediment areas will diminish in size and may eventually disappear.

THE APPLICATION OF GEOMORPHIC CONCEPTS TO GENERAL GEOLOGIC PROBLEMS

The theory of the geographic cycle has been widely used by geologists. Its abandonment must result eventually in changes in many of our concepts. Though it is not my purpose here to elaborate fully such changes, some examples are cited in order to illustrate the extent to which a change in theory may affect geologic problems.

Theories of ore genesis, particularly of deposits classed as supergene, are affected by abandonment of the cyclic concept of landscape evolution. The manganese deposits of the Appalachians associated with lower Cambrian carbonate rocks are a good example. These deposits generally occur in thick residuum preserved beneath quartzite gravels shed from adjacent highland areas. They have been interpreted as of Tertiary age, formed in the Harrisburg cycle of erosion (Hewett, 1916, p. 43-47). By application of the theory of the equilibrium landscape they may be interpreted not as relics of a Tertiary weathered mantle preserved beneath younger gravels, but as deposits that are forming at the present time, or under conditions like the present: They form beneath the gravelly mantle, and are preserved because the gravel covers them, and protects both the ore minerals and the residuum around them from erosion (Hack, 1959).

Some of the greatest changes in concept required relate to the concept of the dissected peneplain. Because we have accepted for many years the idea that a ridge and ravine landscape is formed by the dissection of a peneplain we have also accepted the idea that many highland areas like the Appalachians eroded in steps or cycles and that the orogenies that deformed the rocks of such highland belts were followed by long periods of vertical uplift of a cyclic nature involving repeated changes in the rates of deformation. Having abandoned the peneplain we must reexamine the history of such areas and apply areal studies of erosional process and form to the interpretation of their past history. In the Appalachian Highlands, for example, the general outlines of the present drainage may be inherited in part from conditions that existed as early as Permian or Triassic time. The present landscape may have formed through one continuous period of dying orogeny or isostatic adjustment. Differences in relief and form in different areas are explainable partly by the reaction of various erosive processes on a complex bedrock, and partly by what is probably a long history of complicated diastrophic movements.

Cyclic theories of landscape origin are close relatives of the theory of periodic diastrophism which holds that orogenies have generally occurred in geologic time in brief episodes of world wide extent. This theory is questioned and critically discussed by Gilluly (1949) who shows that the evidence of the sedimentary rock column supports the idea that diastrophism has not been periodic but was almost continuous through time, though the form and location of diastrophic movements has continually changed. This concept of continuity of diastrophic processes is, of course, discordant with cyclic geomorphic theories, but is in harmony with the equilibrium concept outlined here.

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