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GEOMORPHIC DEVELOPMENT IN HUMID AND ARID REGIONS: A SYNTHESIS

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ABSTRACT. Arid-climate landscapes are best explained in terms of Penckian geomorphic concepts and have never been satisfactorily integrated with the Davis system of land-form exposition, although integration seems to be quite possible and certainly desirable. Attention should be directed to those landscape elements common to both arid and humid climates.

The fundamental elements in subaerial landscape evolution are the so-called wash slopes and gravity (or derivation) slopes. These are best displayed in arid regions. In humid regions the grass and forest cover have the effect of breaking up these elements into small units, though their essential functions and relationships remain unchanged. Varying ratios of these small wash- and gravity-slope units give the observed range of hillside slopes characteristic of humid regions, tending toward gradual reduction of overall slope angle. In arid regions these two types of slope remain more nearly unbroken and are therefore more conspicuous. When applied broadly through the climatic range, these two fundamental types are regarded as constituting end members of a continuous series. This point of view provides a unified basis for description and interpretation of all landscapes developed by fluvial erosion.

INTRODUCTION

Geomorphic development in arid regions has always had an anomalous status in the Davis scheme of geomorphic interpretation. In establishing his geographical cycle (as it was called in the early years) Davis drew extensively upon the early works of Powell, Dutton, and Gilbert in western and southwestern United States for most of the basic principles of the cycle concept. Yet in those same arid regions, the contrasts with humid-climate landscapes have so impressed most later workers that a separate scheme of interpretation has seemed necessary. Even Davis himself believed in this necessity, and he is perhaps largely responsible for setting the American pattern of thought and viewpoint on topographic development under arid climatic conditions (Davis, 1905). Maintenance of the separate category in popular geology thus established may have offered better professional opportunity than would have been the case had more effort been directed toward harmonizing the two schemes, inasmuch as the humid-cycle principles then appeared to have been thoroughly exploited. At any rate, American geomorphology has continued to carry the dual scheme of "normal" and "arid" cycles without apparent embarassment.

No strong opposition to the Davis doctrines developed in America while the great author was living. The case for pedimentation instead of "normal" peneplanation in the Southwest was satisfactorily established through the work of Bryan (1922) and others, and earlier workers among whom McGee (1897) deserves special mention. But all this was accepted within the Davisian arid cycle without serious misgivings. Opposition from abroad in the form of Penckian doctrines has not been taken seriously by most American geologists until recently. Formal statement of the Penck system (Penck, 1924) came while Davis was still active, and his writings seemed to refute satisfactorily the tenets of the new school. Consequently the realization that the principles of pedimentation are in essence those of the Penckian system has come as a surprise to many. Now that an authoritative translation of Penck's chief work is available (by Czech and Boswell), its virtues and defects should become more generally appreciated.

The Association of American Geographers sponsored a symposium on Penckian geomorphology in 1939, at which time some of the currently used English equivalent terms were introduced. However, the belated attention of American geologists was drawn more effectively to these geomorphic problems by the publication of von Engeln's *Geomorphology* (1942). Von Engeln had arranged the symposium, and therefore to his efforts we owe a large measure of the present awareness of the Penckian principles among American geologists. But conservatism is strong, and one may detect a perhaps unconscious partisanship in the common tendency to criticize the obvious errors in some Penckian principles or to dwell on their less essential aspects.

Meanwhile other developments have been in process. A recent well-prepared textbook (Gilluly, Waters, and Woodford, 1951) scarcely mentions the time-honored regional young-mature-old Davisian topography, and the omission seems to have created very little comment. This can be taken as evidence of serious and growing suspicion that a goodly part of traditional Davisian teaching is obsolete. Still more specifically, King (1953) has completely rejected both the principle of downwasting of divides and the peneplain as the penultimate land form, in favor of scarp retreat and pediment extension leading to a compound pediment or pediplain. Even Davis himself (1930, p. 136) seems virtually to have acknowledged the existence of pediments in humid climates (he called them valley-floor basements), with the offhand suggestion that he had taken them for granted since about 1908.

Because the primary aim of the Penck system was directed toward interpreting regional diastrophic history, some of the geomorphic principles therein expounded must be disengaged from the tectonics in order to evaluate their significance. Whether the change from convex to concave slopes, in so far as this change can be demonstrated, reflects chiefly rate of uplift may be questioned on the ground that other factors also partially control the angle of slope. For strictly geomorphic interpretation, the diastrophism involved here is as incidental as is the Davisian assumption of rapid uplift followed by stillstand. Likewise the problems of *Knickpunkte* and piedmont benchlands lie only partly in their alleged modes of origin. Of equal or greater importance is the history of these forms once they have come into existence. This is a part of the great central problem of the evolution of valley-side slopes.

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THE PROBLEM AND THE APPROACH

To harmonize the concepts of "humid" and "arid" cycles (and incidentally to combine the best elements of the Davis and Penck interpretations), one must go beyond the obvious field facts that parallel slope retreat prevails in the more arid regions and that gradual reduction in slope angle is equally the rule in the more humid regions. As a first approach, two commonly held alternative propositions may be stated: Either (1) the tendency to parallel slope retreat is inherent in the hydraulic processes and is present under any climatic conditions (Penck); or (2) such tendency arises because of some nonhydraulic factors peculiar to arid climates and absent in humid climates (implied in Davisian theory). A third proposition, namely, that fundamental hydraulic principles depend on the vagaries of climate, is manifestly absurd; yet a hint of this uncritical view is inherent in any insistence that erosion goes on differently in arid and humid regions.

Two related problems seem to hold the possibilities of finding a unifying solution. The first is to recognize in the two climatic domains the fundamental erosion processes and their homologous effects. The second is to account for the differences in terms of controls on the erosion processes.

Most earlier attempts (Davis, 1930; Wood, 1942) to harmonize the phenomena of erosion forms in the two contrasting environments have begun with those of humid climate and proceeded to the arid-climate forms. In reality, the simplest expressions of water-erosion effects are those in arid climates. Therefore on the principle that clarity is best achieved by proceeding from the simpler to the more complex, the following analysis begins with a consideration of arid-type landscapes, followed by those under semi-arid conditions, and then to the humid-climate landscapes. King (1953) has followed this approach in part, but his generalizations have led to revolutionary, rather than evolutionary, conclusions. Nevertheless, all attempts to solve this problem should receive sympathetic consideration.

ADVANCE SUMMARY

This preliminary summary of evidence and deductions is offered in order that the subsequent discussion may be followed more readily.

Slopes are best classified into two fundamental types, in accord with Penck geomorphic interpretation: (1) *wash slopes* (graded surfaces of sediment transport), and (2) *gravity* or *derivation slopes* (surfaces which supply the sediment). In arid regions these two types occur in large-scale units dominating the landscape as pediments of various dimensions, and prominent scarps and mountainsides. Ideally, the wash-slope gradients are controlled only by the local requirements of sediment transportation on them.

In humid regions vegetation impedes both erosion and rate of runoff, resulting in significant contrasts with arid-climate landscapes. (1) Equilibrium wash slopes are under the *dual control* of vegetation and sediment transport over them, and in consequence are steeper than corresponding vegetation-free slopes; whereas valley sides (the chief gravity slopes) are generally less steep. (2) The more complete drainage network creates a correspondingly greater total length of valley sides, and therefore a more varied and intricate areal pattern in which slope retreat may go on. (3) From the beginning of an erosion cycle, rills and sheet runoff slowly lower the upland surface and round off the upper edges of valley walls, creating the characteristic convex portion of the transverse profile. (4) The strong but partial and inconstant control by vegetation gives rise to slopes of various intermediate degrees of steepness. In detail, these slopes consist of minute gravity-slope units alternating with correspondingly small segments of wash slopes. Local and temporary failure of vegetation on wash slopes permits gullying, the gully sides being new gravity slopes, with new and lower-gradient wash slopes eventually developing.

A notable intermingling of small wash- and gravity-slope units occurs in the zone of rounding at the tops of the valley sides. In effect, the upper part of the valley side removed in the rounding is distributed as inconspicuous minor units through the zone of rounding. The degree of steepness of the rounded slope as casually observed at any one place is an expression of the ratio between the two types of small units. Toward the upland divides, wash-slope units become longer and more numerous, and the uplands themselves may or may not be quite devoid of small gravity-slope units. Toward the valley, gravity-slope units prevail increasingly, and the steepest part of the wall may be uninterrupted gravity slope though modified by vegetation. Similarly, at the foot of the steep valley side a few short wash-slope units appear and become increasingly numerous and continuous as the valley floor is approached. This lower, concave portion of the transverse profile is often erroneously ascribed chiefly to alluvial-fan building. While it is true that considerable amounts of alluvium commonly accumulate at these sites, the surface is nevertheless essentially a wash slope.

All gravity (derivation) slopes of whatever unit-size tend to retreat at their characteristic angle of declivity as determined by local conditions. As these conditions change, so may the angle of declivity inasmuch as it develops originally under the control of existing conditions. The tendency to parallel retreat is believed to be everywhere present, but in humid areas it is masked or modified by the effects of more frequent (though less intense) runoff, by vegetation, and by more complete chemical weathering than is characteristic under arid conditions.

The foregoing analysis leads to the conclusion that the fundamental differences between fluvially developed landscapes in humid and arid climates are chiefly those of proportion and arrangement of the basic slope elements; and that, with appropriate adaptation of terminology, the Davisian framework of topographic interpretation may be applied to any landscape thus developed.

The following discussion makes no mention of soil creep and related processes, but such are assumed to go on as is generally understood.

TWO FUNDAMENTAL PROCESSES AND THEIR DOMAINS

It seems scarcely necessary to state that, following weathering of the surface rocks, landscape development by sediment removal involves two distinct and fundamental processes: erosion (or sediment derivation), and transportation. Yet inasmuch as these two processes result in the mystery of parallel slope retreat under some conditions and gradual slope reduction under others, their natures and their particular domains must be carefully noted.

Geomorphically the most significant effect of transportation by running water is the development of a graded slope, whether it be a stream bed or a sediment-mantled rain-washed surface (Mackin, 1948; Fenneman, 1908; Bryan, 1922; Holmes, 1952). So long as an abundance of sediment in various grade sizes within the competence of the current is available, a stable transportation profile will be established leading down to a local baselevel of one kind or another, and changing gradually in response to changes in sediment supply and volume of water from upslope, or to any shifting of the controlling baselevel.

The domain of sediment derivation lies chiefly in the area above the graded transportation surface. In this domain stream beds are being constantly lowered, and slopes leading to the streams are being stripped of whatever sedimentary particles are within the dislodging power of rills and sheet runoff. In both these domains various controls, notably vegetation and rock resistance to weathering and abrasion, introduce endless variation in overall slope declivities.

These two domains have their clearest expression in arid climates where vegetation controls are at a minimum or lacking altogether, and are ideally represented by the pediment and its limiting mountainside or scarp. For purposes of discussion, it seems best to use tentatively the terminology offered by Meyerhoff (1940). The scarp face or mountainside is the *gravity slope* (Penck's *Steilwand* or *Böschung*), which may also be considered as the *derivation slope*. The graded transportation surface is the *wash slope*, equivalent to Penck's *Abflachungshang* or *Fusshang* (Penck, 1953, p. 418-419).[1] The *Haldenhang* or sub-talus rock slope apparently marks the upper limit of steepness of the wash slope because it evidently indicates approximately the angle of rest of the weathered fragments resting upon it.

As a graded transportation surface, the wash slope has much in common with a braided stream channel. Particles at the edge of a rill or minor channel are moved forward into the rill, shallowing it and allowing it to widen correspondingly. Efficiency of the rill channel is thereby decreased, and the widening causes the rill to subdivide. So long as the amount of available sediment exceeds that which the rills can move simultaneously on any and all parts of the slope, no channel cutting or gullying can take place (Lawson, 1932). In Fenneman's words (1908, p. 746), the potential channel-cutting power of the runoff "is *prevented* rather than *withstood*." The entire surface may be slowly lowered or aggraded, but without losing its graded condition. Davis (1938) has described conditions of incipient channeling of a wash slope during a severe rainstorm, but the abundance of available sediment kept the runoff spread in a manner which well illustrates this principle.

WASH SLOPES UNDER SEMI-ARID CONDITIONS

In its simplest development the wash slope should be completely free from vegetational influence, and controlled only by the abundance of granular sediment. In arid regions, sagebrush and other similar types obstruct runoff to some extent, but vegetational control becomes significant where the

[1] Meyerhoff regarded *Haldenhang* as the wash-slope equivalent.

rainfall is sufficient to sustain a grass cover. As observed on the ground surface, the cover may appear thin and incomplete, but the roots form a continuous mat underneath. The stems, whether standing or fallen, impede and spread the flow of rills, and under these conditions the runoff is presumed to carry its maximum load of sediment. The result is an even-surfaced slope that appears essentially no different from that of typical pediments in the more arid regions. At their upper borders they begin against a scarp or hillside from which comes the bulk of sediment transported across them. An essential characteristic is that of dual control—sediment transportation and vegetational resistance. These controls have operated jointly on these slopes from their beginning, and therefore the gradients represent an equilibrium adjustment at the limit of available transportation energy.

The degree of control inherent in the process of sediment transportation is constant, but that of the grass cover is variable and dependent upon the completeness of that cover. If, when, and where the grass cover is broken, gullying can begin. Then the sides of the gully become small gravity slopes, and the gully widens by slope retreat as well as by stream erosion along its base. But the gully floor, being lower and more moist than the adjacent slopes, acquires a stronger vegetation growth that tends to trap much of the sediment, and such gullies may therefore gradually fill or heal. If they do not heal, the entire slope eventually becomes lowered, with consequently lessened gradient on which the need for vegetational control in maintaining equilibrium is correspondingly reduced. Slopes that illustrate these principles are numerous in the area of Fort Union rocks in southern Montana, in Wyoming, and in many other places. However, in many of these same areas most of the slopes are now being dissected and re-established at lower elevations apparently in response to the present, lowered local baselevel.

Around the northern borders of the Laramie Range, Wyoming, are wash slopes that truncate both the Precambrian granite and the overlying Oligocene-Miocene strata without any topographic expression at the unconformity.[2] Their gradient is slightly higher than that of typical Arizona pediments, but they obviously have developed as equilibrium transportation surfaces. Frye and Smith (1942) have described "pediment-like" surfaces in western Kansas, and more recently Frye (1954) has described similar surfaces in the same region as pediments. All are widening by scarp (valley-side) recession and are in all respects typical wash slopes. Whether the term pediment should be reserved for those wash slopes controlled primarily by the water-spreading power of abundant granular sediment is not discussed here. The alternative term would seem to be valley-floor basements (Davis, 1930, p. 136).

In summary thus far, wash slopes are most conspicuous in arid regions but are equally characteristic of semi-arid to sub-humid regions where impeding vegetation absorbs some of the potential hydraulic energy. The remaining problem is therefore to recognize the corresponding slopes in areas of humid climate. First, however, some features of the gravity slope should be noted.

[2] Blackstone, D. L., personal communication.

THE GRAVITY SLOPE

Although the term gravity slope suggests a surface on which gravity is the chief, or sole, agent in moving loosened fragments to its base, its Penckian equivalent seems to have been applied to landscape elements, at least in the alleged piedmont benchlands, which are far from precipitous. Therefore the term seems applicable to any sediment-yielding surface whose slope is steeper than that of the bordering transport-equilibrium surface with which it merges at its lower edge. Transportation slopes in equilibrium under dual control (vegetation and sediment transport) remain in the category of wash slopes only so long as vegetation continues to be effective. Vegetation failure causes such surfaces to revert to the gravity-type category, though generally the reversion is gradual, spreading with the recession of minor scarps that descend to a new surface of lower gradient. A universal feature of the gravity slope is that the transporting energy of water flowing over it is in excess of that which is taken up in moving the available sediment. Any sediment left stranded on such a surface, following an interval of precipitation runoff, does not form part of a depositional equilibrium surface such as is characteristic of the wash slope.

Distinction between gravity and wash slopes rests therefore on a relative and functional basis rather than on an absolute degree of steepness or gradient; though no wash slopes can be steeper than the sub-talus rock slope (Haldenhang), and only wash slopes may occur at or below the gradient locally controlled by abundance of available sediment, free from vegetational influence. Between these limits, ranging in general from approximately 6°

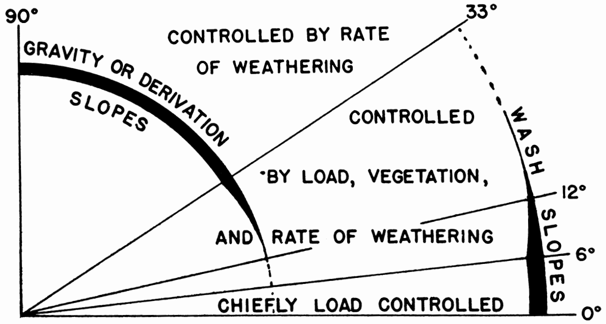

Fig. 1. Diagrammatic interpretation of range in declivities of derivation and wash slopes.

to 30°, both gravity and wash slopes may occur (fig. 1.) In other words, gravity slopes are generally steeper than 6° and wash slopes are never steeper than about 30°. The basis for these distinctions seems clear, necessary, and fundamental; though the possible low angle of the gravity slope makes that term seem inappropriate. *Derivation* slope often seems preferable because it is free from any connotation as to steepness. Gravity slope would then be a special case of the broader category of derivation slopes. At any rate, after the higher gravity slopes have been destroyed, the gradual lowering of wash slopes without loss of graded status involves sediment derivation below the earlier limits of the gravity or derivation surface, but within the limits of equilibrium variation during any one episode of precipitation runoff.

SCARPS AS GRAVITY SLOPES

Except in arid mountain areas where steep slopes extend upward to the ridge summits typical gravity slopes are of moderate height and rise to the resistant edge of a higher surface (wash slope). Most authorities are agreed that such a plains-region scarp cannot retain a sharp or abrupt crest without some kind of resistant capping stratum (Rich, 1938). The degree of resistance required is only relative (and may be inconspicuous), depending on the amount of sheet runoff or rill discharge passing over the brink, and on the rate at which the scarp face beneath it yields to weathering and erosion. The Big Badlands along the White River in South Dakota afford excellent illustrations. Some of the White River strata there are slightly more resistant than others, but the chief brink-forming element is the tough prairie sod. Naturally it cannot withstand the attack of streams flowing from the upland, but it evidently does withstand considerable rill wash. Moreover, it becomes re-established at successively lower elevations and caps many small tabular surfaces at intermediate levels along the general descent to the valley floor. The steepness of scarps beneath these sod brinks is a measure of their control relative to the rate at which the cliff faces recede beneath them. Summits without sod cover either are sharp ridges or are rounded. Obviously a sod cover is far less resistant than most caprocks that come to notice, but the illustrations afforded by the Badlands introduce some important clues regarding scarp retreat.

HUMID-CLIMATE DIVERSIFICATION

The simplest gravity or derivation slope is the ideal straight or linear scarp, which is probably most nearly realized in arid regions. With increasing runoff and humidity of climate, such a scarp would become notched along its weaker segments, with the result that the length of scarp surface is increased. With more surface thus exposed, a more voluminous supply of sediment is weathered and removed from it; and its removal is conditioned by the increased precipitation and runoff. Some of the notches extend ever farther and become enlarged to the dimensions of valleys. This is especially the case with any streams that rise in the hinterland and flow over the scarp face. In effect, therefore, with increasing humidity of climate, the gravity slope is extended along the valley walls throughout the ramifications of the branching and developing drainage system and is best developed in rock at least moderately resistant to weathering. Slopes steeper than about 30° are entirely of the gravity type; and if all valley sides and the slopes around the valley heads were of this degree of steepness, the domain of gravity slopes in humid areas would be easier to discern. Typically, however, the tops of the valley walls lack a sufficiently resistant caprock. They lose their scarp-like appearance by rounding and merge imperceptibly with the lesser gradients toward the divide crests. The basic reason for such rounding is clear. Vegetational resistance to erosion may be approximately uniform over the entire upland; but outward from the divide summit, each unit distance adds its increment of runoff. Therefore the erosive effectiveness of runoff is correspondingly augmented, with the result that increasing steepness of valley-side slopes, outward from the summit, is inevitable. In large part, this convex zone of predominantly wash slope corresponds to any wash slope lying above (and leading down to) a gravity slope, such as the upland above the White River Badlands.

Loss of scarp-like brink at the top of a young valley wall does not mean that the portion of the scarp or gravity slope thus affected is lost. Rather,it is *distributed* as minor scarps over the lower part of the convex area, each minor scarp being a small-scale gravity-slope unit. At the divide, rainwash creates a graded transportation slope, but within a short distance the rills descend individually over miniature scarps (gravity slopes) controlled by tufts of grass, resistant aggregates, fragments too large to move, or some other comparable temporary and very local baselevel. Then may follow more short distances of graded (wash) slopes, and so on. With increasing distance from the divide, the intervals of wash slope become shorter and fewer and the miniature gravity slopes become correspondingly more numerous until the steepest part of the valley side has been reached. Here erosion is at its maximum, and if any straight element of slope occurs anywhere, it is immediately below this line. Lawson (1932) has interpreted such straight segments as indicating removal of sediment as fast as it is loosened by weathering. Also Wood (1942) has called it the constant slope; but it is the most conspicuous and uninterrupted part of the gravity or derivation slope.

Below the limit of uninterrupted gravity slope is the area directly under local baselevel control of the stream channel in the valley. The transition begins with the appearance of small graded rill segments, which become dominant as the rills reach the gentler gradient that completes the concavity of the lower part of the valley wall. Ideally this slope is graded to the top of the stream bank, but with some secondary slopes leading to the stream surface; and if the stream were to follow a permanent course along the valley axis, this ideal might be generally attained. However, with meander shifting and continued valley deepening, the actual elevation of effective baselevel control varies from time to time and from place to place along the valley. Where the stream, having impinged against the valley side, shifts away from that site, the margin of the valley floor there must be aggraded. Immediately upslope, gullying has meanwhile been in progress because of the proximity of the main stream as it cut laterally against the base of the valley side. Then as the fans extend across the new valley floor, the upslope gullies may be filled at least in part in response to the requirements of the longer (restored) graded slope. The amplitude of these fluctuations is commonly beyond the limits of immediate adjustment by the slow process of rill- and rain-wash transportation. This tends to obscure the development of the graded bedrock surface (valley-floor basement of Davis) rising to the base of the retreating valley wall. However, the broad uniformity of these slopes reveals a close approximation to the ideal gradient under local conditions. The amplitude of local baselevel fluctuation caused by meander shifting and lateral planation is seen in the thickness of the alluvial-fan deposits. Were it not for these fluctuations, no true fans would develop except in response to possible accelerated erosion on the uplands. (In this connection, see King, 1949).

As pointed out by Lawson (1932) and by Wood (1942), the zone of maximum steepness becomes narrowed from both above and below. As this zone is worn back, the transportation surface (wash slope) leading to the valley floor rises against its lower edge while downwasting of the upland reduces its upper limit. In approach to mature dissection, valley widening in this manner and the expanding drainage net carry these wash slopes close to the corresponding network of divides, the limit being established by the local conditions governing the divide profile. The central Appalachian Plateau is still the classic example, and typical badlands are essentially the same except in scale and proportions. Height of the gravity slopes at this stage depends on available relief (Glock, 1932) and on texture of topography. These gravity slopes will remain the zone of most active erosion until the convexity of the lowered divides merges directly with the lower wash slopes. At that stage the gravity slopes as such are eliminated from the landscape, leaving only wash slopes. This should mark the full attainment of Davisian old-age topographic development. Peneplanation represents only the continued reduction of the wash slopes (Abflachungshänge).

SLOPE TYPES AS END MEMBERS

Ideally the terms gravity or derivation slope and wash slope should be defined in terms of the processes which they connote. But in practice it seems feasible to apply either term to those slopes or parts of slopes where the particular process is dominant, with perhaps minor occurrences of the other type. Thus the wash slopes in semi-arid and humid regions have innumerable small vegetation-controlled scarps or non-graded spots. Likewise gravity slope may apply to surfaces on which some graded rills occur. But where the proportion of such minor units approaches half-and-half, neither term should be used without appropriate qualification. As applied to broad slope areas, the terms represent end members of a gradational series, which thereby compels recognition of the minor component units (fig. 1).

In summary thus far, dissection of an upland to the stage of Davisian maturity in a humid climate greatly extends the area of gravity slopes along the valley walls. In further consequence of greater humidity, the stronger vegetational control of erosion results in gravity slopes that are less steep, and in wash slopes that are steeper than their respective equivalents in semi-arid regions. The wash slopes are therefore more vulnerable to gullying where vegetation weakens or fails, causing partial and temporary reversion to gravity slopes. Portions of the gravity and wash slopes become broken up into small and inconspicuous units that are further obscured by the everchanging pattern of vegetation, but that are nevertheless real and that have essential characteristics identical with such surfaces elsewhere. Wash-slope units predominate along the divides and, for the most part, control the lower valley-side slopes. Until well past maturity in the ideal Davisian cycle, the steepest parts of the valley sides are gravity slopes which diminish in prominence as they retreat. They disappear when the divides have been lowered sufficiently to come under the direct baselevel control of the valley floors (fig. 2).

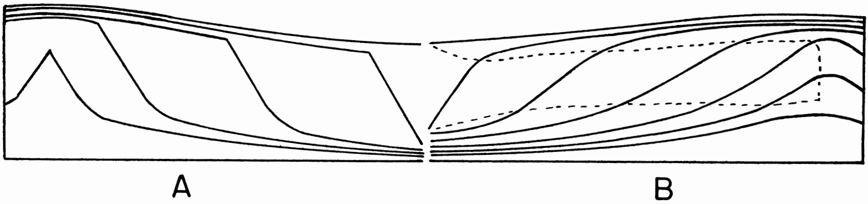

Fig. 2. Composite diagram representing valley-side profiles at successive stages in an ideal erosion cycle or sequence. Modified from Davis and from King.

A. Semi-arid grassland environment such as the western High Plains of the United States.

B. Humid environment of the "normal" Davisian cycle. Dashed line indicates zone of predominant gravity or derivation slopes, gradational to predominant wash slopes both above and below.

PENCKIAN-DAVISIAN COMPLEMENTS

The foregoing analysis shows that the fundamental landscape units developed by running water are derivation slopes and transportation slopes, and that these are present under humid as well as arid climatic conditions. The derivation or gravity slopes, wherever they occur, *tend* to maintain their characteristic gradients as they are worn back, the gradient being governed by local conditions of vegetation, if present, and by bedrock response to weathering.

Differences in gross aspects in the two contrasting climatic environments are basically those of unit size and distribution of the two fundamental landscape elements. Both are the less interrupted and therefore the more conspicuous where vegetation is scarce or absent, the effect of vegetation and greater humidity being to decrease the contrast in characteristic slope angle of the two, and to mingle the two types in small units on the slopes of intermediate average steepness. Progressive elimination of the small gravity slopes, with concomitant extension and integration of the wash-slope units, gives the overall effect of decreasing angle of valley-side slopes as downwasting of the divides goes on.

Therefore the essence of Penckian geomorphic principles amplifies and clarifies an aspect of running-water erosion which Davis left obscure. A possible reason for the long-continued obscurity may be the captivating contrast between aspects of arid- and humid-climate topography. Landscapes in humid climates are the more complex, and they have been treated without realizing that they are a composite of small, unlike elements which, in arid regions, occur as the gross or major units of the landscape. To perceive these slope elements in areas of humid climate requires close attention to details of the surface where erosion is in progress. The derisive caricature of a geomorphologist perched on a breezy hilltop and scanning the far horizon for another peneplain has been well earned; and yet perhaps it was inevitable in the development of a field so rich and varied.

PENEPLAIN AND PEDIPLAIN

With the foregoing analysis as a basis for interpretation, the penultimate land form has fundamentally the same topographic elements under any climatic conditions, the differences being mostly in the proportions and distribution of those elements. In arid regions the wash slopes are well consolidated and the few remaining gravity slopes are therefore relatively conspicuous; whereas on a humid peneplain the wash slopes are still partially under vegetation control and show relatively more range in gradient, with possibly a few minor units of gravity slope still in evidence along the low divides. Each final hillside has become a unit wash slope, and the relatively large number of such units, because of the more complete drainage net, gives the landscape its characteristic undulatory aspect.

In humid regions the controlling baselevel in virtually all cases would be sea level. This is likewise true of many if not most of the extensive pediments now developing in southwestern United States which are graded to through-flowing, though intermittent, drainage lines. However, many of the African pedimented landscapes described by King (1953) apparently have no graded continuity to the sea, but have developed under local baselevel control.

In this connection it is significant that Davis (1909, ch. 10) regarded the uplands of eastern Montana as a typical peneplain now well started on a second erosion cycle. The surface of that semi-arid region bevels the simple sedimentary structure, with residual "lava-capped" buttes indicating the minimum thickness of strata thus beveled. It was this area that in 1883 confirmed the Davisian peneplain, and the interpretation of its development first enlivened for his students that which hitherto had been a dull and boresome subject.[3] To the present writer the butte scarps in that area are typical gravity slopes and the long wash slopes (the peneplain) are equally typical of graded transportation surfaces controlled by both vegetation and transport of sandy-silty sediment. Therefore it appears that Davis' type peneplain or "ultimate stage in the sequence of a simple cycle of development" (1909, ch. 10) has at least as much in common with the Arizona pediments as with the Harrisburg or any other demonstrable humid-climate peneplain. In accord with priority usage. all these near-plains of subaerial erosion should be included in the broad category of peneplains, though the arid-climate forms may constitute a pediplain class within the larger category.

Relatively resistant rock masses may become residual eminences on a low-relief landscape in any climate, whether by virtue of especially resistant lithology or merely a relative lack of jointing or other structural advantage. Due account must be taken of the fact that in many cases the degree of resistance to weathering depends as much on climate as on rock type. In so far as superior resistance to weathering can be demonstrated, the term monadnock would seem applicable to any conspicuous residual eminence, though the environment may indicate advisability of reference to a bornhardt or other type of monadnock. Further subdivision of the bornhardt type should be made where possible in order to distinguish between those having monad-

[3] Davis, W. M., unpublished communication to V. A. Rigdon.

nock qualities and those which are merely traces of drainage-divide heights (Penck's *Fernlinge*) and without relatively superior resistance to weathering.

CONCLUDING REMARKS

For purposes of topographic description and interpretation of subaerially produced topography, no better framework of reference than the erosion cycle of Davis has yet been devised. Historically it is only natural that humid-climate topography should have been considered first, although areally it is far surpassed by the arid and semi-arid types. However, the shortcomings of the Davis system appear to have been in the realm of detail recognition and correlation rather than in fundamentally limited applicability. A concept so useful cannot and should not be abandoned, though it must be augmented and improved where possible. In particular, the many varieties of stream-developed topography over the Earth should be considered from the standpoint of their similarities and common elements, so that their distinctive differences shall then be seen in proper systematic relationship in a single comprehensive and adequate scheme.

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