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The Uniformitarian Nature of Hillslopes

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ABSTRACT

The nature of hillslopes is examined, and their importance in landscape is assessed. The denudational processes operating upon hillslopes are examined and found to be manifold; producing ideally four specific elements in hillslopes, each of which has a distinct mode of evolution. The evolution of hillslopes under the action of denudational processes is evaluated in terms of physical science—involving surface flow of water and mass-movement of soil and rock, and is found to be dependent upon intrinsic strength of the bedrock and available relief. It is almost independent of climate, *per se*, and similar hillforms may be found under like conditions of bedrock and relief in all climatic environments short of glaciation or wind-controlled, sandy deserts.

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I. INTRODUCTION

Our concern is with the study of the earth's surface and its development under the normal agencies of denudation; and particularly with the evolution of hillslopes. Upon this topic, one of the most important advances was made by James Hutton in whose *Theory of the Earth* appears the first clearly-stated, all-embracing vision of the dynamic evolution of landscape. Therein, under the concept of Uniformitarianism, hillslopes are regarded as modified under denudational agencies operating now as they have operated in the geological past, and as they will undoubtedly continue to operate in the future. From this dynamic approach in the study of landscape modern researches begin.

They continue with the rise of geomorphology, or physiography as it was then called in America, towards the end of the last century when much attention was directed to two agencies of landscape evolution (*a*) erosion by rivers, and (*b*) weather-

ing of interfluves, the emphasis in each case being, and remaining, empirical. The rivers were deemed to cut their beds down rapidly to a state of grade, related to base-level, and when this phase was passed, weathering in turn reduced the interfluves so that the relief was diminished to the ultimate stage of a peneplain (Davis, 1909).

Of the precise nature and evolution of the hillslopes that intervened between the river courses and the divides little account was taken though these hillslopes constitute, indeed, almost the whole of a normal landscape. One searches the literature almost in vain for any discussion of hillslope forms under evolution: even where the master geomorphologist William Morris Davis (1909, p. 734) set forth his so-called " Normal Cycle of Erosion " he found no better exposition than that the hillslopes flatten progressively and become convex in cross-section, a statement that, alas, all too frequently finds no support in natural landscapes. Only towards the end of his life (1930) did Davis begin to see and describe hillslopes truly as they are displayed in nature (see King, 1953; Cotton, 1955).

Meanwhile, the uncompleted studies of Walther Penck (1924), now available in an excellent English translation (Penck, 1953), suggested very strongly that major hillslopes do not flatten progressively during a long evolution but that, having achieved a stable form consonant with local geological controls, the hillslopes thereafter retreat parallel to themselves without further flattening. This conclusion is as basic to landscape study as Hutton's uniformitarianism. Unfortunately, Penck's brief life did not suffice for the clear exposition of what he saw truly in the landscape, and his accounts of hillform evolution are confused by the introduction of erroneous and irrelevant concepts relating hillform to rates of deformation of the earth's surface. These irrelevant concepts were readily refuted as they deserved to be; but unfortunately most geomorphologists "threw the baby out with the bath water" and rejected Penck's accurate observations of hillslope form as well.

Only one prominent exponent of " parallel scarp retreat " remained during the thirties of this century, the American Kirk Bryan (1940), who escaped the general condemnation by confining such practices solely to desert landscapes and leaving the " humid " landscapes free to flatten as prescribed by tradition. Considerable research was directed towards the " peculiar " processes by which desert topography was thought to evolve, but the precise operation of hillslope processes under humid regimes was considered too well established to require investigation.

The viewpoint that landscapes evolve very differently under arid, semi-arid and humid influences has long been promulgated, and is widely accepted at the present time. Our thesis will be that the basic physical controls on landscape remain the same in all climatic environments short of the frigid or extremely arid. Water moves over the earth's surface by linear or by laminar flow and in no other way; mass movements of soil and rock are executed under immutable physical laws. Horton (1945) expresses this concept: "The geomorphic processes we observe are, after all, basically the various forms of shear, or failure of materials which may be classified as fluid, plastic or elastic substances, responding to stresses which are mostly gravitational but may also be molecular . . . The type of failure . . . determines the geomorphic process and form." Only in their relative proportions may the agencies responsible for epigene landscape evolution vary, and then only within narrow limits. Hence, as we hope to demonstrate in the sequel, the manner of hillslope evolution is essentially uniformitarian in all climatic realms outside the frigid zones and the erg deserts.

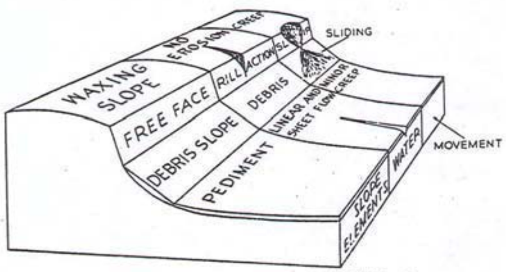

FIG. 1. Elements of fully developed hillslope.

II. Hillslope Elements

The starting point for modern hillslope study is the analysis of hillslope form by Wood (1942) who distinguished the four elements that appear in a fully developed slope. These are, from the top: the *waxing slope*, the *free face*, the *debris or talus slope* and the *pediment* (Fig. 1). Each element undergoes a semi-independent evolution though, of course, on a given slope the elements to a greater or less extent react upon each other. Any element may be absent from a given slope, which is then not fully developed.

These matters have already been discussed (King, 1953) and been made the subject of a number of Canons of Landscape Development.

Wood's contribution is sufficiently important to rank with the fundamental discoveries of Hutton and of Penck, and like them

it is basically uniformitarian in character for it applies to hillslopes all over the world, in all stages of development, and indeed of all geological ages.

Let us briefly review the four elements and state the essential qualities of each. The *waxing slope* is the convex crest of a hill or scarp, usually related to the zone of weathering and measuring from an infinitesimal portion to half the total length of hillslope. It is usually longest where the depth of surficial detritus is greatest, *e.g.* in formerly periglacial regions, or where rivers and streams have recently become incised and the hillslopes have not had time to adjust to new stable conditions.

The *free face* is the outcrop of bare bedrock exposed, perhaps as a scarp face, on the upper part of the hillslope. It is the most active element in backwearing of the slope as a whole.

The *debris slope* consists of detritus slipped or fallen from the free face and resting at its angle of repose against the lower part of the scarp face. As this debris is weathered to finer detrital grades it is removed under erosion and so the debris slope retreats in essential conformity with the free face above. Clearly, if the free face retreats more rapidly the quantity of waste supplied will build up the debris slope to bury the lower scarp face, so that a balance is generally struck between these two elements.

The *pediment* is a broad concave ramp extending from the base of the other slope elements down to the bank or alluvial plain of an adjacent stream. Frequently its profile approximates to a hydraulic curve and it is unquestionably fashioned under the action of running water, though the cutrock surface may often be mantled with surficial deposit.

These four slope elements are to be found in hillslopes all over the world and in all climatic environments; and though locally one or more of the elements may be suppressed, such departures afford no contradiction of the normality of full development.

III. The Agents of Denudation

Hillslope evolution, with production of the several elements, is clearly a function of denudation, involving two phases (*a*) production of land waste, and (*b*) removal of land waste. Accordingly as denudation produces, and removes, land waste so the several elements may appear in virtually any order and in any combination. To understand the development of hillslopes, therefore, we must enquire into the working of the agents of denudation that operate upon the landscape.

The principal agents responsible for denudation are (*a*) running water and (*b*) mass movement. Both are expressions of gravity control and involve overall movement of waste in the downward sense. Wind and glacier ice, which on occasion may carry land waste to higher levels, are of local and restricted dominance. The " flow " of land waste over normal landscapes is downward and lateral, and this is fundamental to the development of such landscapes.

At this juncture a study of the physical laws under which water flows and debris moves over the skin of the earth becomes imperative. Empirical study of existing hillslopes, which has dominated geomorphological thinking hitherto, fails to give the quantities that we need to know, and fails to afford a dynamic concept of the operation of the forces at the surface of the earth.

IV. The Flow of Water over Land Surfaces

The flow of water over a land surface is a matter of hydraulics, and to hydraulics geomorphologists must now turn for enlightenment, following the lead so admirably given by Horton (1945). But although the quantities have mathematical expression to be found in text books we shall eschew the exactitude of symbols and formulae for more general statements in conformity with the constantly fluctuating conditions present upon natural land surfaces across which water is passing.

For water flowing away from the crest of a divide, there is a critical distance over which no erosion takes place. The reason may be stated simply: flowing water cannot erode a slope until erosive power exceeds the resistance of the soil to erosion, or in other words until the turbulence of the water can overcome the cohesion of the soil. At the top of each hill therefore appears naturally a zone of no erosion under water flow, with a non-concave profile corresponding morphologically to the waxing slope of Wood's analysis. Clearly, the greater the proportion of infiltration into the soil, the wider this zone is likely to be, so that on porous soils and bedrock the waxing slope attains maximum width. As examples we may quote the broad convexity of hilltops upon the boulder clay of midland Britain and the chalk country of southern Britain and France, and contrast them with the minimal summit convexity expressed on hard granite and quartzite terrains in Africa where the proportion of runoff is high.

As distance from the water-parting increases, so also does the volume and erosive power of water flowing in rills over the surface of the ground. Even upon a slope of originally uniform gradient, once the critical distance from the water-parting is passed, erosion by rill-wash supervenes and steepens the profile, improving still further the erosive power of the rills. This portion of the hillslope rapidly becomes steeply concave and is

relatively sharply marked off from the waxing slope above.[1] Frequently, the closely spaced rills cut through superficial deposits to the bedrock which may be exposed as " free face " either locally or in continuous exposure as a scarp. Even where a " free face " is not developed the soil is thinnest and poorest and is removed most rapidly in this zone.

Under water wash the middle slopes of major hills inevitably become the steepest, and most actively eroded, element, and hence the retreat of hillslopes and scarps is equally inevitable once the critical limit from the water parting is passed.

Corrasion implies a corollary of waste removal and so the land waste that is actively produced in the upper part of a steep slope is necessarily washed downwards on to the lower part where also the velocity of the surface wash is checked as the controlling base-level of a neighbouring stream is approached. Corrasion diminishes, or even ceases, and the greater part or even the whole energy of the flowing water is devoted to transporting the debris to the local stream. Its efficiency in this task is measured by the extent of the debris zone (the third element in the hill-slope profile) below the free face. Only under very favourable conditions of hard bedrock yielding little waste does the debris zone vanish entirely, leaving a sharp angle carved in bedrock at the foot of a steep hillside. " Inselbergs " afford perhaps the best and most numerous examples of this (Plate VII, A, B).

Following the cutting of a steep hillside by rill and gully action, and perhaps also retreat of the scarp so formed, surface water requires to be discharged across a relatively flat terrain to an adjacent stream channel. This relatively smooth, flat zone is the pediment. The amount of water to be discharged across the pediment is a maximum including all the rainfall of the upper slopes, minus infiltration, together with precipitation upon the pediment itself. In cross section, therefore, mature pediments exhibit the smooth concave profile of a hydraulic curve on which the gradients range commonly between 7° and ½°. Longitudinally, pediment surfaces are often surprisingly smooth with a rise and fall along the inner edge at the foot of the scarp face, the *low* points corresponding to the emergence of gullies through the scarp. Throughout, the pediment, a product patently of water flow, is so adjusted as to impart the maximum efficiency to water flow and in times of heavy rainfall it may often disperse the water flow in sheets. The operation of sheet flow upon

[1] The rapidly increasing convexity often observable towards the edge of the waxing slope may be interpreted as a transitional sub-zone, dependent upon fluctuation in rainfall and runoff, where sometimes the tendency will be to form a convex surface and sometimes a concave surface accordingly as runoff is lighter or heavier from hour to hour or minute to minute. It is sometimes well developed in mist belts.

pediments has been observed in nature (King, 1953) to conform with hydraulic principles and especially the operation of the quantity called Reynold's Number. Under favourable conditions true laminar flow (without turbulence) has indeed been observed towards the inner edge of pediments (King, 1953). But such a system cannot be perfect in nature over more than a small area and within a limited time. Hence the zone of laminar flow, dependent upon a favourable conjunction of precipitation rate and surface smoothness, is often elided, and rill-cutting and gullying appear extensively upon many pediments. The remarkable thing, bearing in mind the general irregularity of ground surfaces, is that the zone of laminar flow should appear in nature at all.

As the sheet of flowing water thickens beyond the inner zone of the pediment, laminar flow breaks down and turbulent sheet flood supervenes. This is the agent primarily responsible for the hydraulic profile developed by pediments.

Under diminished incidence of rainfall, water coming on to the pediment from upper slopes, and the water falling upon the pediment itself, may be insufficient to form sheets and then passes across the pediment in rills only. Where this occurs frequently, pediments are, indeed, scored by rill channels.[2]

Land waste transported across pediments is usually in a relatively fine state, and when deposited in hollows often helps to smooth out any irregularities in the rock floor that have not been eliminated by erosion.

Pediments are best exemplified (King, 1953) on hard rock in semi-arid environments, where the transport of land waste across the terrain is most efficiently conducted. Any departure towards arid or humid extremes is attended by the accumulation of waste in the landscape, and cutrock pediments may to some extent become masked or buried. Nevertheless, pediments are fundamental elements of hillslopes formed necessarily, as we have seen, under the physical action of running water, and hence they appear with greater or less prominence in all epigene landscapes. They are by no means restricted, as American geologists would have us believe, to semi-arid and arid environments but may be admirably studied even in the Appalachians as Davis's paper of 1930 showed. English landscape, too, exhibits some clear pediments in the non-glaciated southern counties, *e.g.* Wiltshire Downs.

So we find that *the four basic elements of a hillslope, as analysed by Wood, all form naturally under the normal flow of meteoric waters across the landscape*: they reflect in form and

[2] In these studies, effects attributable to climatic fluctuation during the Quaternary are important, especially when related to the *incidence* of rainfall, which factor is more important than annual or seasonal total.

evolution the natural results of the application of hydraulic forces.

As the manner of water flow over land surfaces is prescribed by physical laws that are invariable over the globe, the four-element hillslope is the basic landform that develops in all regions and under all climates wherein water flow is a prominent agent of denudation. This includes all regions except those wherein the dominant agents are glacial ice or wind.

The question now arises, *must* all four elements be developed or may certain elements disappear under appropriate circumstances? The standard example that we have considered involves certain assumptions, the first of which is that, after stream incision, the relief available is sufficient for all four elements to appear one above another. Briefly, in regions of low relief insufficient height is available for all elements to be developed, and the first to disappear is usually the free face, followed by the debris slope. Also, where streams are closely spaced, the critical distance from the water parting over which erosion by water flow is ineffective may occupy a large proportion of the hillslope profile and the interfluves become in consequence almost wholly convex. Wide stream-spacing, on the other hand, favours the development of broad pediments and a landscape may result wherein convexity is almost absent from interfluves and more than nine-tenths of the landscape consists of pediments (*e.g.* parts of Rhodesia).

Further, a strong bedrock affording a clear free face tends to provide a fully developed slope with all four elements clearly displayed; but a weak bedrock readily breaking down under weathering, tends to eliminate the free face and produce a degenerate, smooth convexo-concave profile in which the waxing slope from above meets the pediment from below in a smoothly reflexed curve. (Such slopes are common in parts of northern Europe and are achieved principally by prolongation downwards of the waxing slope from above. In Africa, however, the pediment slope is usually prolonged upward. These differences may arise from lighter and heavier incidence of rainfall respectively, or from the prevalence of solifluction in northern latitudes following the Quaternary ice age.)

Considerable range of hillslope form is therefore possible under differences of relief, bedrock, stream spacing, and other variables, but none of the resultant landforms depart from the basic elements; and the fully developed, four-element slope remains the most vigorously retreating, active type of all. Other slope forms, involving a reduction from the maximum of four elements, are decadent and may even atrophy (as shown by a failure of active retreat; unless the migration of Baulig's inflexion point represents retreat).

The optimum hillform, in physical terms, is clearly to be sought in regions of hard bedrock and strong youthful relief. It is exemplified by the bornhardt or " inselberg " in which summit convexity is small, most of the hillslope consists of bare, rocky free face, the debris slope is minimal, and the main hill-form rises abruptly from an extensive pediment (King, 1948). While many bornhardts owe their form in part to decomposition of the rock or to splitting off of slabs at curved joints, in the hardest gneisses such disintegration is suppressed and the surface of the bornhardt is channelled and fluted by rill action, *e.g.* in Rio de Janeiro and Espirito Santo.

On hard rocks which disintegrate to give only very fine debris, readily washed away, inselberg landscapes may appear in miniature even though the relief is very small (Plate VIII, A).

The margins of inselbergs, it should be made clear, bear no necessary relation to local geological structures. The same rock types (and the strike) pass without distinction from the upper slope into the pediment (Plate VIII, B).

V. Mass Movement of Rock Waste over Land Surfaces

In addition to transport of land waste by flowing surface water much rock detritus moves from higher to lower levels under the influence of gravity: by creep, slip, slide and flow (Sharpe, 1938). Such movements are controlled by the physical laws governing the behaviour of earth materials under stress.

Illuminating data upon the behaviour of ideal materials are available in text books of physics, and describe the behaviour of perfect-elastic, perfectly viscous, viscous-elastic and firmo-elastic bodies, also the nature of friction—static and sliding. These are topics with which the geomorphologist must be familiar if his researches are to have real meaning, but which find scant reference in a majority of geomorphic texts. The first report of the Commission for the Study of Slopes (Rio de Janeiro, 1956), for instance, makes little mention of such vital topics and most of the contributions are in the old empirical tradition of geomorphology.

But hard and fast classifications of the phenomena are difficult to maintain because of the frequently heterogeneous nature of the materials involved. Most geological materials are of the viscous-elastic type (the Maxwell body of physicists which deforms according to the equation:

$$\tau = \mu \dot{\gamma} = G\,T\,\mathrm{rel}\,\dot{\gamma}$$

(Stress = viscosity × strain = Young's Modulus × Time of relaxation × strain)

This means that they deform in either or both of two ways according to the manner of application of stress. If the stress is moderate and is applied suddenly the material deforms elastically and if the stress is released the material returns to its original undeformed state. Should the stress be very great that material

may be stressed beyond its yield limit (as defined by the cohesion of the molecules), when the material fractures, so that the stress is suddenly released. On release of stress there is no return to the original state.

Alternatively, however, small stress may be maintained over a prolonged time interval, when release of strain may be achieved gradually by plastic or viscous deformation within the body. The resulting deformation is permanent, and is a function not only of stress but also of time.

All hillslope studies must take cognisance of this dual mode of failure of earth materials—by fracture and by flow—especially as the superficial types of rock matter (sands, silts, clays, weathered and unweathered sandstones, shales and limestones) are generally susceptible of either mode of deformation within the lapse of time covered by a fraction of a cycle of erosion. Illuminating discussions on these topics are by Sharpe (1938), Ward (1945) and Horton (1945).

We may now apply these concepts to the study of mass movement of land waste down a typical hillslope. Towards the crest or divide the amount of waste produced under weathering and requiring to be transported is small; in consequence the natural slope is probably gentle, and soil relatively stable. The only lateral mass movement likely is by creep (a result of simultaneous action of both gravitational and molecular stresses), and even this may be minimised where slopes are very gentle, as is shown by the development of lateritic duricrusts (a product of advanced chemical weathering) upon very flat, ancient divides. With increasing distance from the crest, the quantity of material requiring to be transported increases in direct proportion if the bedrock weathers at a uniform rate. Hence for disposal of the waste by creep the slope must steepen progressively, *i.e.* the slope must become convex and the waning slope of Wood's analysis develops. Creep is a function not only of stress but also of time so that low divides may ultimately develop very broad convexity.

As the steepness of a convex slope increases with distance from the divide so also the stresses increase until accommodation by creep becomes inadequate. On a slope of considerable relief stress may thus be increased beyond the elastic strength of the material (*i.e.* the yield limit is passed) and rupture ensues, accompanied by slipping and sliding of material. (Motion follows because the stresses built up prior to fracture are much greater than the stresses required to move the mass once the bonds across the surface of failure are overcome.)

Slipping occurs characteristically upon arcuate (nearly circular) sections and hence such slipping leaves behind *a steepened arcuate section* in the hillside. In this way, free movement of material tends to steepen middle or upper hillslopes; in other words, it produces a free face, which will continue to retreat by calving off further slices consecutively behind the slip scar. This phenomenon is all too familiar to engineers and geologists concerned with stability of hillslopes and road cuts.

On suitably steep situations, material may not slip out upon curved fractures but may fall freely, roll or bounce from higher to lower levels. Static friction is greater than sliding friction and movements once triggered may continue for a distance and time limited only by the relief and the nature of the country rock.

The detritus from slips and slides then accumulates as a talus below, adding the third element, " the debris slope," to the hillslope profile. Resting in place a talus weathers and the finer products of weathering pass downward through and over the mass, the finer being transported the farthest, so that the toe of the talus flattens into a concave profile, a pseudo-pediment or perhaps a bahada, thus adding the fourth slope element. At this stage the action of running water can no longer be ignored, even in deserts, and the final transport of rock waste over the flat, lower hillslopes is seldom, if ever, by gravity alone.

Like water flow, the natural action of mass movement tends, therefore, to produce a fully developed, four-element hillslope, each component of which is capable of semi-independent evolution. This both agencies can do even from an originally uniform slope. For this reason we must mistrust all analyses which treat hillslopes as though they were simple landforms from top to bottom. Even mathematical treatments on such a basis possess no real validity. Thus the purely mathematical treatment of ideal homogeneous media by Bakker and le Heux (1ier Rapport, Comm. de l'Etude des Versants) does not really aid geomorphologists, who derive much more assistance from the mathematical studies by engineers who have learnt to deal practically with earth materials (see later).

We return to the former question asked under water flow, *must* all four hillslope elements arise under mass movement, or may elements be suppressed under certain circumstances? The answer given is the same. Full development of all four elements is dependent upon local factors, chief of which are adequate relief and strong bedrock. Failing these, the free face tends first to disappear, followed of necessity by the debris slope. A decadent convexo-concave hillslope results. As relief is necessarily low over most of the country in the later stages of a cycle of erosion, a broad convexity often appears spreading laterally from the divides in the penultimate stage of interfluves already reduced by dominant pediplanation (scarp retreat and pedimentation). This *semblance* of peneplanation by downwearing, acting during the penultimate stages of the erosion cycle, has been mistakenly thought to have been operative *throughout the*

cycle. All stages may be observed consecutively in spurs reaching forward from a major scarp. Near the scarp they are steep-sided and dominantly bi-concave in transverse section. At the distal extremity they are low and become convexly rounded. Baulig (1956, fig. 1) illustrates by a migrating inflexion point the evolution of such decadent slopes and spurs.

Pallister (1956) found in Uganda the normal four elements of hillslope profile, and also that parallel retreat was typical until the final stages of degradation when flattening occurs. This is in a humid tropical region of deep weathering and soil, and again it shows the independence of slope development from climate. The relief is only 400 feet and quite half of this is lost relatively quickly during the stage of scarp retreat so that the remnants of laterite pertaining to the initial " mid-Tertiary " summit surface are now scattered and small in area. Most of the terrain thus now falls under the class wherein relief is so small that slope flattening now dominates by both water-wash (which maintains concave pediment forms) and mass movement (which tends to cover and obscure them and introduces convexity on the lower slopes). Where this latter is prominent (Dixey 1955) " we arrive at a very gently undulating surface that is very close to the general conception of a peneplain." But, of course, this is only in the senile landscape; the full vigour of change from the " mid-Tertiary " to the modern aspect of Uganda was accomplished (as Dixey and Pallister point out) by scarp retreat and pedimentation—there was no peneplanation in the Davisian sense in the production of the later cyclic landscape from the first.

After landscape has been reduced to low relief by scarp retreat, *two* kinds of old-age surface may appear (*a*) where water-wash is dominant, and upon hard rocks (such as may be widely seen in Africa), the land surface is multi-concave upwards, (*b*) where mass movement is dominant, and upon weak rocks, the surface may show both concavities and convexities perhaps with the latter more obvious in the landscape, as in parts of northern Europe.

Our manner of treatment has overemphasised the independent roles of water flow and mass movement, idealising two separate systems as it were. But in nature these seldom act independently, rather they aid and abet each other, and the phenomena appropriate to one system pass by gradation into those of the other. Thus dry materials commonly exhibit high cohesion and tend to deform elastically and slowly until the yield limit is passed, when rupture takes place and sudden motion ensues along localised planes of maximum shear. But the same materials in the wet state may lose much of their elastic strength and deform plastically by flow. Any clots of elastically strong materials are carried along upon the flow, as blocks of hard rock may travel " bobbing like corks " upon the surface of a mudflow.

A plastic flow will stop on a slope when the yield limit is raised or the stress falls below the yield limit. Hence most mudflows come to rest upon lower hillslopes where the gradient flattens though some may continue until they block stream channels in the axis of a major valley. Critical at this stage is the amount of water present in the mass (and consequent fluidity). When the proportion of water is very high, fluid rather than plastic flow ensues and flow does not stop until the end of the slope is reached. Thus the phenomena pass over into the water dominant realm of hydraulics, the solid particles being carried discretely in a medium of low viscosity, that is, in suspension in water. The phenomena of denudation under mass movement and under water flow are thus amenable in the ultimate to a single, unified physical treatment. In consequence, also, much of the supposed distinction between " peneplanation and pediplanation " (Cotton, 1955; Holmes, 1955; Baulig, 1956) disappears from the consciousness of the field observer who finds all types of gradational processes operating upon hillslopes in every quarter of the globe —and every type of resultant hillslope.

The general physical relations of hillslope elements are now clear. In nature, of course, many complexities may be introduced by erosional factors such as renewed or continuous stream incision and lateral stream corrasion at the foot of slopes. Non-homogeneous bedrock, of course, may produce strongly scarped free faces on resistant rocks above, while the ends of minor spurs on weak rock below are convexly rounded, a combination which illustrates clearly the fallacy of peneplanation throughout the cycle. Dixey, Pallister and Fair, all of whom subscribe to the doctrine of pediplanation dominant in the cycle, severally discuss the function of a hard caprock in slope form. Such structures do not involve any departure from the general principles of slope development. Infinite variation exists to delight the geomorphologist in the field, but the basic plan is surely clear and simple.

Yet there is one case that we must consider further, bearing in mind the dependence of hillform, and particularly the development of an actively retreating free face, upon the factor of *relief*. Beyond a critical measure of relief, upon any type of bedrock, a free face *must* develop under the physical agencies discussed above.

Where landscapes have been warped or tilted, therefore, by an amount exceeding this critical measure a scarp inevitably develops upon the displaced surface and separates higher and lower portions of what were once the same landscape now appearing at different levels. Where the cumulative uplift is sufficiently great such effects may be multiple, giving rise to a stepped landscape whether the uplift was intermittent or continuous.

Thus the piedmont-treppen concept of Penck, demonstrated in the field in many lands, is proved valid and inevitable under the natural physical laws governing the development of tectonically active terrains. In the light of modern knowledge, the Davisian analysis (1932) is quite unsound.

VI. Some Typical Earth Materials and their Behaviour under Stress

Laboratory study of earth materials as carried out by engineers concerned with the stability of works yields data of importance to students of hillslopes. We note, therefore, some of the more useful contributions from this source.[3]

Sand. Even so simple and inert a substance as quartz sand exhibits quite contrasted properties when stressed, accordingly as its state is dense or loose. A densely compacted sand increases in strength when stressed for deformation implies an increase in volume. Loosely compacted sands, however, decrease in strength when stressed as the grains fit more closely together and the volume decreases. Loose sands cannot stand more steeply than the angle of internal friction (angle of repose), and this is the same whether the sand be wholly immersed in water or in air, but compacted sands may stand in vertical or even overhanging faces when capillary water or salts give intergranular cohesion.

Clays. Not only are clay minerals more complex in constitution, but the grains are commonly flattened so that, fitted together, they leave a much larger proportion of pore space than do normal sands. Clays as a mineral group are therefore relatively porous. Furthermore, the particles bear a negative electric charge which becomes large when compared with gravity or the mass of a particle. The charge is sufficiently strong to ionise adjacent water, and hence a layer of water about two molecules thick is held rigidly in contact with the grains. Because of this, clays do not compact like sand, but retain an open void structure between the grains and remain porous.

Only when sufficient stress is applied to overcome the rigidity of the bound layers of water and destroy the open structure of clay mass do clays compact. Such overstressed clays are no longer porous and lose many of the properties normally associated with clays. These properties are not regained with time, as may be observed in clays of significant geological age that have been subjected to stratigraphic loading. Destruction of the original structure leaves a consolidated clay that is widely traversed by minute fissures. Relief of load, as by denudation of overlying strata, permits the fissures to open slightly and admit water extensively through the mass. Such clays, of which the London Clay is an example, are very weak. Many details of surface

[3] In the preparation of this section I have been greatly aided by Mr. N. Hobbs, Lecturer on Soil Mechanics at the University of Natal, South Africa, to whom my sincere thanks are here expressed.

weathering in stiff Tertiary clays, *e.g.* crumbling, may be traced to this factor.

The shear strength of clays varies hyperbolically with water content; with some qualification upon the type of test or loading conditions in the field. A slowly applied load squeezes out the water and the strength increases. With rapid application of load the clay is subjected to conditions comparable with an undrained test, when with constant water content the strength remains constant.

Valid differences exist between sodium or marine clays and calcium clays. The former have a strong adsorbed layer of water and are more resistant to stress. But leaching of salt may reduce the strength of the clay considerably. Loss of strength from this cause may be cured by pumping in salt water. Most clays in water-laid sedimentary sequences are of this type.

The calcium clays, on the other hand, have only a thin adsorbed layer and comparatively large pore space. Hence such clays disintegrate more readily and the particles are readily dispersed by wind to accumulate elsewhere as loesses, parnas and calcium-rich aeolian soils.

Application of properties such as these can aid geomorphologists materially in understanding the behaviour of earth materials upon hillslopes; but even more useful are the analyses of stress relations in hillslopes and engineering works. What, for instance, are the conditions of stability pertaining to a vertical wall cut into sand or clay?

The treatment is standard: such a cut can retain its form until the height becomes so great that the shear stress overcomes the cohesion between the particles. The stress conditions are illustrated by Fig. 2, the corresponding equation for which is

$$\text{Horizontal Pressure } P_A = \frac{1-\sin\phi}{1+\sin\phi}\, 4\,\gamma\,\frac{H}{2}$$

For a specific material the expression $\frac{1-\sin\phi}{1+\sin\phi}$ will be a constant (K_A). *The horizontal pressure increases with depth, and there will be a critical height beyond which any given material cannot stand unsupported.*

For clean sand, which has no cohesion *per se* the height of such an excavation is clearly zero. But if the material has cohesion (c), then the critical height may be derived:

$$H_{crit} = \frac{4c}{\gamma\sqrt{K_A}}$$

if ϕ equals 0, then $H_{crit} = \frac{4c}{\gamma}$

and as an example we may quote a dense clay in which c equals 1,000 lb./sq. ft. when γ equals 200 lb./sq. ft. The critical height is 20 ft.

Or, in a rock with a cohesion of 3,000 lb./sq. in. and a K_A of ·25, subjected to a stress of 288 lb./sq. ft.:

$$H_{crit} = \frac{4 \times 3{,}000 \times 144}{288 \times \cdot 5} = 12{,}000 \text{ ft.}$$

which approaches the height of some of the highest mountain faces in the Himalaya.

These examples show the control exercised by rock cohesion upon (a) *the development of a free face,* (b) *the maintenance of a free face.* Also, the concept of critical height explains clearly the necessity for adequate relief in a landscape if a fully developed, four-component slope is to be generated, and also the inevitable appearance of piedmont treppen in tectonically rising regions.

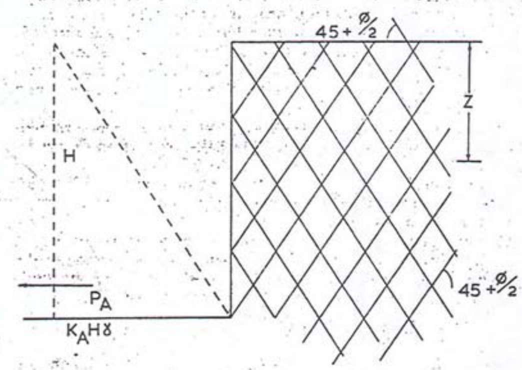

FIG. 2. Vertical wall stresses.

In nature few rocks are massive and devoid of minor planes of weakness. Where such planes exist, failure takes place much earlier and occurs not upon the theoretical planes of mechanical analysis but upon the weak planes themselves. This is especially so if these planes dip towards the face, when the problem of stability involving static friction along the plane may be solved by inclined-plane mechanics.

Virtually the only rocks in which few weak planes appear are those of plutonic origin: the granite-gabbro suite with regional gneisses and charnockites. It is amid these massive rocks therefore that the greatest smooth rock faces are displayed giving rise to the famous bornhardt or inselberg type of landscape wherein the free face attains maximum development among the tetrarchy of slope elements (*e.g.* Africa, Rio de Janeiro). As I remarked in an earlier work (King, 1948) these characteristic landforms are the combined result of (*a*) rock type, (*b*) scarp retreat following (*c*) incision in a new cycle of erosion. Also, such rock types may be expected to develop free faces in a minimal relief, as indeed they do (Plate VIII, A). These landforms owe their existence not to any peculiarity of climate or weathering (indeed they occur in all major climatic environments) but to the massive quality of the rock between joint planes.

It is to be hoped that geomorphologists will be encouraged to employ the observations and methods of engineers more freely in their future studies of hillslopes.

VII. Some Secondary Factors

The transport of waste over land surfaces does not take place without physical and chemical changes in the materials that may result in the production of soil. Raw soil, as developed in deserts, may consist only of disintegrated fragments of rock and crystals. Such primitive material has no coherence and is readily washed and blown away.

Under weathering, the feldspars decay and produce clay. Coherence is an essential property of clays, meaning in terms of geomorphology that the surface deposits, bound by fresh molecular forces, now exert a definite activity in the development of hillforms that is in essence opposed to that of the agents of denudation. To clay is added the binding effect of roots as plant growth is established, and ultimately the addition of humus, a fresh product with bonding properties.

The soil thus passes through a series of changes in which its physical constants, as they affect hillslopes, are profoundly modified. As coherence is in general increased with advancing soil maturity the effectiveness of denudational forces is diminished—both water flow and mass movement—and the sharp distinctions between the four elements of hillslopes and other asperities tend to blur until, finally, smoothly degenerate, convexo-concave slopes tend to be produced.

These changes may be linked with climatic and vegetational factors, which has led to the erroneous view of control of landforms by climate, but the basic controls are still the physical constants of specific earth materials.

Soils

The development of soils implies a local sedentariness in the mantle of waste; but widespread removal of soils is no less real, and apart from the duricrusts no ancient soils seem to have survived from much before the Quaternary Era. Mature soil profiles are only a few inches or feet in thickness, and a thin planing or skinning of the surface, almost negligible to the geomorphologist, may nevertheless result in the total loss of a soil profile acquired only after 100,000 years, or more, of surficial stability. Familiar though I was with the poverty and precariousness of African soils, I was surprised on a recent study tour of Australia[4] to find in some districts how widely and how often, even in that continent of extensive duricrust, the soil mantle had been stripped in geologically recent time. The stability of the waste mantle represented in the production of soils seems therefore to be, in geomorphic essence, transient.

Vegetation

Even though soils themselves may be geologically transient they exert an influence out of all proportion upon the stability of hillslopes through the nourishment which they provide to a vegetal cover. How many hillslopes, stable beneath a close mat of grass with its binding roots, would remain so if the grass were destroyed? And is not the soil conservationist's primary objective to make grass grow? The presence of vegetation, particularly grass with its close binding roots, alters the physical cohesion of soil aggregates and so minimises the development of a free face, either by gullying or stripping and encourages the development of convexo-concave slopes.

Climate

Perhaps it is significant that most of the supporters of climatic interpretation of denudational cycles have come from the ranks of geographers, not geologists. Most of the landscape differences that they quote arise not from climate at all, but partly through the nature of vegetation. Thus the influence of carpet grasses, as contrasted with tufted grasses, upon the physical properties of soils and their erodability under water wash and mass movement may be profound, and productive of significant differences in the elemental proportions of a hillslope profile. Basically these are still controlled by the physical properties of bedrock and waste mantle. Climate is not the fundamental controlling factor at all.

Bornhardts (inselbergs), for instance, were first described from East Africa, and from studies in Southern Africa Passarge referred to them as a special product of *arid* denudation. The multitudinous bornhardts in the maritime states of Brazil were later attributed by de Martonne to a special kind of *humid tropical* denudation. Similar hillforms occur occasionally in the *sub-*

[4] Under the guidance of Mr. Bruce E. Butler of the Soils Division, Commonwealth Scientific and Industrial Research Organisation, Canberra, Australia.

tropical coast belt of Natal; and numerous others, of which Stone Mountain, Georgia, is an example, appear in regions quoted as of "*normal humid*" climate. Comparable rock faces are known in the south-west of New Zealand which is *wet, cold temperate;* and even from the Antarctic in Queen Maud Land. Bornhardt hillforms are thus recorded from every climatic environment on earth. What are the real common factors in all these, and other, occurrences? Hard, massive rock types, and plenty of relief! The physical properties of earth materials govern the development of bornhardts, as indeed of all hillslopes, wherever they are.

Currently, many slope profiles are being surveyed in attempts to probe the manner of slope development; but how seldom are these profiles related to adequate studies of the physical elastic constants of the rock and soil variants below? As matters of observation iron falls faster than cork, and cork faster than feathers—but the physicist has long since appreciated the basic principle of gravitation. So must the geomorphologist appreciate what he is measuring, in physical terms, on a hillslope before proceeding to theorise upon the evolution of such slopes.

Reverting to the use made of data upon earth-materials by engineers concerned with the stability of works, may we remind ourselves that though these practitioners measure carefully the physical properties of the materials with which they deal, they seldom consult the local climatologist!

And, lastly, during the past six years I have travelled over 100,000 miles in five continents, patiently observing all types of terrain and endeavouring humbly to let it teach me, and the abiding impression I have received—despite admittedly minor differences due to local structural, tectonic and climatic factors—is of the essential and basic uniformity of landforms and their evolution in all environments. *As a matter of direct observation all forms of hillslope occur in all geographic and climatic environments.*

The basic homology of all landscapes needs to be appreciated before the differences which, in literature, have been unduly magnified. Within the basic homology, as stated formerly (King, 1953), the standard evolution of landscape is at its optimum under (*a*) "semi-arid" regimes, when waste is most efficiently removed from the surface and retreat of scarps is perhaps at a maximum. Deviation from the semi-arid mean decreases the effectiveness particularly of water wash, and hence waste tends to accumulate at points within the landscape and clog the physical system.

At extremes of aridity wind becomes a potent agency and may dominate over running water as in the *erg* or desert sand sea, while at the opposite extreme the action of glacial ice supersedes that of freely flowing water. These are extremes when the action of the usual physical forces are partly opposed or suspended.

But before either extreme is reached there exists a field wherein abnormal developments occur. Periglacial conditions, including frost action, have exercised widespread effects upon soil and superficial deposits (cryopedology). Of the real extent of such modifications geomorphologists have only recently become aware. All of North America beyond a southern fringe has felt the periglacial touch of the Pleistocene ice age; and according to a statement by Edelman, in Europe only the *terra rossa* soils of the Mediterranean are free of periglacial influence. In New Zealand such effects are now recognised near Wellington (Te Punga).

How then can the landforms of such regions be quoted as "normal" or standard for comparative purposes either now or for the long corridors of the geologic past? They can no more be accepted as "normal" or standard among geomorphologists than a contaminated substance can be accepted as a standard of purity among chemists.

Studies upon the hillslopes of these regions, lacking uniform control during their history, need further analysis in terms of multiple controls, and full of interest though they may be, fall for the time being beyond our present scope.

VIII. Conclusion

As the physical laws of water flow and mass movement are invariable over the land surface of the globe, and as the rock materials of which the upper crust is composed are sensibly the same in all lands, we reach the simple conclusion of a basic homology between the landforms developed under these physical agencies the world over. This has been borne out by field observation and laboratory study. So we conceive an *uniformitarianism of hillslopes* dominating the evolution of epigene landscapes that would surely bring a slow nod of approval from the shade of James Hutton, gentleman and geologist, late of Edinburgh.

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