MORPHOLOGICAL ANALYSIS OF LAND FORMS

A CONTRIBUTION TO PHYSICAL GEOLOGY

BY
PROF. DR.
WALTHER PENCK

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PREFACE

This work of Walther Penck's was published posthumously by his father, the famous geographer Albrecht Penck. The latter's preface points out that for ten years his son had been carrying on his investigations into the course of crustal movements, making use of the earth's surface forms as starting point. In 1921 he termed this method *morphological analysis*. A letter, written in 1922, outlined his plan for a projected work, larger than what he actually accomplished before his early death in 1923.

The first chapters have the titles found in the present book—up to 'Development of Slope'. He wrote '. . . development of the entire slopes and their dependence upon the downcutting of running water . . . I thought of then continuing with erosion by running water. But that will not do, since the work of running water depends not only upon the water, but more especially upon the gradient down which it flows; and the gradient is dependent upon the movement of the earth's crust. If this rises rapidly, the angle of inclination is great (since the area concerned then rises high above its surroundings); if it rises slowly, the angle of inclination is produced slowly, and remains slight. Thus, dealing with erosion, I have already come to the crustal movements which were to be my goal; and so I am compelled, like my predecessors, to go straight from the whole collection of the earth's land forms to the crustal movements, when I have not yet described the way in which those forms are to be observed. That will not do. What is this collection of forms? What does one see in mountains, in Swabia, etc., over the whole world? *Surfaces, denudational slopes*, make up the whole set of land forms. And it is where the surfaces meet downwards in valleys, that the rivers are to be found. Thus what we see is emphatically not the vertical incisions produced by running water, but only slopes which develop upwards, with a definite form, from the eroding rivers, *whilst* these are eroding. In brief: what is seen at the earth's surface is not land forms due to erosion, but merely a relief produced solely by the development of slopes. This slope development, however, is not possible by itself, but presupposes simultaneous downcutting by rivers. The eroding river creates the vertical distance between the height and the valley bottom; denudation, however, creates the slope, the material surface, which actually unites valley bottom with high-lying part. It thus follows that—after the slope development and its dependence upon erosion have been treated—the description of the land forms, i.e. of the relief of the earth's surface, must logically come next. It belongs organically to the investigation of the slopes, and not to that of erosion. There is no need whatever to know how erosion works, how it depends upon the movements of the earth's crust, in order to be able to describe the manner in which slopes are combined into a wealth of land forms, into form associations. This is controlled by laws, as comes out clearly in a presentation kept free from any interpretation. A presentation of the land forms found on the earth is no easy task! It could not be accomplished were there not quite definite relief *types* occurring in quite definite areas of the earth. I have now just finished the treatment of those types which are characteristic of the monotonous continental regions—such as Africa, Australia, etc.—and furthermore of the regions of uplift within those areas (e.g. the type of the German Highlands, with the Scarplands; this type is repeated all over the earth in zones of analogous structure). I am about to contrast these phenomena with what is to be seen in the mountain belts (these are the zones of mountain chains which border the Mediterranean Sea continuing across south and central Asia to the Pacific Ocean, and the analogous belt that surrounds the Pacific Ocean . . .). In this way I shall come to erosion, and after that to crustal movements. It will then be relatively easy and simple, since there is a logical connection: the relief type described, X, signifies a certain thing as regards crustal movement; that is to say, only on a crustal unit of the earth which moves in this quite definite way can that relief type X come into existence. This, therefore, indicates to me what course the crustal movements take. I envisage it in this fashion, and I think of fitting in detailed treatment of definite regions, e.g. the Black Forest—Alb—Alps—certain characteristic forms of Central Asia, of the Andes, etc. This would serve not only as an illustration of how to apply the whole method and the results that can be obtained from it, but also to present a picture of the types of crustal movement and their distribution over the earth. In this culminating chapter, wide and surprising vistas will appear leading towards the *causes* of crustal movement. It is to this fundamental problem of geology that I intend to devote the whole of my labours, possibly to the end of my life.'

Then follows a long account of Walther Penck's life, which is here summarised.

He was born in Vienna on the 30th August, 1888. He developed into a first class mountaineer, his earliest considerable climb being at the age of eight when he accompanied his father on a scientific expedition. Austrian schools provided good training in Natural Science; and he was specially fortunate in having as teacher Paul Pfurtscheller, one of those to whom he dedicated this book. When his father left the University of Vienna for that of Berlin, Walther Penck began his university studies there—to be interrupted by a visit to the United States of America, where he followed further courses whilst his father was delivering lectures. They travelled extensively; and under the guidance of G. K. Gilbert saw the earthquake fissure at San Francisco. The return journey was via Hawaii (where his deep interest in the volcanic phenomena decided the young man to become a geologist), Japan, north China and Siberia. Berlin University was soon exchanged for Heidelberg, as being better suited to the line he wished to pursue. After graduating, he studied further at Vienna.

In 1912 he became geologist to the Dirección General de Minas in Buenos Aires. His mountaineering training stood him in good stead as, with merely the trigonometrical points supplied, he mapped 12,000 sq. kms. in north-west Argentina, and made a reconnaissance across the whole width of the Andes.

While home on leave in 1914, war broke out, and he served for a while with the German army in Alsace. The report made on his first year's work at the southern edge of the Puna de Atacama had meanwhile qualified him for a post in the Department of Geology at Leipzig University. But towards the end of 1915, Turkey being under the influence of the Central Powers (to whom she had allied herself), he was appointed Professor of Mineralogy and Geology at the University of Constantinople (Istambul). In 1916 he investigated the coal deposits of the Dardanelles, as well as visiting the Bithynian Olympus (Ulu Dağ) with a party of students. In 1917 he added to his duties those of a Professorship at the Agricultural College of Halkaly on the Sea of Marmora. But recurrences of malaria, after a visit to the southern coast of Anatolia, made a return to Germany necessary in the summer of 1918; and the conclusion of the war prevented him from getting back to Constantinople. He became an unsalaried teacher (*Privatdozent*), with the title of Professor, at the University of Leipzig, and had a paid lectureship in

Surveying (topographical and geological). He worked at the results of his researches in the Argentine sierras and in Anatolia, and spent a good deal of time tramping the German Highlands with his wife—the Fichtelgebirge, the Thuringian Heights, the Franconian and Swabian scarplands, the Harz and the Erzgebirge, as well as visiting the Eastern Alps.

The value of money became less and less, and his Argentine savings were at an end. It was found later that he endured considerable privation. But he refused more lucrative posts that would have prevented him from continuing his research and preparing for publication the results and his views on them. Conditions were slightly better after the end of 1921 when he recovered some of his property from Turkey. But by then he was already far from well, though he made further expeditions, the last being to check his observations in the Black Forest. On 29 September 1923, he died of cancer (in the mouth), leaving a widow and two small sons.

He was only 35. W. Salomon, the professor under whom he had graduated, wrote to his father of the high hopes they had entertained that he would have lived to become one of the world's leading geologists.

In reading the *Morphological Analysis*, it has to be remembered that it is only part of a projected larger work. Nevertheless, he considered this part to be complete, so that Albrecht Penck published it as it stood, without any editing. The author had dedicated his work to Albrecht Penck and Paul Pfurtscheller, his 'two teachers in the art of observing nature'.

A list of Walther Penck's publications will be found on pages 352 ff.

Ten years or so ago a number of American geomorphologists engaged in a co-operative effort to provide a synoptic translation of *Die Morphologische Analyse*. Some progress was made; but the project came to a halt, partly because Professor O. D. von Engeln, Cornell University, who was promoting the enterprise, learned of our work on a full translation, and generously suggested that its success would be a happy solution and should have American encouragement.

The object of the translators has been to give as exact a rendering as possible of an important work which it has not been easy for English speaking students to assimilate, on account of its difficult and sometimes obscure style and its use of unfamiliar terminology.

In view of the controversial nature of some of Walther Penck's views, the translators have felt it right to keep very closely to his own wording, even at the cost of some verbosity and repetition. However, summaries of each section have been prepared, and will be found at the end of the book (pp. 355 ff.); so that readers can find relatively quickly the parts which they wish to study in detail in the full text.

The English expressions for the terms coined by W. Penck will be found in the Glossary, as well as other words for which students may wish to know what was in the original.

Our grateful thanks are tendered to various members of University College, Southampton: to the late Professor O. H. T. Rishbeth, whose influence stimulated the desire to understand this book; to his successor as Head of the Department of Geography, Miss F. C. Miller, for encouragement and constructive criticism; and to the staff of other departments for their assistance with doubtful points. We also wish to express gratitude to Professors Alan Wood, A. A. Miller, J. E. Kesseli, P. G. H. Boswell (and through him, Professor Reid), the late Professor J. Sölch and others for kind help over specific difficulties.

We are particularly indebted to the late J. F. N. Green, F.G.S., who spent much time during the last year or so of his life in reading through the whole script (whilst one of us was abroad), making valued comments and suggestions.

Some mistakes may thus have been avoided. For any that remain, responsibility must of course rest with us.

H. Czech
K. C. Boswell

KATHARINE CUMMING BOSWELL
1889–1952

This book was still in the proof stage when, to the deep regret of all concerned with its production, the news was received that Miss Boswell had died of heat stroke at Beni Abbès on September 19th, 1952, while attending the Nineteenth International Congress of Geology in Algiers. The tragedy of her death before she could see her work completed is heightened by the fact that it occurred on a journey into the Sahara, where she was trying to resolve some of the controversial points raised by Penck in his discussion of desert conditions.

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[ ] = not in Walther Penck's text

CHAPTER I

INTRODUCTION

1. NATURE OF THE PROBLEM

Study of the morphology of the earth's surface has developed as a borderland science linking geology and geography. The reason for this is the knowledge that land forms owe their shape to the processes of destruction which engrave their marks on the solid structure of the earth's crust; and that the properties of this crust decide the details of the sculpturing, as well as the arrangement in space of the individual forms. Its immediate purpose being to explain the origin of the multifarious land forms which appear at the surface of the earth, morphology very soon had a specially close connection with geography; and today, it is considered an integral part of geography proper, the study of the earth's surface, and treated as such[1]. Thus work on morphological problems has been overwhelmingly, though not exclusively, in the hands of geographers; and there has been scarcely any attempt to go beyond the aims prescribed by geography.

The material of morphology, however, contains within itself problems which reach far beyond the limits set by geography, and are neither exhausted nor solved by a genetically based description of the surface forms of the planet. *The significance of these problems lies in the realm of geology*; and their solution seems reserved for general geology, especially physical geology. *The problem is that of crustal movement.*

To see the matter more clearly, we must examine the character of the main and fundamental question of morphological science. However keenly geology and geography may be interested in the solution of this question as to the origin and development of land forms, the problem is neither specifically geological nor geographical, but is of a *physical nature*[2]. This results from the relationship and interdependence of those forces, or sets of forces, which produce the surface configuration of our planet. The destructive processes sculpturing the land, all of them together included in the concept *'exogenetic' forces*, cannot become effective until the earth's crust offers them surfaces of attack, until it is exposed to them. Parts of the crust covered by the sea are as much protected from the sculpturing forces as are those parts of the dry land which are being not destroyed but built up. Here, as there, material is not being removed from the earth's crust, but is being piled up on it in the form of rock strata; no unevennesses, no definite relief, are being created, but any unevenness of the crustal surface is being levelled up as by freshly falling snow. The activity of the destructive forces is limited to those parts of the earth which rise above these zones of deposition. Thus the indispensable prerequisite for attack by exogenetic processes of destruction is the activity of those *endogenetic* forces, originating within the planet, which are responsible for raising individual portions of the crust above sea level, and which, on dry land, raise individual blocks above their surroundings, in general create *upstanding parts*, thus giving rise to the altitudinal form of the earth's surface. Leaving aside endogenetically-caused volcanic accumulation (which attains morphological importance only to a modest extent, is limited to a few localities, and moreover has its further fate determined by that of its substratum), the endogenetic processes consist of *movements of the earth's crust*. In view of our present geological experience, their existence requires no further proof. The fact that we know of no piece of land which has not been once or several times submerged below sea level, is by itself striking evidence. Adequate proof that it is a matter of movement of the solid land and not fluctuations of sea level is this: the displacements of level which are of morphological significance, i.e. those which determine present altitudinal relationships on the earth, have never been of a corresponding amount everywhere on the earth's surface, now or at any other period[3].

The earth's surface is not only a limiting surface between different media, nor merely a surface of section giving the desired information about the structure of the earth's crust; *it is a limiting surface between different forces working in opposition to one another*. Both produce displacements of the rock material: the endogenetic forces displace it by raising parts of the earth's crust above their surroundings, or sinking them below these—at present it does not matter whether the direction of the forces is vertical or otherwise, so long as they lead to vertical displacement of level at the planetary surface; the exogenetic forces displace it by transporting solid material along the earth's surface. In the latter case, the transference usually takes place from higher to lower parts, the motive power always being the force of gravity. The endogenetic transference of material, on the other hand, is independent of the force of gravity. It is manifestly against gravity that magma reaches the crust and even the surface. *On this contrast depends the characteristic of mutual opposition between endogenetic and exogenetic processes.* The conflict goes on at the surface of the crust and it finds its visible expression

in the tendency—long recognised—for exogenetic transference of material to lower the projecting parts of the land and to fill in depressions, in short to level, to remove any unevennesses which the endogenetic processes have created and are still producing on the crustal surface.

Thus the earth's surface is a field of reaction between opposing forces, and the effectiveness of the one depends upon the preceding activity of the other. On all surfaces so conditioned as to be the scene of interaction between opposing and mutually dependent forces, there is a tendency for a physical equilibrium to become established. This obtains when both forces do the same amount of work in unit time, i.e. when they work at the same rate or have the same intensity. Accordingly, there is equilibrium at the earth's surface when the exogenetic and the endogenetic processes, when uplift and denudation, subsidence and deposition, take place at the same rate; and not only when—as is generally assumed—both processes have died out, and their intensity is consequently zero.

The visible results of endogenetic and exogenetic influences at the earth's surface are *forms of denudation* on the one hand, and, on the other, the *correlated deposits** which are formed simultaneously. The two stand in a similar relation to the forces producing them as do the cut surface and the sawdust that are formed when a log is pushed against a rotating circular saw. It is clear that very different forms develop according to whether denudation is acting more slowly than uplift, more quickly, or at the same rate; and so whether the ratio of the intensity of exogenetic to that of endogenetic activity works against the former or in its favour, or whether there is a state of equilibrium. Therefore it is possible to see plainly in the forms of denudation not merely the results of endogenetic and exogenetic transference of material; but even more that they owe their origin and their development to a relationship of forces, *to the ratio of intensity between exogenetic and endogenetic processes.*

The physical character of the morphological problem comes out clearly. The task before us is to find out not only the kind of formative processes, but also the development of the ratio of their intensities with respect to one another. None of the usual geological or specifically morphological methods is sufficient for the solution of this problem. As is now self-evident, it requires the application of the methods of physics.

Which physical methods are concerned, and at what stage in the morphological investigation they not only may, but must, be applied, follows from the nature of the three elements which together form the substance of morphology.

[* See glossary].

2. BASIS, NATURE AND AIM OF MORPHOLOGICAL ANALYSIS

These three elements are:

1. the exogenetic processes,
2. the endogenetic processes,
3. the products due to both, which may here be collectively called the actual morphological features.

It is well known that *the exogenetic forces* are at work over the whole earth, in all climates. They consist of two processes, the onset and the course of which are fundamentally different. The one has already been characterised elsewhere as a process of preparation: *the reduction* of rock material.* By this is to be understood all the processes which lead to a loosening of the solid rock texture, to disintegration of the rocky crust so that it becomes changed into a mobile form, transportable. Climate and the type of rock are what decide in the first place the nature and the course of the reduction, the rendering the material mobile. The structure of the earth's crust, which determines the world distribution of rock types, is therefore just as important for morphology as the world distribution of different climatic conditions.

Rock reduction alters the composition and texture of the material. It does *not* produce denudational forms. These do not appear until the reduced material has been removed: only when matter has been taken away from a body does it change its shape. Only if its composition and texture are altered does there arise what the mineralogist calls a pseudomorph. *Earth sculpture is due to exogenetic transference of material. The sum total of this constitutes denudation.* Rock reduction is an essential preliminary to its occurrence; the rock material must have acquired a sufficiently mobile condition before there can be transport at all, either of its own accord (spontaneous) or by the aid of some medium. The processes of denudation are, one and all, *gravitational streams,* obeying the law of gravity. Climatic conditions and type of rock influence the details of their further course. Their effects, therefore, are of different magnitudes in areas of differing climatic nature and differing geological make-up; nevertheless—and this must here be stressed in view of widely held misconceptions—they are *not of different types.*

All the processes of denudation have, as gravitational streams, a non-uniform character—which, as will be shown, is in contrast to the processes of reduction. That is their fundamental property. Their commencement, their course of development, take place before our eyes. They can be observed in all their phases, and their systematic investigation

[* *Aufbereitung*. See glossary.]

is thus possible everywhere on the earth, not only qualitatively—as has already been more or less fully done—but quantitatively, a matter which so far has been hardly attempted. Here there is a wide field of inductive research, as yet unworked. And it promises results of as great or even greater importance to morphology than those which that recent branch of knowledge, soil science, has already produced with regard to rock reduction.

All the *actual morphological features* can, like the exogenetic processes, be directly observed, and are thus an object of inductive research. However, their limits must be extended far more widely than is customary. It is by no means enough to determine and to characterise the forms of denudation as they actually appear in their various combinations; the *stratigraphical* relations of the *correlated strata,* formed simultaneously, are of just as great importance. Their thickness and the way in which they are deposited on the top of one another, how they are connected with their surroundings in the vertical and in the horizontal direction, their stratification and especially their facies, reflect both the type of development in the associated area of denudation, and its duration, and they supplement in essential points the history recorded there. The position of this record in the geological time sequence depends entirely upon investigation of the correlated strata and their fossil content. As a rule far too little weight is given to working on this stratigraphical material. Because of this, our knowledge about the actual morphological features is correspondingly scanty. True, we must take into account that these are not, like denudation, for instance, subject to one uniform set of laws; but that they are peculiar to each individual part of the crust which will have undergone a special development of its own. *They are individual in their character.*

This individuality is essentially dependent upon the way in which the activity of the *endogenetic processes,* particularly crustal movements, varies from place to place. Since crustal movements cannot be directly observed—with the exception of earthquakes—information about them is deduced from the effects they have produced. These, however, are to be regarded merely as indications that crustal movements are taking place, and bear much the same relation to them as the shaking of a train does to its forward motion. The passenger, now and then looking out from the window of the moving train, recognises its movement by the jolting and by the shifting landscape visible outside. The geologist recognises crustal movements by earthquakes and by disturbance in the stratification of rocks. The latter shows the earliest time at which the crustal movements took place at the given spot, and the total amount of disturbance produced up to the time of observation. But the conditions of bedding give practically no clue as to what, during the period of movement, was the distribution of the separate effects which add up to this total resulting disturbance; neither do they indicate the intensity of the crustal movement—whether it was rapid or slow—the changes of intensity in successive intervals of time—whether increasing or decreasing, nor the course of the movement—whether continuous or by fits and starts, nor whether it is still continuing or came to an end in times past. Yet all these have often been assumed in a perfectly arbitrary manner.

Crustal movements cannot be observed directly, and no adequate tectonic method is known for ascertaining their characteristics. Thus, in studying land forms, it is not permissible to make definite assumptions as to their course and development, and to base morphogenetic hypotheses upon them. Moreover, it is perfectly clear that of the three elements—endogenetic processes, exogenetic processes, and the actual morphological features—dependent upon one another, in accordance with some definite law, like three quantities in an equation—it is the crustal movements which correspond to the unknown, about which statements can be made only as a final result of the investigation, not as one of the premises. On the other hand, it has been shown that each of the other quantities can be established by observation, completely and with certainty for each individual case. Their dependence upon one another, in conformity with some definite law, has already been recognised, and it will subsequently be further developed. The equation—to continue the simile—permits of an unequivocal solution. *Morphological analysis is this procedure of deducing the course and development of crustal movements from the exogenetic processes and the morphological features.*

The function of this analysis of land forms, and its aim, is therefore *geological, or more exactly, physico-geological*. The first thing to be done is to state clearly and solve the problems of the origin and development of denudational forms. The present book treats this complex of problems as a matter of physical geology, to which it organically belongs in virtue of its nature—as was emphasised at the beginning. Having found the outlines of its solution, we have a base from which to move forward to the ultimate aim of morphological analysis, as indicated above. Far-reaching possibilities open up from this point. As has already been more fully set out elsewhere[2], the analysis of land forms gives totally different information about essential features of crustal movement from that which geologico-tectonic research can find out from the structural characteristics of the earth's crust. The two methods, the morphological one here developed, and the geologico-tectonic, supplement one another; at no point is one a substitute for the other. Only the two together supply

that sum of basic facts which affords a prospect of solving the main problem of general geology, *the causes of crustal movements*. This is a matter which does not seem to allow of a solution by any purely tectonic method; and so far any attempt to solve it upon this far too narrow basis has been of no avail.

3. CRITICAL SURVEY OF METHODS

(a) Cycle of Erosion

A first attempt in the direction of morphological analysis was the theory of the Cycle of Erosion developed by W. M. Davis[4]. Familiarity with it is here assumed. The cycle theory has, it is true, a purely geographical aim, viz. the systematic description of land forms on a genetic basis, which has been aptly called their 'explanatory description'. Thus there was no direct attempt to discover more about endogenetic processes. Results in this direction have been obtained only by the way, and they were not meant for further use except so far as they were considered to serve the explanatory description[5]. This totally different orientation of the setting of the problem does not in any way alter the importance for morphological analysis of the *principle* of the cycle concept. *That principle is the idea of development*, in its most general sense: a block, somehow uplifted, presents one after another, in systematic sequence, forms of denudation which result from one another; and their configuration depends not only upon the denudation which is progressing in a definite direction, but also—as Davis himself suggested, though merely as a conjecture[6]—upon the character (the intensity) of the uplift.

What has found its way into morphological literature as the cycle of erosion is what Davis expressly defined as a special case of the general principle, one which was particularly suitable to demonstrate and to explain the ordered development of denudational forms. It is postulated that a block is rapidly uplifted; that, during this process, no denudation takes place; but that on the contrary, it sets in only after the completion of the uplift, working upon the block which is from that time forward conceived to be at rest. The forms on this block then pass through successive stages which, with increase of the interval of time since they possessed their supposedly original form, i.e. with increase of developmental age, are characterised by decrease in the gradient of their slopes.

They are arranged in a *series of forms*, which is exclusively the work of denudation and ends with the peneplane*, the peneplain. If a fresh uplift now occurs, the steady development, dependent solely upon the working of denudation, is interrupted; it begins afresh, e.g. the pene-

[* See glossary.]

plane is dissected. A new cycle has begun; the traces of the first are perceived in the uplifted, older forms of denudation. Thus it has become usual to deduce a number of crustal movements, having a discontinuous jerky course, from the arrangement by which more or less sharp breaks of gradient separate less steep forms above from steeper ones below.

It was possible to draw this conclusion, in such a general form, only because the above-mentioned special case, chosen by Davis mainly for didactic reasons and developed in detail on several occasions, is usually taken as the epitome of the cycle of erosion, and is quite generally *applied* in this sense. Both Davis himself[7] and his followers have made and still make the tacit assumption that uplift and denudation are successive processes, whatever part of the earth is being considered; and investigation of the natural forms and their development has been and is being made with the same assumptions as underlie the special case distinguished above. There is, therefore, a contrast between the original formulation of the conception of a cycle of erosion and its application. Davis, in his definition, had in mind the variable conditions not only of denudation, but of the endogenetic processes; in the application—so far as we can see, without exception—use is made only of the special case, with its fixed and definite, but of course arbitrarily chosen, endogenetic assumption. And criticism, with its justified reproach of schematising, is directed against the fact that the followers of the cycle theory have never looked for nor seen anything in the natural forms except the realisation of the special case which Davis had designated as such. Thus even opponents of the American doctrine have taken their stand not against the general principle of the cycle of erosion, but against its application; and they referred merely to the one special case that alone was used[8]. Thus there seems throughout to have been a misunderstanding with regard to the cycle of erosion: its originator meant by it something different from what is generally understood. The way in which the theory is applied, the trend of the criticism it has received, hardly permit any doubt of this. Thus it is necessary to consider more closely the application of the *cycle of erosion* and the criticism directed against it.

As a method, the theory of the cycle of erosion introduces a completely new phase in morphology. Deduction, so far used only within the framework of inductive investigation, or as an excellent method of presentation, has become a means of research. Starting from an actual knowledge of exogenetic processes, the cycle theory attempts to deduce, by a mental process, the land-form stages which are being successively produced on a block that had been uplifted, is at rest, and is subject to denudation. Not only is the order of the morphological stages ascertained by deduction, but also the forms for each stage; and the ideal forms arrived at in this way are compared with the forms found in nature. There are two points in this method which must be considered critically: (*a*) deduction as a means of investigation; and (*b*) the facts on which the assumptions are based.

To begin with, it is obvious that the ideal forms, which are supposed to develop on *a stationary block*, can be deduced successfully only if there are no gaps in our knowledge of the essential characteristics of the denudational processes. Should this pre-requisite not be fulfilled, the deduction is nothing but an attempt to find out from the land forms alone both the endogenetic and the exogenetic conditions to which they owe their origin. It is like trying to solve an equation having three quantities, two of which are unknown; we can expect only doubtful results. The American school may be justifiably reproached with not considering it their next task to eliminate one of the unknown quantities by systematically investigating the processes of denudation all over the world. On the whole, their part in throwing light upon the exogenetic processes has been a very modest one. Yet this is not a decisive blow to the cycle concept. For amongst the 'exogenetic' assumptions made, there is no principle which has not been verified by experience, and criticism by opponents has been unable to show any mistakes in this field[9].

Till very recent times[10], no one has even seriously examined the second or 'endogenetic' assumption of the applied cycle of erosion, namely, uplift and *then* denudation. On the contrary, morphologists of every school have generally started from the same assumption as soon as they came to discuss the problem of the development of land forms. Even the opponents of the American school have done this, and indeed tacitly still do so, even in those cases when they have completely disregarded any endogenetic influence on the forms of denudation, and have done no more than consider how the individual land forms might have arisen purely from the work of denudation: for instance, the way in which they depend upon rock material. Invariably they have started with a given fixed altitude for the crustal segment considered; that is, they have begun by considering uplift already completed and followed by a period of rest.

Thus, up to now, it cannot be said that there has been any really well-grounded criticism directed against the factual assumptions of the cycle of erosion.

The second point was the use of deduction as a method of morphological research—though of course in addition to induction and essentially based upon it. A. Hettner utterly and roundly repudiated the use of this for morphology[11]. However, no such conclusion would be drawn from

Hettner's remarks and his arguments. In these he deals with the concepts of Davis—which he considers are not precisely enough formulated—especially the concept of morphological age; further, he points out that inadequate attention has been paid to the character* of the rock and to the exogenetic processes; and finally he considers the application of the theory to specific cases. At one point only does he touch upon the problem of method, and that is when he levels the reproach against the cycle of erosion that it rests upon inadequate assumptions as to the exogenetic processes. That reproach has already been considered above. But so far as the erosion cycle is concerned, this is only *one* side of the question; for, as has already been shown, it makes further very definite assumptions about the endogenetic processes. Apparently Hettner considers them to be correct and admissible, since he does not examine them also. But the possibility that the deductive method used for the cycle of erosion may be based upon inadequate assumptions does not permit the passing of judgment upon the applicability of deduction itself to the whole sphere of morphological research[12]. In addition, this statement may be made: *In morphology, as in any other branch of knowledge concerned with physical problems, deduction as a means of research is not only permissible, but also imperative; unless we wish to renounce the greatest possible exactitude and completeness in the results, and to exclude our branch of learning from the rank of an exact science, a rank which it both can and should acquire in virtue of the character of the questions with which it deals.* It is merely a matter of finding out where, in the process of investigation, we should resort to the method of deduction; and above all making sure that correct and complete data are then provided for it. The provision of these is, as before, exclusively the domain of inductive observation; it only can accomplish this, the deductive process never. It is by no means the deductive character of the method itself which makes it impossible to go along the American way of applying the cycle of erosion, but the incompleteness and, as will presently be shown, the incorrectness of the assumptions made. Thus opposition to the deductive method as a tool for use in morphological investigation has been unable to do serious harm to the theory of the erosion cycle, and it is not to be expected that it will ever succeed in doing so.

We now turn to the assumption made about endogenetic processes when applying the concept of the cycle of erosion.

(*b*) Relationship between Endogenetic and Exogenetic Processes

Exogenetic and endogenetic forces begin to act against one another from the moment when uplift exposes a portion of the earth's crust to

[* See p. 19 for what this term comprises; or glossary.]

denudation. So long as uplift is at work, denudation cannot be idle. The resulting surface configuration depends solely upon whether the endogenetic or the exogenetic forces are working the more quickly. Were there no denudation, a block, however slowly it is rising, might in course of time reach any absolute height; and its increase in altitude would be limited solely by the physics of the act of formation, provided that it is inherent in this not to continue indefinitely. It is rather like the way in which an impassable limit has been set to the increase in height of volcanoes by the extinction of volcanic activity, which often comes to an end prematurely, as soon as a certain height has been reached, because lateral effusions replace the summit eruptions. However, it is from the outset that exogenetic breaking-down at the earth's surface works against endogenetic building-up, i.e. denudation works against uplift, in-filling by sediments against subsidence. It is easily to be understood that an actual elevation can come into existence only if uplift does more work in unit time, and so is working more rapidly, than denudation; a hollow appears only when subsidence takes place more quickly than sediment is supplied, than aggradation. *This state of affairs forms the substance of the fundamental law of morphology: the modelling of the earth's surface is determined by the ratio of the intensity of the endogenetic to that of the exogenetic displacement of material*[13].

A brief survey of the earth's surface shows that this ratio very often changes, or has changed, to the prejudice of the exogenetic forces; the accumulation of a volcanic cone is possible only because it takes place more rapidly than the removal by denudation of the accumulated material. Faults can become visible as unlevelled fault scarps, for instance in the zone of the rift valleys of East and Central Africa[14], only when the formation of faults takes place more rapidly than levelling by denudation. Generally speaking, the origin of any outstanding elevation, any mountain mass, is bound up with the assumption that mountain building is more successful, i.e. works more rapidly, than denudation. Thus the varied altitudinal form of the land shows that in many cases the work of denudation is lagging behind the endogenetic displacement of material, here more, there less, or has done so in the past. *The one consistent feature, however, common to every region, is that the activity of exogenetic happenings is subordinate to that of endogenetic processes.* This relationship, most impressively brought to the observer's notice by the different kinds of relief and the different altitudes occurring at the earth's surface, forms the basis of morphological analysis. For if the exogenetic forces are less active than the endogenetic movements, then their effect, the earth's whole set of land forms, must also in its main outlines accommodate itself to whatever law has its visible expression stamped by crustal movement upon the face of our planet. Any change in kind or in intensity which these movements undergo must therefore—as has long been known—leave its traces upon the landscape.

If the intensity of denudation consistently lagged behind that of the endogenetic movement, then in course of time a block rising in such a way could, even in spite of the exogenetic processes, reach any absolute height; though it would of course do so more slowly than if the earth were not subject to denudation. But the relationship is not an unchanging one. For, like all other gravitational streams, the processes of denudation increase in intensity with the gradient, in a definite manner to be discussed later; and the gradient increases with the increase in *vertical distance* between summit and foot of the uplifted portion of the crust. This is true provided the *horizontal distance* between the two points is not at the same time proportionately increased; and, as a rule, it is not. Thus it was possible, even some decades ago, to formulate it as an empirical law, fundamentally correct, that intensity of denudation increases with absolute height, other things being equal. This means a shift in the relationship of the endogenetic to the exogenetic rate of working, in favour of the latter, and an ever closer approximation to physical equilibrium. The actual attainment of the equilibrium could be prevented only where there was no limit to the *increase* in endogenetic movement, so that rising blocks would gain in height indefinitely. The insignificance of the altitudinal modelling of its surface bears witness to how little such conditions obtain on the earth, an insignificance which is not clearly brought out, with distinctness, till comparison is made with the dimensions of the earth as a whole.

The above short survey shows that it is essential, when investigating the origin and development of denudational forms as they appear at the earth's surface, to *ascertain the relationship between the intensity* of the endogenetic and of the exogenetic processes, in short, between uplift and denudation; and it is necessary to follow out how this changes as time goes on. None of the present methods used in morphology brings us nearer to achieving this end; none even attempts to do so. The assumption generally introduced, that uplift and denudation were successive processes, or could at any rate be treated as such, has stood in the way. In this respect the only difference between the cycle theory and its opponents is that Davis made the above assumption in order to provide a specially simple case, of particular use in illustrating the cycle concept; but, at the same time, he kept well in mind[15] the importance of concurrent uplift and denudation. To be sure, this was a notion of which he scarcely ever made use, and his followers never. Those of the other school, no less schematically, start in every case from the same

assumption; they, moreover, have occasionally tried to justify the general correctness and permissibility of such a course[16]. It is as if they made use of a device familiar in school physics, which is merely a makeshift for presenting in a physically correct manner the resultant of processes acting concurrently. This is a grave mistake in method.

It is permissible to proceed in this way only in the case of *uniform forces* which, in successive units of time, produce effects that remain of equal magnitude. If, in a diagram such as Fig. 1, the co-ordinates *ab* and *bc* represent the effects of simultaneous, uniform forces, the straight line *ac* represents the resultant effect *during* the whole process. In order to ascertain this, it is sufficient to follow the events first from *a* to *b*, then to *c*.

(c) The Differential Method

It is quite different, however, when forces acting simultaneously are *not uniform*, i.e. are changing their intensities in successive units of time and are therefore doing different amounts of work. To find out the resultant during the whole process, it is here necessary *to follow* the course of Nature *continuously*, as was made possible in physics, where such problems are constantly cropping up, only by the invention of the differential calculus[17]. To make this clear, let us remind ourselves of the problem: to find the trajectory of a missile fired horizontally from a point *a* (Fig. 1). As the effect of the firing, it would reach *b*; but at the same time, under the influence of the force of gravity, it would drop down by the amount *bc*. To find point *c*, which the projectile reaches, it would really be sufficient to follow events first from *a* to *b*, then from *b* to *c*, that is to imagine the effects of the firing and of gravity as coming into play successively. The trajectory, however, has not been found in that way. It lies on a curve of some kind between the initial and final points, between *a* and *c*. To determine it, we must find out how the magnitude of the operating forces alters in successive exceedingly small units of time. This can be done by plotting a diagram of forces for each moment, as in our figure, e.g. ab^1c^1, $a^2b^2c^2$ . . . $a^mb^mc^m$, etc., so that the simultaneous effect of the forces is represented by the very minute distances ac^1, a^2c^2 . . . a^mc^m, etc., as if they were uniform during these extremely short intervals of time and took place successively. The error thus made becomes infinitesimally small, if the values chosen for the diagram are made infinitesimally minute; and this method, consisting of an infinite number of infinitely small variables, comes infinitely near the *continuous* course of Nature. This becomes clear if in our figure the triangles ab^1c^1, $a^2b^2c^2$, etc., are, as is necessary, made infinitely small; they then disappear completely in the full line *axc*. Since the forces are now changing from moment to moment, the very small distances ab^1, a^2b^2, etc. and b^1c^1, b^2c^2, etc., are thus of different lengths, and so the infinitely small resultants ac^1, a^2c^2, etc., are also of different lengths and at different inclinations. Strung out after one another, they do not form a straight line, but bend in a curve: the trajectory *axc* which was to be found. *This is the differential method. It is the only way that leads to our goal, which is the exact representation of the resultant of several simultaneous processes that are not acting uniformly during their course.*

The forces which take part in modelling the land do not act uniformly. It has already been shown that this is so for denudation, and it is a matter of course for crustal movements. They begin from the position of rest,

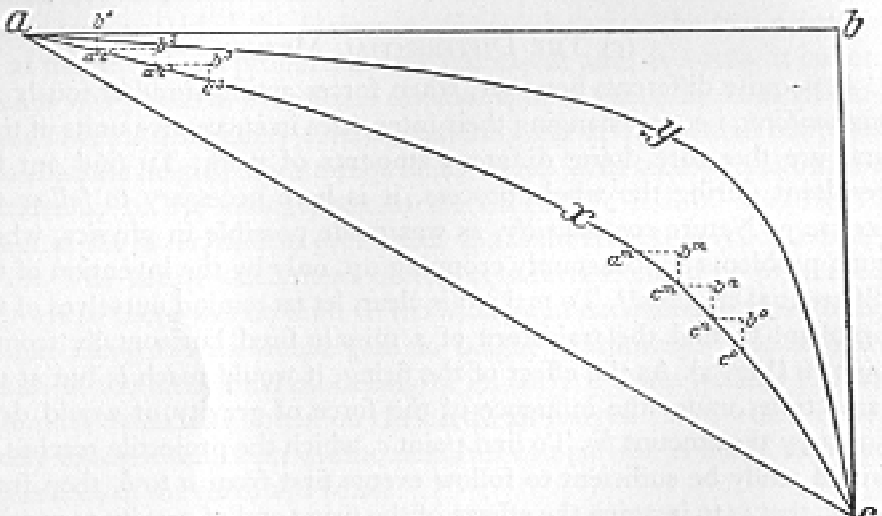

FIG. 1

so they must then be accelerated; and they end with the position of rest, having then suffered deceleration. Whether or not the starting point and the end coincide with a position of absolute rest is of no importance. If indeed we think of the alternation of uplift and subsidence, as has so often, if not as a general rule, taken place on the earth, then the position where subsidence changes to uplift (or vice versa) is the position of rest. *In any case, the movement of the crust is a non-uniform process, which becomes uniform only temporarily during its course, but can never begin uniformly with any definite velocity.* It is not superfluous to stress this obvious factor in view of the often inadequate conceptions which are widespread as to the physics of motion, and even of the fundamental concepts of physics.

To illustrate the position, let us draw a diagram (Fig. 1), in which the

co-ordinates represent the effects of crustal movement (*a b*) and of denudational processes (*b c*). The result of their simultaneous action, the forms of denudation, then appears in the shape of curves between *a* and *c*. Naturally they are all situated within the triangle *abc*; since any curve drawn outside it, as for example, a curve deviating in convex fashion downwards from the straight line *a c*, would signify that denudation had begun before subsequent endogenetic action had exposed the crustal fragment to exogenetic destruction or, in other words, that denudation was the prerequisite for crustal movement. Within the triangle an infinite number of curves are possible, all of which begin at point *a* and end at *c*. Each of these curves represents not a single form, but a *developing series of forms* through which a crustal fragment passes when it is being uplifted and denuded. It is obvious that all the series of land forms which can possibly develop on the earth have one common starting point and one common final form. The former is characterised by the beginning of uplift and denudation (point *a*), the latter by the extinction of endogenetic and exogenetic displacements of material (point *c*). In between lies the endless variety of forms that correspond to the varying ratio of intensity of exogenetic processes to that of endogenetic ones; and they are arranged on an infinite number of curves, each of which represents a series of forms peculiar to the surface development of a crustal fragment which has had a particular course of endogenetic development.

Thus we see that land forms are not, as the erosion cycle postulates, a single developing series, but that they form an infinite number, and that they are arranged [on the diagram], *not in a line, but on a surface.* This surface is enclosed by two limiting curves that, at least as regards total dimensions, represent developing series which, on the earth, are *just not possible*: the straight line *a c*, that is the series of forms arising from the uniform development of uplift and denudation, and the axes *a b*—*b c*, which would be the series of forms that would arise if uplift and denudation succeeded one another. Whether *fragments of the limiting curves* can be observed as component parts in the development of forms on the earth, and which fragments might in that way be realised, will have to be decided by the following investigation.

The relationship of the cycle of erosion (and of methods based upon similar assumptions) to the complex of problems concerning development of land forms now becomes evident. Point *b* in the diagram represents denudation which sets in only after the completion of uplift; and the series of forms that arise purely as the work of denudation on a motionless block is represented by one limb of the limiting curve: the line *b c*. Its starting point *b* by no means coincides with the point (*a*) from which all development of forms on the earth begins. The perfectly arbitrary choice of that starting point is clearly shown. But, on the other hand, there also emerges the fact that although the method adopted for the erosion cycle (in its applied form) is incorrect in principle, yet it must nevertheless lead to the discovery of the correct final form common to every one of the series of denudational forms that develop on the earth, provided that the method was logically correct and not based upon faulty exogenetic assumptions. The theory of the cycle of erosion does satisfy both these requisites, as cannot be doubted even by its opponents. Point *c* in the diagram represents the end-peneplane,* the peneplain, the origin of which was made clear by W. M. Davis, and a little later, independently, by A. Penck, both basing themselves upon detailed inductive observation[18]. One could not, however, in this way deduce a single one among the infinite series of developing land forms which are not only possible but actually exist on the earth in the different parts which have had various endogenetic histories. Almost everything in this field still remains to be done by morphology. Not merely must the investigation start at the beginning of uplift and denudation (point *a*); it must take into account not only the simultaneous effects of endogenetic and exogenetic action, but above all their variable intensities[19]. *For this one must turn to the methods of physics, and indeed to such as permit a continuous following of the variable quantities, that is, the differential method.* This method not only can, but *must* be used in investigating the interdependence between the *processes of movement* which take part in the modelling of the land. For mass-transport of eroded material depends upon a gradient, the factors producing which are crustal movements; and mass-movement of denuded material depends upon a gradient, the processes producing which arise from the results of erosion†[20].

This leads to the

(*d*) Present Method of Approach

The main stress is laid upon investigating the ways in which denudation works, and the preparatory processes, the aim being to find out if denudation follows laws which are uniformly applicable and what these are. Thus, in the first place, it is a matter of studying those processes of denudation the course of which depends directly upon the *surface gradient* of the crust and therefore indirectly upon its movements. These

[* See glossary.]

[† Translators' note: The author's distinction between erosion along the line of a watercourse and denudation over a whole surface must constantly be borne in mind. This point of difference between German and English-American usage was discussed by W. M. Davis, *Journ. Geol.* XXXVIII (1930), p. 13.]

fall into two categories: (*a*) denudational processes in which the movement is spontaneous*; (*b*) those making use of an agent that is itself in motion (air, water, ice). Now group (*b*) includes also processes which depend only remotely, or not at all, upon the surface gradient, and which do not show any direct connection with crustal movement. Currents in standing water, particularly in the sea, are examples of this, and air currents. In both cases, lines of movement within one and the same medium are caused by *differences of pressure*. They imprint upon the surface of the crust features having no connection with crustal movements, which have but a limited value, or none at all, for discovering these. Hence this book does not treat of ocean currents; and the effects of wind are considered only in so far as they act with and influence other sub-aerial streams that are dependent upon gravity. Their work must be distinguished from endogenetic influences, even though it is restricted to certain parts of the earth, and is of limited importance in these. It is particularly over arid stretches of land, devoid of any continuous cover of vegetation, that wind effects are encountered; and the lowest base level to which they can possibly extend is the surface of any accumulation of water. For arid regions this means, in the first place, the water table. This is so for basins of inland drainage, the visible surface of which forms the base level of erosion for the bordering slopes; and its position is determined—if not exclusively, yet in the main—by climatic conditions and not by those of crustal movement. Wind may here play a considerable part in the modelling of those slopes; not indeed directly, as observation shows, but indirectly through bringing the base level of erosion down to the level of the (dry season) water table.

Minor forms due to wind action appear all over the world, wherever there is an arid portion of surface exposed to the wind, provided weathering has previously done its work. But even apart from these, it is *climate* which primarily conditions the denuding as well as the depositional activity of the wind. Nowhere indeed are the forms which it produces dominant, not even in the regions of its greatest importance; but they are overprinted upon the dominant forms, forms which there too have been created by denudational processes bound up with the surface gradient.

The movement of ice and snow, and the effects produced by them, present similar relationships. True, their movements follow the surface gradients; yet their existence is a response to climatic conditions. It is unsuitable, therefore, to use forms produced by them for the deduction of crustal movements. That their origin has no direct connection with these is at once evident from the character of their level of reference, the

[* See p. 64.]

base levels of erosion below which their sculpturing cannot possibly reach. For glaciers, that level is the melting lower end; for the stretches lying between them, it is the snow-line. The position of the melting tip depends both upon that of the snow-line, determined exclusively by climate, and upon the mass of each individual stream of ice which, other things being equal, increases with the size of the gathering ground. With stable climatic conditions, the influence of crustal movements is to alter the position of the glacier snout and that of the snow-line, not with reference to the base level of running water, e.g. sea-level, but with reference to the glaciated summits or to the original position of the snow-line. Thus, investigation of glacial phenomena can establish to what extent the observed displacements of the snow-line are due to climatic changes or to crustal movements, but no clue is thereby given as to the nature or course of these events. Hence the whole set of phenomena belonging to glacial geology also falls outside the scope of this book.

And finally, an examination of coastal development has no place here. Knowledge is assumed of the processes which are today considered to be modelling the details of sea-coasts, whether by denudation or by deposition, and of how these processes are believed to transform coasts which are neither rising nor sinking. For the problems here treated, the only phenomena of importance are those from which it is possible to deduce vertical movement of the coast-line, with the necessarily associated horizontal displacement, uplift and subsidence of the solid earth, rise and fall of sea-level. In so far as eustatic fluctuations can be successfully excluded, these phenomena supply information as to the occurrence of the crustal movements, the time of their commencement, and their direction (relative to sea-level); but only in a limited degree to their course of development and changes in intensity. In this respect they fall into the same category as the conditions of rock stratification. This does not remove the necessity for a somewhat detailed consideration of the proved oscillations of the coast-line; for this concerns the *oscillations of the base level of erosion for running water*, which—whatever their origin—have the greatest conceivable repercussions on the modelling of the land, the type of denudation and deposition, and the distribution of these.

That the investigation may be directed aright with reference both to matter and place, we are beginning with a short survey of the earth's crust and its structure, this being the stage for all geological and morphological occurrences.

CHAPTER VI

DEVELOPMENT OF SLOPES

1. GRADIENT AND FORM OF SLOPES

How local base levels of denudation come into being and disappear is really the same question as that of the origin and development of the slopes which, grouped and combined in many different ways, produce the denudational forms found at the earth's surface. What has been observed to take place, away from the actual lines of water-courses, perennial or intermittent, and the way in which it follows definite laws (see Chapter III, sections 4–9) provide all the support needed to make this absolutely clear. Rock material becomes more highly mobile the further the process of reduction has gone (the longer it has been at work); and it has been definitely proved that the more mobile the material on a given slope, the less the gradient of that slope need be before the material can only just move away. On gentle slopes, therefore, the intensity of denudation is less than on steeper ones: a much longer time must elapse before the material is reduced to such a degree as to become unstable. Where *lower horizons of the soil, forming relatively quickly* (on steep slopes), are set in motion, renewal of exposure takes place far more rapidly than where only the upper horizons, which take much longer to develop, are moving (on slopes of a proportionately slighter inclination). What matters is [i.e. this renewal of exposure depends upon] the rate of formation of the uppermost horizon of reduction, the one which is at that time lying freely exposed. Other things being equal, its exposure is everywhere the same. On a given slope it is the first part that can no longer hold in place, but must move off as soon as the requisite mobility is attained. The rate at which it is formed gives the intensity of denudation. As the topmost layer moves away, the profile of reduction below it sinks to the same extent into the previously unattacked rock. On a slope of *uniform gradient* and equal exposure, a profile of reduction is formed which shows everywhere the same development and the same thickness. In the same time that the uppermost horizon of that profile has taken to acquire the mobility necessary for migration, a rock layer of the same thickness throughout has become reduced. At the close of a further equal interval of time, a further layer of rock, again of the same thickness and of equal thickness at every part of the slope, passes over into the reduced form.

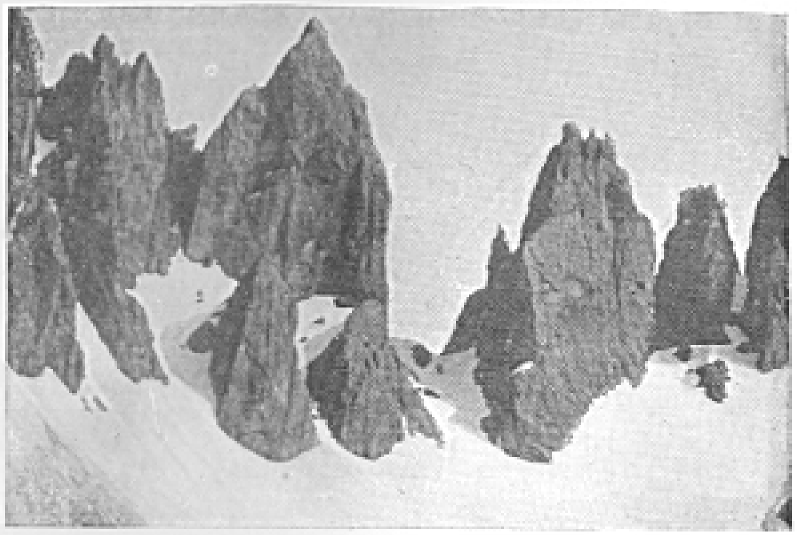

Photo. by K. Lampert

1. Steep relief. The northern Pala group from the Mulaz Pass, South Tirol

Photo. by W. Penck

2. Medium relief. Ranges to the south of the Gulf of Izmit, seen from the north. Western Asia Minor

Photo. by W. Penck

3. Flattish relief. Rolling landscape in Uruguay

I. Relief Types

What has just been recapitulated holds true only on the assumption that the *character of the rock is* everywhere *the same*. It is true for each rock just as rock, but each behaves in a special way as regards reduction and becoming mobile, and so, other things being equal, has an intensity of denudation peculiar to itself. Bearing this in mind, our investigations will be made first of all on the assumption that all the rocks have the same character.

Denudational slopes present every degree of inclination, from those scarcely to be distinguished from the horizontal right up to 90°—leaving aside caves and overhanging crags. Because of the limitations of rock stability, normal gradients are less than 45°, anything steeper than this being quite exceptional. However, these gradients are not distributed over the globe in a haphazard fashion, but by individual regions which are often easily recognisable as tectonic units. They have such a marked occurrence of slopes with almost identical maximum gradients that the average or mean of these is one of the characteristic features of that particular natural region. This long-recognised fact, which is quite independent of the position of the climatic belt concerned and so of the type of climate, makes it possible to speak of *uniformity of relief for a district* meaning by this the total effect of the arrangement and combination of all the slopes with approximately the same angle of inclination. Thus the frequently used term 'Alpine relief' is associated with the idea of the steep land forms found in the Alps; and the less steep conditions found in the German Highlands have provided the type for 'Highland forms'. Since no association that can be reduced to a law exists between the average steepness of slopes and their absolute—in addition to their relative—heights, we shall replace these terms by the purely descriptive expressions: 'steep forms—steep relief' for a set of land forms having average slopes round about the maximum gradient for resistant types of rock; 'intermediate forms—medium relief' for those with slopes which, as in the valleys of the German Highlands, reach a steepness approximating to that of basal slopes*; and 'flattish forms—peneplanes'† for landscapes with slight gradients throughout (see Plate I, illustrations 1, 2 and 3)[171]. It must be borne in mind, though, that we have not gained more than a means of making ourselves understood. For although these three form-types are often actually to be seen as characteristic features, and although they can then be recognised without any ambiguity[172], they are yet merely *types of relief* chosen out of an infinite number of members of a transitional series; round them can be grouped similar types which it is impossible to demarcate from one another except by agreeing to take specific limiting angles for the mean gradients.

[* See glossary; and pp. 93, 135.] [† See glossary.]

Within any one relief type characterised as a unit, variations in the angle of gradient do, then, occur in individual cases; but, as has been repeatedly stressed, these differences are due to differences in the resistance and attitude of the rock[173]. They are details fitted into the general type without effacing it.

One great problem presented by denudational forms is the way in which *slopes of uniform gradient* are associated together in definite limited regions. The second relates to the *form of the slopes* (see Plate II, illustrations 1, 2 and 3). The slope profiles are convex, or concave, occurring as continuous curves or divided up by breaks of gradient, salient or re-entrant; or else they may be stretched out into an approximately rectilinear course. These various forms, too, are not distributed haphazard, but are arranged in a regular fashion. Examination of the slope profiles on the upper parts of the German Highlands or the Scarpland peneplanes, shows them to be *concave* throughout. Comparison with the steeper slopes on their sides, i.e. those of the younger valleys dissecting them, shows that these latter generally have *convex* profiles. These are examples of a rule which is world wide in its application and independent of any climatic peculiarities. Wherever a younger, steeper set of land forms separates an older upraised landscape from its former base level of erosion, the slopes of the older forms are always concave in profile, and the younger forms dissecting the highland characteristically have convex or straight profiles, although concave ones may occasionally appear. Throughout, the convex and straight profiles are associated with zones where there has been vigorous erosion. Also, in broad outline, the distribution of the various forms of slope follows an unmistakable arrangement. It appears that the form associations with convex slopes are most typically found in the two mountain belts, and that they occur less frequently on the continental masses. Hundreds of thousands of square kilometres on the Canadian Shield, between the Guianas and La Plata, between the mountains of the Atlas and the Cape regions, retain the stamp of concavity on their slopes, although otherwise these vary in respect of steepness. Typical inselberg landscapes belong to this group. There is nothing like it in the mountain belts. It is true that on the summits of the chains similar relief types, the uplifted hill country and peneplanes already mentioned, do occur extremely frequently; but there are immense spaces from which they are absent. This large-scale distribution is, naturally, not due merely to chance.

However, in the mountain belts and indeed wherever the slope corresponds to the maximum gradient for the rocks concerned, convex slopes are replaced by what are on the whole *straight profiles*. They find their purest expression in the steep relief of mountains which escaped Pleisto-

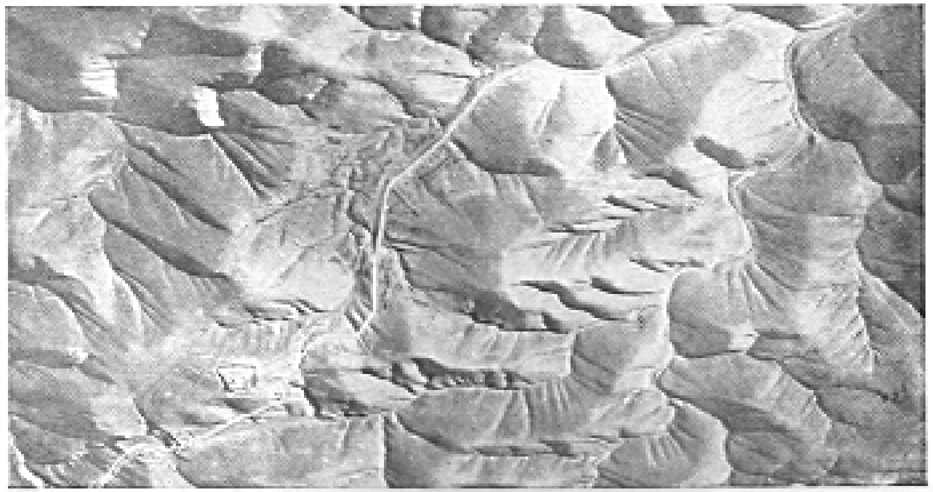

Photo. by L. Weickmann

1. Convex slopes. Road from Jerusalem to Jericho

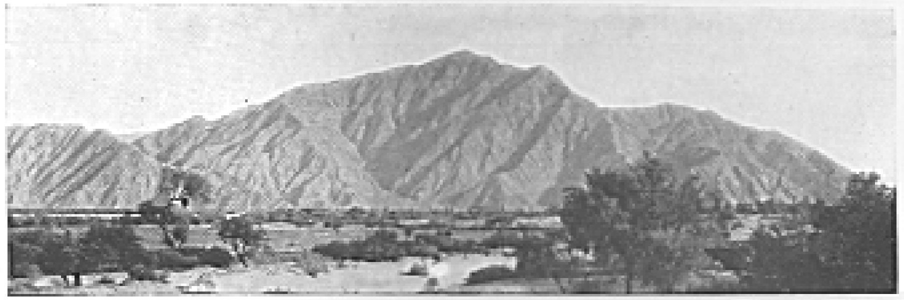

Photo. by W. Penck

2. Straight slopes. Sierra de Fiambalá, near Anillaco, Western Argentina

Photo. by W. Penck

3. Concave slopes. Cerro Colome, from the south. Puna de Atacama, Western Argentina

II. Forms of Slope

Photo. by A. Penck

1. Convex slopes of Badlands, near Adama, New Mexico

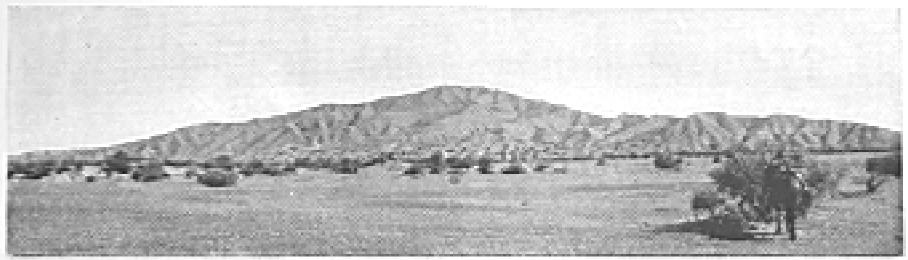

Photo. by W. Penck

2. Straight slopes on a hill near Sanjil, Western Argentina

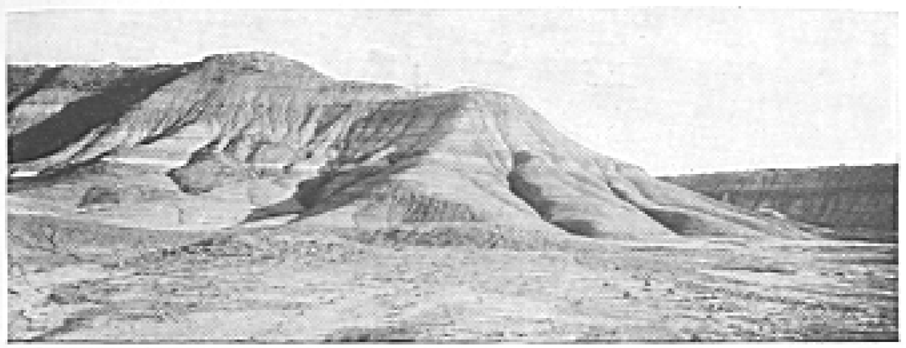

Photo. by Wichmann

3. Concave slopes. Roca Beds on the Rio Negro, Western Argentina

III. Badlands

cene glaciation, whether these are covered with tropical virgin forest or belong to arid regions. They are also very common in the Alps. Nevertheless it must be stressed that straight slope profiles are not a peculiarity of steep relief, but also occur with medium relief. They are the rule for sharp V-shaped valleys of the type found incising the Muschelkalk or the Malm of the Scarplands. They often develop in landscapes where crests-lines are formed by the intersection of slopes; and the steeper the slopes, the sharper the ridge crests, while with gentler slopes they are less sharp. The Badlands are among the areas providing excellent examples of this—as also of convex and concave slopes (see Plate III, illustrations 1, 2, 3).

When two or more surfaces cut one another, lines of intersection or points of intersection are formed. Theoretically, slopes which meet at their upper extremities should, irrespective of their steepness, rise to sharp linear edges or sharply pointed peaks. In nature this is not so. On the contrary, the zones of intersection are always blunted and broadened, the more so the gentler the slopes concerned. This blunting and rounding is a characteristic of intersecting slopes: *these* are flattened near the place where they meet, no matter what the shape of the remainder whether steep or gentle, and irrespective of the type of rock and type of climate. The flattening, however, cannot continue to an indefinite amount. It is never very great, and is obviously dependent upon the gradient, diminishing as the steepness increases. Consequently the degree of sharpening of the zones of intersection most distinctly increases with the gradient of the slopes that are meeting one another.

The upward rounding of convex slopes is evidently part of the convexity itself. With concave or straight slopes, on the other hand, it is obviously an independent problem, since here the rounding-off of the zones of intersection signifies a deviation from the given form of the slope.

G. Götzinger thought that in this flattening from above he could recognise the process by which a ridge of ever-increasing breadth and flatness was produced from a sharp edge[174], and R. Gradmann in his derivation of scarpland peneplanes starts from similar assumptions[175]. This view cannot be correct since—as Gradmann himself recognised—it conflicts with the phenomena of valley deepening. Götzinger has not yet seen this difficulty, but it is shown by direct observation. A rock wall, subjected to denudation, retreats backwards upslope, and a gentler declivity, the basal slope,* is seen to form at its expense and to grow upslope by the same amount as the cliff vanishes[176]. If such cliffs are entirely destroyed, the basal slopes meet in a sharp edge, as may be excel-

* *Haldenhang.*

lently seen at the Paternsattel [Forcella Lavaredo] (Drei Zinnen [Tre Cimi di Lavaredo], Dolomites), and this forthwith experiences that definitely limited amount of rounding which has been mentioned above[177]. The gentler slope, that replaces the steeper one, thus develops at the foot of the latter; and the flattening of the land progresses from below upwards and not in the reverse direction. This fact has not escaped G. Götzinger in so far as the development of cliffs, i.e. steep forms, is concerned. But in his derivation he jumps to a conclusion which cannot be justified by observation or in any other way, taking it for granted that, as further development occurs, the flattening all of a sudden takes place the other way round, viz. from above downwards. If rounded ridges did arise in that way from sharp edges, and flattish forms of convex curvature from such ridges, then it would have to be assumed that denudation was always working more rapidly on the flattish ridge summits than on their steeper flanks. This cannot possibly be expected of Nature, as is obvious, and as was stated years ago[178]. Rounded ridges with convex profiles, such as occur in the Wiener Wald, can never arise from sharp edges. Only the reverse is possible. One of the objects of the following sections will be to show that this is the case.

2. FLATTENING OF SLOPES*

Concave Base Levels of Denudation

A steep slope, say a cliff of homogeneous composition and uniform gradient, rising directly from a non-eroding river, constitutes a form system† [slope unit]; and its base level of denudation lies at the water level of the river (*t* in the profile, figure 2). The whole surface of the cliff has the same exposure and succumbs equally in every part to the process of reduction. In unit time a superficial layer of rock, of a definite thickness the same everywhere, is loosened and removed. The method of removal is that loosened particles of rock crumble away and fall down. For this to happen the gradient must be too great to allow the little pieces of rock, just loosened by weathering but not further comminuted and reduced, to remain at rest. This gradient is available for each unit of the rock face except the lowest, which is adjacent to the base level of denudation. At the end of time one, therefore, this alone has not been taken away. There is no change in the steepness of the cliff, but it has retreated from its original position *t*-1 (in the profile) to the position 2′–2. Beneath it there is a ledge left. Such ledges may also appear temporarily in the middle of the rock face as a tiny piece *x* breaks off. The part of the cliff immediately above is then deprived of its support. It is undercut

[* See note on p. 120] [† See p. 129 for definition.]

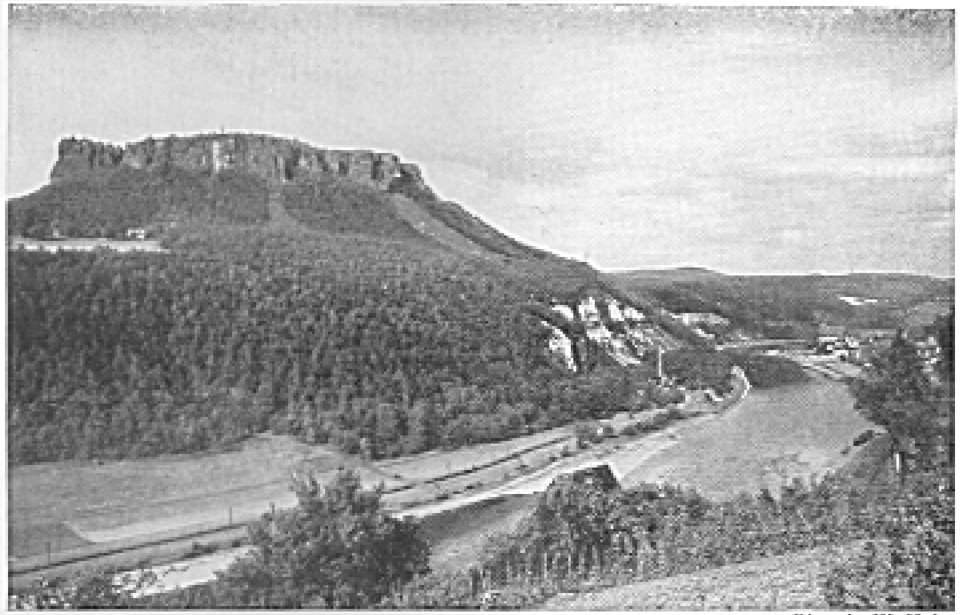

Photo by W. Hahn

1. Concave breaks of gradient. Lilienstein in the Elbe Sandstone Mountains. Cliff above basal slope

Photo. by W. Penck

2. Convex break of gradient. Steep drop of the Sierra de Fiambalá to the Bolson of Fiambalá, Western Argentina

IV. Breaks of Gradient

and further breaking away is accelerated. The ledge cannot, however, maintain itself, for by the end of the first unit of time the layer *tx* below it has also crumbled away, even before reduction of the more rapidly exposed rock face above *x* (*x* 2) has loosened new material and prepared it for removal.

This same process is repeated in the second unit of time. But only that part of the rock face above the ledge *t* 2′ can be weathered back in the allotted time; and once more the lowest particle (2′–3′) is without that same [necessary] gradient at its disposal, i.e. it has not in the interval acquired the mobility essential for movement on the much smaller gradient. The rock face moves into the position 3′–3, in the third unit of time it retreats to 4′–4, and so on. If sufficiently small units are taken, we come very near to the actual process, and the exceedingly small ledges

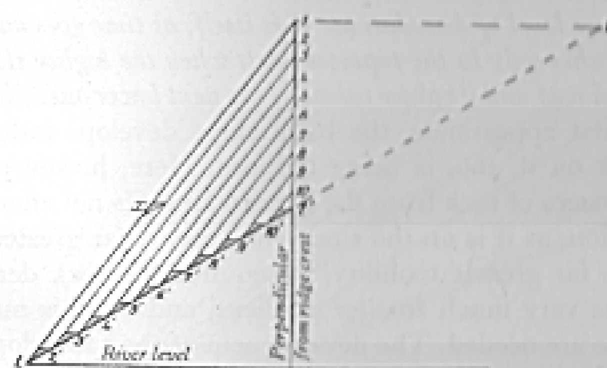

Fig. 2.

t 2′, 2′–3′, 3′–4′, and so on, combine to give a continuous slope of uniform gradient (*t t*′).

This is the *basal slope*,* along which the broken fragments derived from above slacken their pace, to migrate further in free, cumulative mass-movement, provided that conditions are suitable for their accumulation (see Plate IV, illustration 1).

The following statement may therefore be made: *A steep rock face left to itself, moves back upslope, maintaining its original gradient; and a basal slope of lesser gradient develops at its expense.* Should the cliff culminate in a sharp edge, as is assumed for fig. 2, this edge is lowered to the same extent as the rock face recedes; it moves from 1 to 2, then to 3, and so on. After the tenth unit of time, the steep rock face would be gone, and in place of the precipitous ridge there would be a lower one where the gentler basal slopes meet. If, on the other hand, the cliff face is the scarp

* *Haldenhang*.

of a tableland, it would not disappear till after a longer interval of time, in the figure about the twenty-second time unit; and the steep drop would then be replaced by a gentler slope ($t\ t''$) with the gradient of a basal slope.

After time one, the development of the cliff face is no longer related to the river level t, but to the concave break of gradient which separates it from the basal slope. *This break of gradient is the base level of denudation until the disappearance of the receding cliff face. A new slope unit, the basal slope, is interposed between it and the river level. The upward growth of this is determined by the rate at which the rock of the cliff face is reduced, i.e. by the development of the steeper, higher slope unit, the special development of which was in the first instance related to the position of the river. Whatever may happen to the basal slope, whatever fate may befall its lower end, the development of the cliff face is unaffected by it. This has become independent of the general base level of denudation, and what ensues is related to a newly-formed local base level of denudation. This itself, as time goes on, moves upslope, and vanishes only in the topmost parts when the higher slope unit has been finally removed and its place taken by the next lower one.*

From its first appearance, the basal slope develops independently, since the rock on it, too, is being reduced. Here, however, the mere loosening of pieces of rock from the general fabric is not enough to produce denudation, as it is on the steep cliff face. A far greater degree of reduction, i.e. far greater mobility, is required for rock derivatives to migrate on the very much smaller gradient, and for this much longer periods of time are needed. The development of the basal slope is therefore very much slower; but it proceeds in the same direction as that of the cliff face above.

It is still being assumed that the rock is all of the same composition and also has the same exposure.* In unit time a layer of definite thickness, everywhere the same, is loosened from the basal slope. But it is only when a multiple of that unit time has elapsed that the loosened material is sufficiently mobile to migrate spontaneously. This occurs as soon as there is a definite degree of reduction, i.e. a definite mobility of the rock derivatives, corresponding to the gradient as it then is (p. 71). In other words: if, after a certain period of time, the rock material derived from the basal slope attains a certain mobility, its downward movement on the existing gradient is inevitable. *That length of time is the unit by which the rate of development of the basal slope is measured.*

At the end of the time unit just defined, a layer of rock, of a definite thickness, the same over the whole of the basal slope, has been changed into a sufficiently mobile form; and during that time the rock particles, one after another, all quit their place of origin[179]. All, then, move down

[* See pp. 36, 52.]

except the lowest, that adjoining the general base level of denudation (t in fig. 3), since it is the only one not provided with the requisite gradient for movement. Still maintaining the same inclination, the slope now moves from the position $t\ a$ to $2'$–2. The same thing is repeated during a second time interval of equal length[180]. The time available, however, does not allow all the rock particles of the new slope 2–$2'$ to migrate; for again the lowest ($2'$–$3'$) has at its disposal not the same gradient as that for all the particles above but a smaller one, one for which the degree of mobility so far acquired is insufficient to permit of migration along it. The slope moves into position $3'$–3, and after a third unit of time it would reach $4'$–4, and so on. By making sufficiently small the dimen-

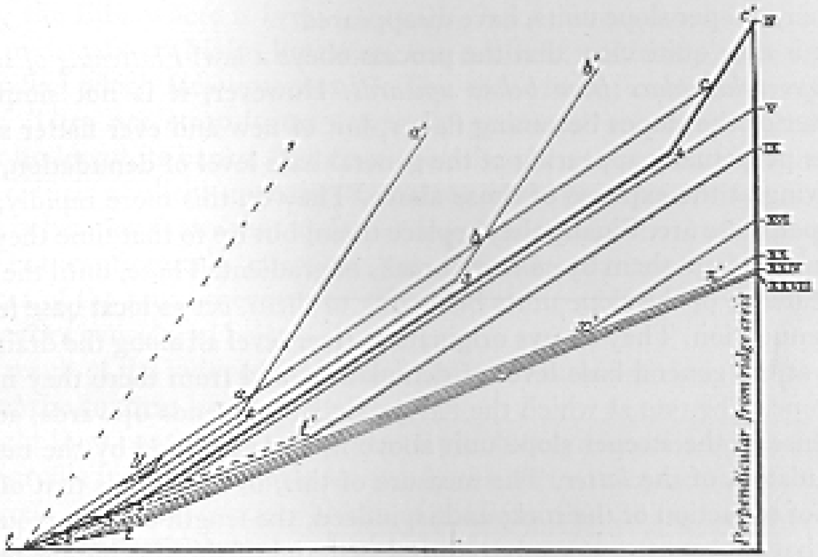

FIG. 3.

sions considered, we come near enough to reality, and find this state of affairs: below the basal slope there is forming a new, flattened-out slope of gradient $t\ t'$, which grows at the expense of the former, and at the same rate as the basal slope is being denuded. After the first unit of time (as defined above), the basal slope no longer develops with reference to the general base level of denudation, but with reference to the concave break of gradient at $2'$, and to that at $3'$, $4'$ . . . x', etc., which, until it disappears (in the diagram after time twenty), separates it from the slope of diminishing gradient* below. The break of gradient is the local base level of denudation for the basal slope, and it moves upslope from the edge of the river.

* *Abflachungshang.*

There is no need to trace further development in the same detail. Below the slope of inclination *t t′*, another still flatter slope unit *t t″* develops. This begins to form immediately the slope above it has appeared, and continues to do so by the same amount as the latter retreats from the edge of the river. Between these two there appears a fresh concave break of gradient, still more obtuse, and the speed with which it moves upslope is determined by the intensity of denudation on slope *t t′*. The value of this is but small, on account of the slight gradient. In the diagram (fig. 3) the youngest, flattest slope is not perceptible till after the eighth unit of time—see slope position *t* IX—and even after the twenty-seventh unit the lowest break of gradient has only reached point *t″*. By then, all the other local base levels of denudation, which separated higher, steeper slope units, have disappeared.

It is now quite clear that the process obeys a law: *Flattening of slopes always takes place from below upwards*. However, it is not simply a matter of the slopes becoming flatter; but of new and ever flatter slope units perpetually appearing at the general base level of denudation, and growing at the expense of those above. They do this more rapidly, the steeper these are. Finally they replace them; but up to that time they are separated from them by concave breaks of gradient. These, until the disappearance of the slope units belonging to them, act as local base levels of denudation. They always originate at river level all along the drainage net, at the general base level of denudation, and from there they move upslope. The rate at which the flatter declivity extends upwards, at the expense of the steeper slope unit above it, is determined by the rate of denudation of the *latter*. The measure of this, in its turn, is that of the rate of reduction of the rock; and is, indeed, the length of time required for that process to get ready reduced material of the specific degree of mobility needed, in that particular case, to make removal from the given slope just possible—thus making migration inevitable. Since the preparation of the more highly mobile material is proportional to some root of the duration of the reducing process (p. 51), the lower, flatter slope units, which appear later, develop more slowly than the older steeper ones found above them. Development is most rapid when cliff faces are being pushed back and replaced by upward-growing basal slopes; these latter are replaced much more slowly by the slopes of diminishing gradient which are developing from below; and the slowest replacement occurs in that slope unit below which is the slope having the greatest possible flattening and smallest gradient. This undergoes no further denudation; and transport of material from above can take place, at most, to but a limited extent.

To sum up: the process of flattening begins at the general base levels of denudation. *While the position of these remains unaltered, the ever flatter forms that are developing there, one after another, maintain a constant gradient as they recede.* Each successive, flatter slope grows upwards at the expense of the steeper one above it, and brings about its disappearance in the case of the highest parts. Such being the development, it is in these highest parts that the steepest forms are to be found. This is the picture presented by the German Highlands, amongst other places. The last ruin-like remains of rocky steep-forms are found there—in the Harz, in the Fichtelgebirge—as granite tors in the midst of an area composed throughout of the same kind of granite. They are perched upon intervalley watersheds which *belong to the summit relief*[181]. Similar features may be seen at many places in the Danube valley below Tutlingen, or along the Elbe where it breaks through Saxon Switzerland. The light-coloured walls of Malm limestone are confined to those slopes of the meanders which face upstream[182]. The cliffs do not come down to the river. They are steep-forms originally produced at places where the river undercut its banks. But since then they have moved back from the water, their gradient unchanged, making room for a basal slope below. This behaviour shows that undercutting of its concave banks by the river was not continuously effective, but suffered occasional interruption. Traces of the recommencement of undercutting at the same places will be further considered below.

A result of the independent development of each individual slope unit is that the concave base levels of denudation do not move upwards along straight lines continuing the slopes of which they form the upper edges. The profile in figure 3 shows accurately the correct displacement of successively appearing concave breaks of gradient, this having been worked out from the particular values for angle of slope and intensity of denudation upon which the diagram is based. Other values might have been taken without in any way altering the character of the results obtained. It is only qualitative results with which we are here concerned. The construction has been worked out completely only for the first four slope positions. From it, the break of gradient between cliff face and basal slope can be seen, as well as the first [sic] positions 2′, 3′, 4′ . . . *x′*, of the [next] break of gradient. For later development, only a few slope positions have been drawn. These show the displacement of the lower breaks of gradient of the type 4′ . . . *x′*, *z′* and *t″*. The slope *t t″* is taken as possessing the smallest possible gradient.

After unit time, the cliff face has moved back into the position *a a′*, the upward-growing basal slope has reached 2′–2, and a slope diminishing gradient *t* 2′ is beginning to appear. The base level for the denudation of the cliff face is actually found not at *a* but somewhat lower at 2, because of the flattening [at the bottom] of the basal slope [as it weathers back]. The cliff face has been extended a little downwards. After two units of time, the position of the cliff face, the basal slope, and the slope of diminishing gradient are b' b 3, 3–3′ and 3′ t. The base level in question is not at b, but at 3; and it can easily be seen that the amount b 3 by which the cliff face has been increased in length is twice the length of a 2. The development of flatter and flatter slope units thus causes the successive positions of the base levels forming their upper limits to be arranged, not on a straight line, but on an arched curve. If a line is drawn through the points 2, 3, 4, etc., it shows the path taken by the base levels of denudation in successive intervals of time. It is a continuous convex curve. This is generally true for the displacement of concave breaks of gradient. The curvature of the paths along which they move upslope is flatter, the gentler the gradient of the slope units which they separate. For the local base levels marked by the numbers 2′, 3′, 4′, the convex curvature showing the path of the displacement is so slight* that—on the small scale of the diagram—it coincides with the line t 4′ for the first three positions of the slope, and does not become visible before its 9th–16th positions (t IX and t x' XVI). The lowest break of gradient which can develop at all, and which forms the upper edge of the slope with the least possible gradient, is from the outset displaced along a rectilinear path (t t''), for below that slope no further slope unit of still slighter inclination is developed. It already possesses the greatest possible degree of flattening, and widens at the expense of all the slope units above it, extending landwards [back from the river].

It follows that, in general: *If nothing disturbs the process of flattening, the concave breaks of gradient are displaced not only up the cliff, but also further and further back into it. The backward working component—which would be absent were the lower parts of the slope not being flattened—becomes of increasing importance as the distance from the general base level of denudation increases. Thus it is more effective at the upper edge of steep slope units than at that of flattish ones.* This means that the higher, steeper slope units can actually be preserved longer than if those slopes below them were not becoming flatter; and they are removed and replaced by such flatter portions of the slope only at a considerably greater distance from the river than would otherwise be the case.

If left undisturbed, a slope of any gradient whatsoever, provided it is uniform, becomes a slope system concave in profile. In figure 3, if the cliff face was originally of the form t 1, then after three units of time it would have become a slope system t 4′–4 c'. Further development can easily be seen

* [because mobility is attained more slowly the gentler the gradient.]

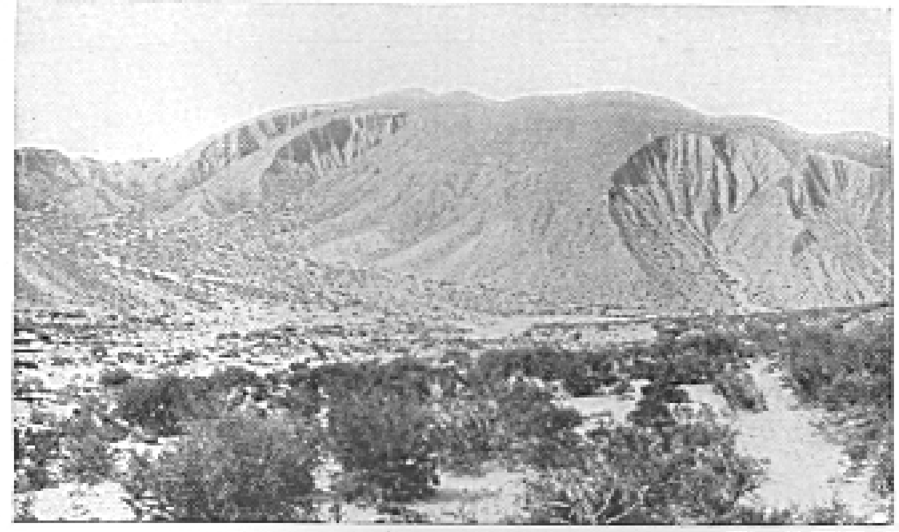

Photo. by W. Penck

1. Convex break of gradient. Casadero (Eastern Puna), Argentina

Photo. by W. Penck

2. Tors on an intervalley divide. Granitic heights of the Cerros de las Animas, Western Argentina

V. Breaks of Gradient

from the diagram. It holds so long as the general base level of denudation remains constant. For more on this, see p. 151.

3. UNEQUAL EXPOSURE. ROUNDING OF HEIGHTS

The basal slope and, to a greater extent, the slopes of diminishing gradient appearing below it, are not only regions for the supply of material moving downslope, but also regions of transit for material from above. When the general base level of denudation remains unchanged in position, material is bound to accumulate on the widening flattened parts of the slopes, since here the downward movement slackens. This accumulation is not unlimited, however, as can be seen from inspection. It is not only that an increase in weight (p. 84) is associated with the accumulation, but also that with length of time the material is further reduced and so more mobile. The ratio of gradient to mobility, which is the determining factor in the movement of rock derivatives, has on this account the same value everywhere on a concave slope; the slighter mobility corresponds to the greater gradient and conversely. This constant ratio is inevitable and is the reason why the transport of material coming from above is actually accomplished on the slopes of diminishing gradient right down to that with the least. Obviously, then, on the flattish parts of the slopes thicker profiles are slowed up, and on the steeper parts thinner ones move more rapidly by way of compensation.

But the accumulation of rubble, which increases downward, brings about inequality of exposure (p. 54). Even when the gradient is uniform, rock reduction goes on more quickly at the freely exposed surfaces; the mobility needed for migration is reached more rapidly than on flattish surfaces covered with rubble, to whatever extent. Exposure is therefore renewed more quickly than on the flatter slopes (p. 78). As soon as the migrating material has accumulated to some extent, differences between the various parts of the slope become noticeable: the upper, steeper slope units, where there is nothing to hinder development, are differentiated from the lower, flatter ones on which denudation is impeded. But if, in such a case, the development of newer, ever flatter slope units should be retarded, then the concave base levels of denudation do not recede upwards along the strongly curved convex paths demonstrated in the previous section; instead, their successive positions—in profile—are arranged upon a line which becomes more and more stretched out until it becomes approximately a straight line. This would mean that the upper, steeper slope units would be removed whilst closer to the river, being replaced by the corresponding slopes of diminishing gradient. The great importance of corrasion lies in the fact that it counteracts this process by once more accelerating denudation, which means renewal of exposure and, with this, flattening beneath a thicker covering of soil (p. 112).

It follows that lessening of exposure on the lower parts of a *slope system* does not influence the type of development; but under certain conditions, e.g. when corrasion is absent, influences the rate of development. It does not therefore lead to fundamental changes of form. It is different in the case of slope units which stand up freely, intersecting in the highest parts of the country. If within such a slope *unit*, exposure is greater above than in the parts below, more rock material is there prepared for denudation in unit time, since reduction is penetrating the depths more rapidly. The result is a flattening of the upper, better exposed parts of the slope unit, and this appears *as a rounding of the zones of intersection, rounding of the heights* (see Plate VI, illustration 2, and p. 78).

With the flattening of the higher parts of the slope unit, conditions become less favourable for the migration of reduced material. Greater mobility is required, which necessitates a longer period of reduction. Therefore denudation is decelerated, and with this, flattening from above is brought to an end. This happens as soon as renewal of exposure takes place at the same rate both on the flattened parts of the slope unit and on the unchanged parts below. That means a balance between the slowing up of denudational intensity below, because of soil accumulation, and that above, due to diminished gradient (pp. 64, 65). Then in equal times, similar amounts of rock material leave their places of origin both above and below. But those above, on account of their better exposure, acquire in the same period a higher degree of reduction than those below, where the rate of reduction is retarded (p. 54). This stationary ratio marks the limit of flattening from above, a limit which cannot be overstepped. *The amount of flattening is thus limited, and is directly dependent upon the inclination of the slope, the upper parts of which are undergoing flattening. The less the gradient, the greater the flattening; and vice versa; but its extent remains unchanged, so long as the gradient of the slope unit remains unaltered.* It is thus utterly impossible for broad rounded ridges and from them, ultimately, flattish forms, to be derived from sharp edges or peaks by means of flattening from above (see pp. 133–134).

Rounding of heights attains a strongly marked development when the gradient of the intersecting slopes is equal to or less than that of the basal slopes. For only then is the accumulation of rubble possible. In regions inimical to plant growth, such accumulation does not begin (other things being equal) until the gradient is gentler than that for [climatic] belts where the vegetation cover is continuous. This accounts for the greater sharpness, especially in deserts, of the zones of intersection of slope units which, if of similar steepness in a temperate climate, would clearly show

Photo. by W. Penck

1. Steep forms not rounded from above. Taton Gorge, below Corral de Piedro, Sierra de Fiambalá, Western Argentina

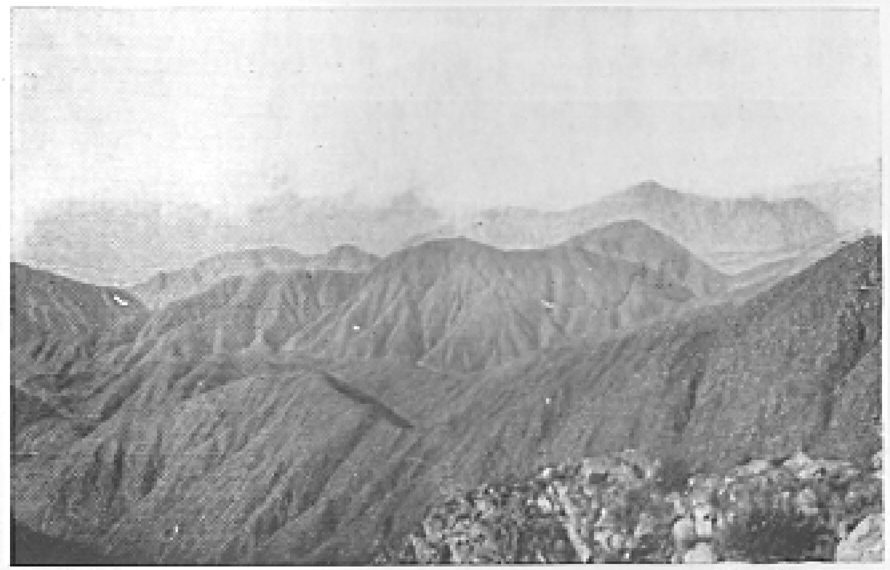

Photo. by W. Penck

2. Steep forms rounded from above. Eastern side of the Cerro Negro Range as it drops to the Bolson of Andagalá, Western Argentina

VI. Rounding taking place from above

rounding because of dissimilarity in exposure (see Plate VI, illustration 1). Where the reduced material is thoroughly removed by rain wash, as for instance in regions of Badlands, it is most striking to find an almost complete absence of blunting where the slopes (concave or straight) intersect, even when the gradient is slight. Such climatically determined differences of form become especially clear when the comparison is between upstanding areas where intersecting concave slopes are of the same average steepness. In districts of sparse vegetation these, e.g. inselbergs, are characterised by a sharper concave curving of the foot-slopes* and greater sharpness of the zones of intersection as contrasted with otherwise similar upstanding areas in humid regions where the foot-slopes* are less concave and the heights more rounded. This, however, refers only to rocks of the same or similar character. Analogous differences can also be found within one and the same climatic zone between upstanding masses of very resistant rock providing little debris, and those which are otherwise similar but composed of easily destroyed rock. In the former case the covering of rubble is slight, other things being equal, and conditions are favourable for renewal of exposure; in the latter case the reverse holds. For the rubble cover, which causes the difference in the forms considered above, is always the result of a *quantitative ratio* between the amount of rock debris prepared and its removal.

4. STRAIGHT SLOPE PROFILES. UNIFORM DEVELOPMENT

If the position of the general base level of denudation remains unchanged, as was assumed in the preceding section, it means that the rivers are neither incising nor depositing. A river working merely as transporting agent cannot prevent the upslope recession of a cliff that originally rose up directly from it, nor the formation of a basal slope, nor the development of slopes of diminishing gradient appearing in succession below that. After some time, the whole slope system—with its cliff face above, and its slope of smallest possible gradient below—has retreated so far from the river that this now cuts only the loose material that has rolled down to form the talus heap; after a further period of time it no longer does even this. The whole slope system retreats inwards, ever further from the edge of the river, so that the higher, steeper slope units in the uppermost parts disappear one after another; the steeper ones generally do this whilst they are nearer the river than is the case for the flatter slopes that succeed them below. The slope with minimum gradient is spreading further and further inwards between the rest of the slope

[* See glossary.]

system and the stream. It is the only one of the slope units that is in this way constantly gaining in area.

If the cliff face, or any other slope unit preserving an unaltered gradient, is to remain adjacent to the general base level of denudation, the river must erode it. In every unit of time during which the slope unit recedes by its characteristic amount, the river must remove that lowest particle $t\,a\,x$ (in fig. 4, p. 145) which would become the starting point for a slope of diminishing gradient so long as the position of the general base level of denudation remained unchanged. The river must erode downwards at least from t to a, or sideways from t to a', and must in all the following units of time perform the same, ever-recurring task. In short, *there must be a constant ratio between the intensity of the denudation acting on the slope unit and the intensity of erosion by the stream*, a ratio characterised by the relation:

$$t\,o = t\,a \sin(90-\alpha), \text{ from which } t\,a = \frac{t\,o}{\cos\alpha} \quad \ldots\ldots\ldots\ldots(1)$$

$$\text{or} \quad t\,o = t\,a' \sin\alpha \quad \text{from which } t\,a' = \frac{t\,o}{\sin\alpha} \quad \ldots\ldots\ldots\ldots(2)$$

where $t\,a$ = the amount of downward erosion
$t\,a'$ = the amount of lateral erosion
$t\,o$ = the amount of denudation (the amount of the retreat of the slope unit)
} in unit time

and α = the angle of inclination of the slope unit.

Figure 4, from which the corresponding values and relationships can be seen for a steep slope (A) and for a flattish slope (B), shows that this formula can be applied to any slope unit immediately adjoining the base level of denudation. *A slope unit can then maintain itself with unaltered gradient only when the intensity of erosion is constant (uniform erosion) and proportional to the intensity of denudation on the adjoining slope unit.* Since this increases with the angle of inclination α, which in its turn depends as regards detail upon the character of the rock, the intensity of erosion has a definite relation to the angle of inclination of the slope unit rising up from the river. The flatter the adjoining slope, the less intensity of erosion is needed to bring about equilibrium; and the limiting case is equilibrium between a river which is not eroding and a slope with the smallest possible gradient (the theoretical condition of the final surface of truncation, the end-peneplane or Davisian peneplain*).

Equilibrium is inevitably established, however, not only when erosion is uniform, but also between any value of the erosional intensity at a given time, and the denudation taking place on the slope unit adjoining

* *an der Endrumpfläche, dem Endrumpf oder der Peneplain von Davis.*

the river *at that time*. Suppose a cliff to rise up directly from a river, and that the river is eroding with less intensity than what is needed to balance the denudation of the cliff face. Let the intensity, however, be greater than that of denudation on the normal basal slope—i.e. the one that would develop if the general base level of erosion remained in a fixed position (see p. 135 ff.). Then obviously the cliff face could not remain at the edge of the river, but would recede from it by characteristic amounts. The slope appearing below it would not, however, correspond to the normal basal slope. Such ($t\,t'$ in the profile of fig. 5) could develop, and maintain its position at the water-course unaltered, only if the stream were downcutting uniformly with an intensity such that its value

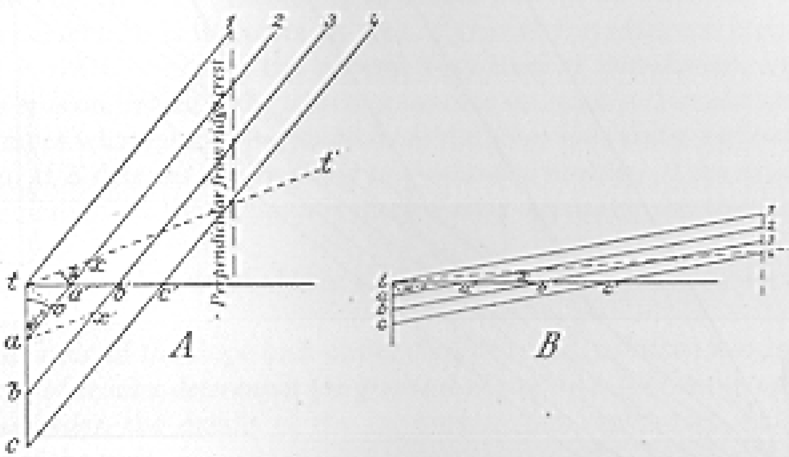

FIG. 4.

corresponded to this equilibrium. But a greater value has been assumed for the river's erosional intensity.

As the cliff $t\,w$ moves back in successive units of time into the positions 1′, 2′, 3′, etc., let us suppose that the general base level of denudation sinks from t to a_1 and furthermore, by equal amounts to b_2, c_3, etc. On such an hypothesis, the infinitely small basal slope t_1 which (theoretically, but not in reality) appeared in time one, has been undercut; an infinitely small step a_1a_1' has formed in the cliff. This must migrate upslope at the same rate as the cliff face, since it has the same inclination. If, in time two, this latter has arrived at 2–2′, then that break of slope would be at a_2a_2' and would have left a new basal slope a_1a_2 behind it. However, this has in the meanwhile been once more undercut. The newly appearing step in the cliff, b_2b_2', would have migrated to b_3b_3' by the end of time three, the a-step to a_3a_3', the cliff face to 3–3′. The new basal slope b_2b_3 has, however, in the meantime, again been undercut

(c_3c_3'), and so on. If events took place successively in that way, a many-stepped basal slope would develop below the receding cliff, its mean gradient being greater than that of the normal basal slope *t t'*. In the diagram the successively appearing steps of undercutting have been marked by the letters *a, b, c, d* . . . etc., and their positions reached in successive times bear the corresponding indices. After time three, the slope system is represented by points c_3c_3' b_3b_3' a_3a_3' 3–3' (the fine lines in the diagram).

However, in reality, river erosion and sheet denudation, over the

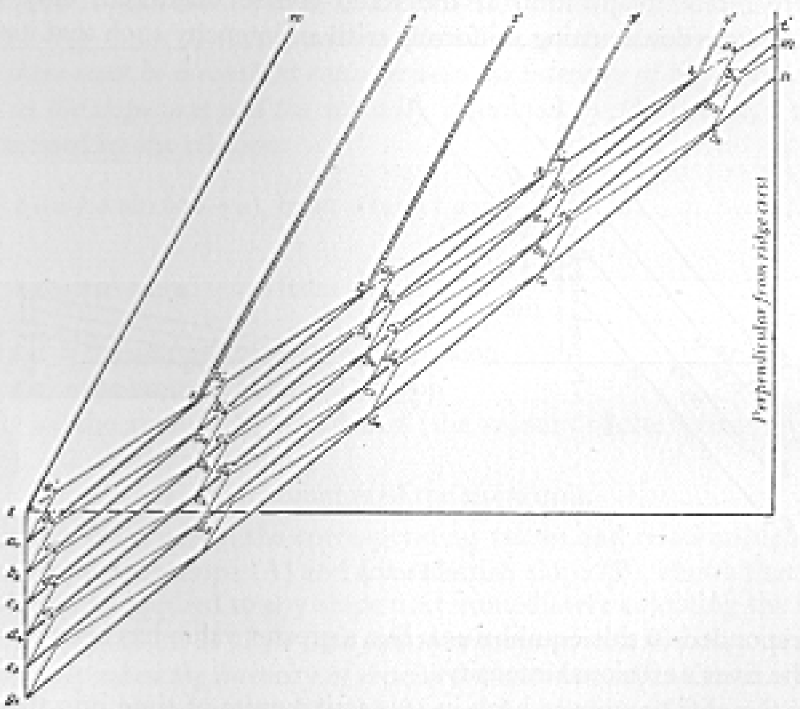

Fig. 5.

whole rock wall as well as that over the slope unit appearing below it, happen simultaneously for all the phases; and so, neither the little steps of undercutting, nor the basal slopes *t t'* below them, actually arise. Each infinitely small undercutting on the part of the eroding river creates an infinitely small slope of steep gradient, on which denudation is more vigorous than at any other position on the growing basal slope. Thus, from the moment of its origin, that infinitely small slope reaches up to what is at that instant the base of the cliff face, swallowing up, as it were, the gentler basal slope. In successive times this latter moves along the same path as it would follow were there no erosion, *since its position is*

determined exclusively by the intensity of denudation on the cliff face itself. If the cliff face has already nearly reached the position 1–1', there arises at the edge of the river only the last infinitely small slope of undercutting which by the end of unit time disappears from the foot of the wall, which has during this same time moved to point 1. At each moment, river erosion brings about accelerated denudation, and this is transmitted to the upper margin of the slope unit. If we choose to consider very small values, we come very near to the natural course of events and the deduction becomes exact. Then the infinitely small steps of the slope a_1a_1'1 pass into the thickly drawn lines of the gradient $a_1$1.

The slope that develops here is from the very outset steeper than the normal basal slope *t t'*. Assuming as before that the rock remains of the same character, it is therefore an area of greater denudational intensity; and it is the lowering of the general base level of denudation, by the river's erosion in unit time, which causes the increase in denudation and determines what intensity is possible on the slope unit rising up from the stream. If E denotes the intensity of downward erosion, A the intensity of denudation on the slope unit immediately adjoining the stream, the general relationship that holds is: $E = \frac{A}{\cos \alpha}$, where α represents the angle of inclination of the slope unit under consideration. In other words: *The intensity of erosion determines the gradient of the slope unit rising up from the river edge,* the details of the inclination then depending upon the nature of the rock.

So long as the intensity of erosion remains constant, there is one slope unit and one only, its form and its inclination remaining always the same, which can grow upwards from the eroding stream. Under these circumstances, no local base levels of denudation, concave in form, can develop. On the contrary, *the slopes have straight profiles,* and these are maintained so long as the intensity of erosion remains unchanged (assuming the character of the rock to be still the same). This is called *uniform development.* Its primary characteristic is a straight profile; thus, the slopes have a specific form, but not a specific gradient. Rather is it true that slopes of any gradient whatsoever—from the least possible to the greatest which can be formed and maintained for the particular type of rock at the place in question—may acquire a straight profile when uniform development sets in, provided only that the erosional intensity keeps its corresponding value unaltered.

In figure 5 we began with a cliff face *t w*. This, if produced beyond the diagram, would meet an analogous slope unit in the vertical line dropped from the ridge crest [*t' m n* in the figure]. Further development leads to a single concave break of gradient. As this moves upslope and shortens the cliff from below, the rocky arête becomes lowered to the same vertical extent. Between the time periods four and five, the cliff face would have disappeared and been replaced by the slope e_5m; and thus the arête would have been replaced by a less sharp edge, the intersecting slopes being not so steep as previously. Up to that moment, there has been a lessening of the vertical distance between the zone of intersection and the general base level of denudation which is sinking uniformly, i.e. the relative height (pp. 135–136) has been diminishing. From now on, this is changed. The uniform straight slope is being shortened from above, at the zone of intersection, by the same amount as it is being supplemented from below at the edge of the river. In other words: regardless of the gradient of the slopes which are meeting in the particular case, and irrespective of rounding of the summits—which does not interfere with the stationary condition, but causes it (p. 142)—the zones of intersection are lowered in unit time by the same amount as the rivers cut down. This follows directly from the rectilinear nature of the slope profiles and the constancy of their gradient, and can be read off at once from figure 5: the lengths e_5-g_8 (amount of erosion) and *m*-*n* (lowering of the ridge), both between the same slope positions, are equal to one another.

If uniform development lasts sufficiently long, straight slope units are produced in every case; the steeper ones, which emerge from rapidly eroding streams, appear after a shorter time than the flatter ones corresponding to less intense erosion. They then hold the field alone. *As soon as this stage has been reached, the relative heights become constant. Nothing changes in this respect so long as the intensity of erosion maintains a uniform absolute value.*

5. CONVEX BREAKS OF GRADIENT

Development of convex breaks of gradient might be deduced directly from the law that the gradient of slopes is determined by the intensity of erosion. However, we prefer once more to follow continuously the natural course of events so as to reach exact results by this somewhat lengthy method. In order to deal with the problem by constructing a diagram, fig. 6, p. 149, is once again based upon taking definite values for the intensity of denudation acting upon the individual slope units: any numbers may be chosen for these values so long as merely qualitative results are desired, and so long as they fit in with the known law that intensity of denudation, which is equal to the rate of development of the slope units, increases with their steepness. Differently chosen values would alter merely the [particular] gradients of those portions of the slopes which are represented in the profile, and not—as we wish once

more to stress emphatically—the fundamental results which alone matter here.

A slope with a straight profile, rising up from a stream which is eroding uniformly, recedes in three successive units of time from its position *m m'* to *t t'*. *m* to *t* denotes the uniformly maintained amount of erosion, *m'* to *t'* the lowering of the zone of intersection by similar equal amounts during the same periods of time. If from that time onward the intensity of erosion increases, development can no longer continue in a similar way: the general base level of denudation is lowered more rapidly; but the denudation of the slope unit with its given gradient cannot be accelerated during the same period. The balance has been upset.

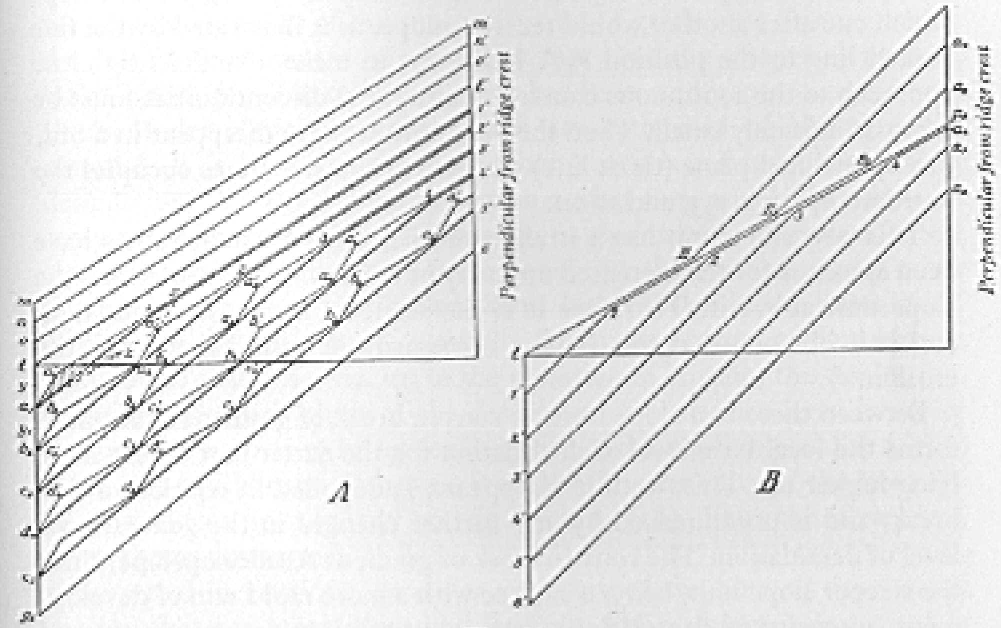

FIG. 6.

Starting from the position *t t'*, the slope can, and must, reach position $a_1'1'$, in time one, because of the renewal of exposure taking place on it at a definite velocity. In the meantime, however, the general base level of denudation has been lowered from *t* not only to *y* but to a_1, which would be just double the amount occurring in the previous time intervals. Theoretically, therefore, there remains a small undercut declivity a_1a_1' which separates the slope $a_1'1$ from the general base level of denudation. But in fact neither this nor its similar successors, shown in the diagram, ever develop. For at every instant the river, eroding with increased force, brings about a minute undercutting, produces a minute steep slope, which from the moment it appears is a surface of more intense denudation. As such, it recedes vigorously upslope and eats away the lower end of the slope unit which is simultaneously receding, but at a slower rate. If, at the end of time one, this reaches the position 1′1, then the last of these minute undercuttings (i.e. slopes with an inclination of maximum gradient) has been produced at the river's edge, and has vanished at point 1. This point is as far as the undercutting can recede upslope in unit time on account of the intensity of denudation peculiar to *it*.

Thus, while the one slope unit moves in successive times from $t\,t'$ to 1′–1, 2′–2, etc., there is also a new slope unit growing up from the more intensely eroding river. This might be considered to have arisen discontinuously, as has been shown on p. 146 for an analogous case. The newly formed slope would then be dissected by exceedingly small steps which one after another would reach upslope, as is illustrated by the fine kinked line in the position $e_5 5'$. However, to make a sufficiently close approach to the continuous course of nature, the discontinuities must be taken as infinitely small. Then the very minute steps disappear in a uni formly inclined plane (thick line) which at successive times occupies the positions $a_1 1$, $b_2 2$, $c_3 3$, and so on.

This new slope unit has a straight profile, since constant values have been assumed for the increased intensity of erosion. It is steeper than the slope unit above it. Therefore it is the scene of increased denudation and it is obvious that this is now necessarily in equilibrium with the erosion.

Between these two slope units, a convex break of gradient appears. It forms the local base level of denudation for the flatter part of the slope lying higher up. This, until it disappears, is denuded in relation to that break, and is uninfluenced by any further changes in the general base level of denudation. The convex break of gradient recedes upslope, since the steeper slope unit, being a surface with a more rapid rate of development (intensity of denudation), retreats upwards more vigorously and eats away that part of the slope which is above it, undercutting it and thus preventing it from being flattened. This latter slope is displaced only in a direction parallel to its former position; but it is continuously shortened from below until it disappears from the parts at the highest altitudes.

Thus in general: *Convex breaks of gradient owe their origin to an increase in the intensity of erosion*[180]. *They originate at river level all along the drainage net, and from there they recede upwards at a rate that is determined by the intensity of denudation of the steeper slope unit. On account of their presence, the development of the higher, flatter slope unit becomes independent of the behaviour of the erosional channels, i.e. independent of the base levels of erosion* (see Plate IV, illustration 2, Plate V, illustration 1).

Additional Notes on the Origin of Concave Breaks of Gradient

In their origin, behaviour and function, convex breaks of gradient agree in every way with concave base levels of denudation. Both start from the general base levels of denudation, *both recede upslope, and in both cases the rate of retreat is determined by the intensity of denudation, which equals the rate of development of what is at that time the* STEEPER *slope unit*. Both are local base levels of denudation and render the development of the respective slope units above them independent of the behaviour of the erosional channels and of the base levels of erosion.

These analogies, and especially the fact that the change in position of the convex as well as of the concave breaks of gradient is determined by the rate of development of what is at that time the steeper slope unit, make it now possible to add to what has been said about concave base levels of denudation in areas which are composed of homogeneous material. It is by no means only when there is a fixed base level of denudation, as was assumed in section 2, that they arise. They do so *in every case where there is any diminution in the intensity of erosion*. If this intensity becomes zero, there is the possibility that flattening may occur down to the smallest possible gradient. Interruption in the lessening of erosion, on the other hand, naturally limits the process of flattening as well. Up to that time, viz. up to the cessation of erosion, the diminution of gradient in each phase of the development of the erosional intensity can only be such as to bring the intensity of denudation peculiar to that slope into equilibrium with what is at that time the value of the intensity of erosion (see pp. 145, 147 and fig. 5 on p. 146). Thus the succession, from above downward, of flatter and flatter slope units, together with their actual inclinations, provides a picture of the kind of decrease in erosion that has taken place and its limit. Other things being equal, a sharply concave curve of the slopes indicates rapid deceleration of the erosional intensity, a concavity of less strong curvature indicates a slower rate of deceleration (cf. with this, pp. 159–161).

6. DEVELOPMENT OF RELATIVE HEIGHT WAXING DEVELOPMENT AND WANING DEVELOPMENT

Figures 2–6 show the development of the relative altitudes. To simplify matters, the lines along which the zones of intersection move in successive units of time are recorded as vertical lines dropped from the ridge crests. No account has been taken of the rounding of heights. When the general base level of denudation is constant, the zone of intersection is lowered, and with this the relative height is lessened (pp. 136–

137, fig. 3). This decrease, however, is not the same for all phases. If the slope positions *t* 1, 2 *a'*, 3 *b'* (in fig. 3, p. 137) are produced to cut the vertical line through the ridge crest, the lowering in successive intervals of time is found to be greatest, and—as can also be seen from fig. 2, p. 135—to be constant in amount, so long as it is the same steep surfaces of intense denudation, the cliff faces, which are intersecting (positions I–IV). Suppose, for the scale chosen, that this lowering is 22 millimetres per unit of time. After time three, the cliff disappears, and from then onwards the basal slopes meet in the highest parts of the country. The lowering of the zone of intersection now takes place more slowly; in the diagram, it will be only 10 millimetres between the positions IV and V, i.e. during one unit of time, and it falls still further to 1.2 millimetres in unit time. This amount remains constant so long as the zone of intersection is formed by the basal slopes—positions V to XX—and is in no way affected by the fact that in the meantime further, flatter slope units are developing at the edge of the river and growing upslope. After time twenty, the basal slope has been completely replaced by the next flatter slope unit, in which the zone of intersection now occurs. The lowering of this is hereby further decreased—0.16 millimetres in unit time—and this decreased amount remains constant until the slope unit in question has been itself removed and replaced by the one next below it with the next degree of flattening.

If the general base level of denudation remains constant, decrease in the relative height takes place more and more slowly. This slowing down comes about because, in the course of development, ever flatter and flatter slopes meet in the zones of intersection; and on these, denudation achieves less and less in successive units of time. *The lowering of the zones of intersection depends solely upon the development of the slope units which meet there, and it is determined by whatever intensity of denudation is characteristic of these latter.*

The general base level of denudation is constant only as a special case. This can occur at the end of a series of developments which are characterised by decreasing erosional intensity, i.e. there is a decrease in the amounts by which the general base level of denudation is sinking [in each unit of time] (p. 151). Considering any phase of the development, e.g. that represented by fig. 5 (p. 146), what occurs is as follows: So long as slopes with the gradient *t w* intersect, the zone of intersection is lowered by an amount proportional to the sine of the angle of inclination of the slope unit, regardless of the fact that in the meantime the river is eroding less intensely and is allowing a flatter slope unit to develop. This becomes evident if in fig. 5, p. 146, the slope positions *t w*, 1–1', 2–2', 3–3', 4–4' are produced to meet the vertical line through the ridge crest. Until the flatter slope unit has pushed its way through and forms the zone of intersection, this latter is lowered in each successive unit of time by an amount greater than that by which the general base level of denudation is sinking. *The result is a decrease in relative height.* The relative height remains constant if the slopes, which intersect in the highest parts of the country, rise in rectilinear fashion from a watercourse that is eroding with an intensity which has been decelerating but which—it is assumed—is once more uniform.

The course of development which is due to decrease in erosional intensity may be called WANING *development. It is characterised by the occurrence of concave breaks of gradient, concave profiles, and decreasing relative height.* In the limiting case, the erosional intensity sinks to zero; the slopes then develop with a constant position for the general base level of denudation, and a lower limit is set to flattening only when slopes with the smallest possible gradient appear. As soon as these intersect on the interfluve summits, there is naturally an end to the lowering of the zones of intersection. With this, the lower limit has been reached for the decrease of relative height. This height is determined (*a*) by the inclination of the slope unit which has become the sole prevailing one, viz. that with the greatest possible degree of flattening; and (*b*) by the horizontal distance between the zone of intersection and the edge of the river, increasing with this distance and vice versa. This process ends with cessation of all denudation of the land, with the establishment of minimum angles of slope and of a relative height which can be no further decreased. It is, however, possible only when the course of waning development proceeds completely undisturbed and for an unlimited time. It is called peneplanation of the country. Every phase, except the theoretically final result, is characterised by a concave slope profile. That final result would be the end-peneplane, Davis' peneplain or '*Fastebene*' (see p. 128).

Waning development may follow from the uniform type; but it is just as likely for the uniform type to follow it, and this is what was assumed in the construction of fig. 5 (p. 146). The characteristics *of uniform development* have already been established (pp. 147–148). They are based upon constancy in the amount of erosion produced in successive units of time. Slopes with straight profiles develop, and as soon as these intersect in the highest parts—but not before—the relative height also becomes constant. Then the lowering of the zones of intersection is not only proportional to the sine of the angle of inclination of the slope units which are meeting, but also it is equal to the amount by which the general base level of denudation has sunk.

Fig. 6, p. 149, illustrates the development of the relative height as the intensity of erosion increases. The construction in diagram A starts with a slope unit of uniform development. As far as position $t\,t'$ of the slope, the amounts by which the zone of intersection is lowered, and those by which the general base level of denudation sinks, keep pace with one another. From that point on, it is otherwise. The river incises more strongly, but the rate of lowering of the summit remains unchanged so long as the zone of intersection is in the same slope unit: *the relative height increases*. This goes on until the new steeper slope unit rising from the river, which (according to the assumption) is again eroding uniformly though with increased intensity, has succeeded in reaching the zone of intersection.

The construction of diagram B can now easily be understood. It is based on a system of slopes which is exhibiting waning development, and which consists of cliff face and basal slope $t\,II\,a$. For the sake of clearness, the relationship $E = \frac{A}{\cos \alpha}$ has been assumed between E, the intensity of erosion, and A, the rate of denudation of the cliff face $II\,a$ with angle of slope α. Then from the incising water-course there will again rise a cliff face with the same gradient, assuming the character of the rock to be homogeneous. After time one, a slope has been formed, having the position $1'1\,H_1a_1$: a fresh cliff face $1'1$ has appeared and is separated from the receding basal slope by a convex break of gradient which migrates upslope at the same rate as the concave base level of denudation at the foot of the upper cliff face. The basal slope is shortened from below by as much as it is increasing above. Were the erosional intensity greater, the more actively undercut lower cliff face would increase upslope more strongly and shorten it from below more rapidly than it can grow upwards. It would be removed, the lower cliff face would merge into the upper one as a uniform slope unit, over the whole surface of which intensified denudation would then occur, brought about by accelerated caving in of the river bank due to its undercutting. Before this condition had been reached, however, stepped cliff faces would be visible in such a case also. These, occurring on valley slopes of homogeneous composition, show that erosion has repeatedly begun and ceased at the same places (p. 139). Excellent examples of this are to be seen in the valley of the Danube below Tuttlingen. There it is a matter of the repeated action, alternating with its absence, of predominantly lateral erosion at the undercut slopes of the valley meanders: the cliffs are not invariably stepped, nor is the number of steps nor their altitude consistently repeated at analogous places. No terraces, that could be correlated with these cliff steps, have been observed on the corresponding slip-off slopes.

If the upper cliff face intersects a slope unit of the same type then, according to what has been assumed for diagram B, the zone of intersection is lowered by the same amount as the river cuts down, until the basal slope reaches it—see position $3'3\,a_3$. From that time on, the lowering, which corresponds to the rate of denudation of the slope, goes on very much more slowly. The river is now at the same time cutting down with undiminished vigour, and so the relative height increases. This behaviour is again associated with the presence of a convex break of gradient, and once more the lowering of the ridge crest is independent of what is happening at the river's edge, provided that the slope leading from it to the ridge crest is not a single slope unit (lit. a uniform form system). *The occurrence of convex breaks of gradient and of convex slope profiles is as necessarily bound up with increasing intensity of erosion as is the increase in relative height. We call this* WAXING *development.*

This general statement can be made: Lowering of the zones where slope units intersect at the tops of the slopes does not necessarily mean a decrease of relative height, nor a lowering of the general level of the land. *The development of relative height is the story of the vertical distance between the zone of intersection and the corresponding position of the general base level of denudation at any given moment; the lowering of the zone of intersection is the steady decrease in the vertical distance between it and a definitely chosen fixed level, e.g. any individual position of the general base level of denudation.* Lowering of the zones of intersection is the immediate consequence of the denudation that is taking place on the intersecting slope units; like this, it goes on steadily and comes to an end only when denudation ceases. *The amount of lowering is determined solely by the intensity of the denudation on the intersecting slope units, and so is proportional to the sines of their angles of inclination; the steeper these are, at the zones of intersection, the greater the lowering in unit time; and this is independent of what is happening on the lower parts of the slopes and at the general base level of denudation.*

Variations in the relative height, on the other hand, depend upon differences between the behaviour of the erosion channels *and* that of the zones of intersection. If the intensity of erosion diminishes, the relative height becomes less. But this does not occur till the slope systems of concave profile, i.e. those which are broken up by exclusively concave breaks of gradient, have extended up to the topmost parts, without necessarily affecting the rounding of heights previously considered (waning development). If the intensity of erosion increases, so does the relative height. But here, likewise, it is not till the developing slopes, divided up by convex breaks of gradient, have established themselves (waxing development). And it is only in those special cases where straight slopes, due to a uniformly incising stream, intersect on the summits, that the relative height remains constant. Then it does not alter any more than does the inclination of slope, whatever it may be at that time, so long as the intensity of erosion maintains its value, not even when the denudation and the lowering of the zones of intersection are of unlimited duration (uniform development).

7. RATES OF GROWTH AND AREAS OF SLOPE UNITS*

The regular upward recession of concave and of convex breaks of gradient, in regions composed of homogeneous material, brings about a change in area of the slope units which adjoin one another at any given moment. Those immediately above the receding break of gradient are shortened; those which happen at the time to be below it, spread upslope. *This latter process is the growth of slope units.* The rate of growth varies with the intensity of denudation. Since the latter increases with the gradient, steeper slope units grow more rapidly than flatter ones. During their development, therefore, slope units are constantly changing in area; and which kind of change it is depends upon their arrangement. Only with uniform development is there no such alteration; in that case the slopes consist each of a single slope unit, and are uniform and not composite. There is compensation for shortening at the zones of intersection by the addition of an equal amount at the general base level of denudation; the area of the slope unit is in that case as constant as the gradient.

But with waning development, in which the steeper parts of the slopes are at the top, and the flatter ones below (p. 137, fig. 3), each higher break of gradient recedes upslope more quickly than that next below it (p. 150); and so the area of the slope unit between them increases. That increase is not, however, unlimited, nor is it very considerable even over long periods of time; since except between cliff and basal slope the differences of gradient between neighbouring slope units are never very great and they become smaller, the slighter the inclination of the slope units which join one another by concave breaks of gradient. It is only the slope of greatest possible flattening which is continuously increasing its area at the expense of all the slopes above it, since at its lower margin, the fixed general base level of denudation, there is no flatter slope unit appearing.

The arrangement is reversed in the case of waxing development; here the steeper slope units lie below, the flatter ones above. Convex breaks

[* See glossary.]

of gradient, which recede upward more quickly, form the lower margin of each of the slope units. These, in unit time, are shortened from below by greater amounts than the upward extensions of their top edges. All of them thus decrease in area except the one that rises directly from the general base level of denudation. It is inevitable that in this way slope units vanish before they have reached the zone of intersection in the highest parts. This is illustrated in fig. 7, which has been drawn for 13 successive positions of slopes which result from an assumed increasing intensity of erosion. It would occur with a slope which had been produced by first, an increase in erosional intensity, then followed by uniform incision of the amount 1 to 2 in unit time. Two slope units, *a* and *b*, are present. A third steeper one (*c*) becomes associated with them as soon as the river incises more vigorously (from 2 to 3, then 4, 5, 6, and so on), and a further fourth one (*d*), which rises up from the river when it erodes yet more powerfully still after having reached slope position 9. That fourth slope possesses the greatest inclination that the character of the given rock permits.

Slope unit *b* is so vigorously undercut and shortened by the slope below, that between the slope positions 12 and 13 it has been completely eaten away and replaced by slope unit *c*, which then immediately adjoins the much flatter slope unit *a*. A more pronounced convex break of gradient separates them from one another. This result would have been achieved more quickly had the river erosion increased to greater amounts in unit time than has been assumed. Conditions which could obtain only after the 9th slope position in the figure would then have come about sooner. The amount of erosion by the river in unit time is the rate or intensity of erosion; the increase of such amounts in unit time is the acceleration or increase of erosional intensity (conversely: the diminution of these amounts is the decrease of intensity or deceleration of the erosion).

The removal of intermediate slope units by steeper ones produced later may occur even before those intermediate slopes have extended up to the highest parts; and it takes place the more quickly and, other things being equal, affects a larger area, the greater the acceleration of the erosion (see p. 160). Such a slope, therefore, no longer shows all the slope units, one above the other, as they were successively formed at the general base level of denudation; but some of them are gone and have been replaced by more sharply convex breaks of gradient. They separate the far older and flatter slope units from the far younger, steeper ones. This phenomenon is widespread: sharp breaks of gradient, the origin of which has been explained above, always form the lower limit of upraised landscapes with gentler slopes, and they mark the upper edge to which the younger, steeper slope units have worked back from the deepened erosional channels. It is quite wrong to deduce from this a duality of uplift[183]. Amongst many other examples of this there are the dissected peneplanes of the Vogtland and the Rhenish Schiefergebirge, and the highland landscapes of the Harz and the Black Forest, etc., with their edges eaten into, as it were. The phenomenon is most sharply marked where acceleration of erosion has produced slope units of maximum gradient. If the watercourse in fig. 7 should finally cut down in unit time not only from 9 to 10, but twice as quickly right down to 11, no steeper slopes would develop, not even with a further acceleration of erosion, since the maximum gradient had already been attained. But the slope unit *d* would increase

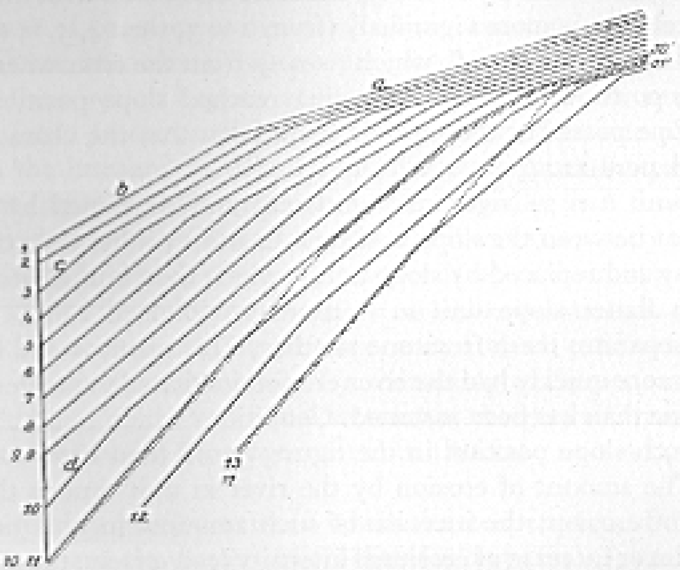

Fig. 7.

to an extraordinary amount. The accelerated undercutting of the higher slope units would lead to their rapid removal (dotted slope positions 10–10′, 11–11′, fine figures); very soon a specially sharp convex break of gradient would make its appearance, and here the precipitous undercut slopes would directly adjoin a far older and flatter slope unit (fig. 8 and Plate IV, illustration 2).

Such undercut slopes always have a straight profile. It is no longer possible to tell from their shape whether the water-course from which they rise has had uniform, accelerated, or decelerated erosion, whether they belong to the type of uniform, waxing or waning development, so long as the intensity of erosion is more than what just balances the spontaneous denudation on a slope of maximum gradient. If such undercut

slopes meet in zones of intersection, the relative height becomes constant. This behaviour, then, no longer indicates uniformity of development, a point which must be kept in mind for later investigation.

Continuity of the Curvature of Slopes

For the accentuation of convex breaks of gradient, which takes place on the removal of intermediate slope units, it is not necessary to presuppose a sudden increase in the intensity of erosion. This has, so far, been assumed in order to facilitate approach to the laws governing slope development. Erosion may be locally accelerated in such a way as to give the impression that the intensity increases suddenly by comparison with the very slow processes of sheet denudation. Such a superficial im-

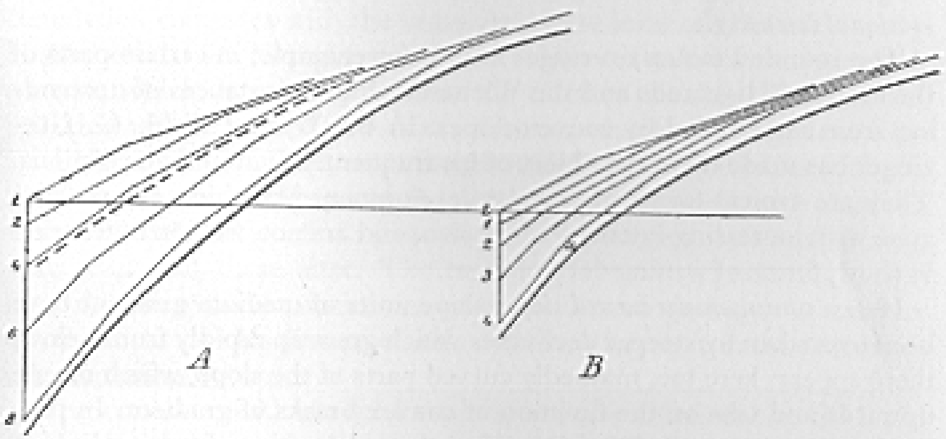

Fig. 8.

pression must not, however, be allowed to tempt us to misinterpret the essential nature of erosion, which changes its intensity only in a steady, not in a discontinuous manner. Erosion is lowering the general base level of denudation at every moment, i.e steadily, by a very small amount. With increasing intensity of erosion, these very small amounts become larger in successive units of time; with lessening intensity, they become smaller. At every moment, therefore, very minute slope units rise up from eroding rivers and, when the amount of erosion increases, they become somewhat steeper in each successive unit of time. *They combine in a continuously curved convex slope.* The kind of curvature can be seen in fig. 8 in which the continuously curved slope profiles are drawn in heavy lines or in broken lines inserted under the corresponding slope positions of the construction. On the left (A) the *acceleration of erosion* has been taken as exactly half that on the right (B); so that in the latter case it is always exactly half the time, as compared with A, which elapses before the erosional intensity has risen to twice, three times or four times the amount of the initial value, the same in both cases. It is only after time eight that A has reached the same erosional intensity as B had already attained after time four. In both cases there appear successively the same number of similarly inclined slope units, but in B twice as quickly as in A. Therefore the area of the individual slope units—of the same inclination—is smaller in B, and the inevitable removal of intermediate slope units by lower and steeper ones takes place sooner than in A. In figure 8 B this has already become visible after time four (at x); in A, nothing can yet be seen of it after time eight. It is apparent that *the curvature of the slopes is more markedly convex, towards the valley incision, the greater the acceleration of erosion, the more rapid the rate of increase in erosional intensity.*

The rounded mountain ridges found, for example, in certain parts of the German Highlands and the Wiener Wald, are instances of upstanding areas surrounded by convex slopes. In the Wiener Wald, G. Götzinger has made them the object of his frequently quoted investigations. They are typical forms of waxing development [184] which of necessity arise with increasing intensity of erosion; and are not, as Götzinger tried to show, forms of waning development.

If in a *continuously curved slope*, slope units of medium gradient have been overtaken by steeper declivities which grew up rapidly from below, there appear, here too, markedly curved parts of the slope, which recede upwards and take on the function of convex breaks of gradient. In particular, they are markedly visible when the acceleration of erosion has led to the formation of slopes of maximum gradient (p. 158).

The break of gradient is a discontinuity in the slope; but it is brought about by a continuous increase in erosional intensity. For the first time we are meeting the case of a steadily acting cause producing a morphological discontinuity. This result is of great importance in the evaluation of the convex breaks of gradient that are being considered here and that play a highly significant part among the world's land forms. It will be referred to again.

Just as increase of erosional intensity goes on steadily, so does decrease. Thus the concave profiles of waning development are also in reality continuously curved. The same naturally applies also to those profiles which develop when the general base level of denudation remains constant, and which suffer flattening to the utmost possible amount. For at each moment there arises here also a fresh, very minute, slope unit of an inclination steadily becoming somewhat slighter. These combine to form an unbroken concave slope. In fact, even the transition

from cliff face to basal slope is no sharp nick, as can easily be seen in mountain regions, but a more or less strongly re-entrant curve. The only place where this cannot be clearly seen is where talus reaches up to the foot of the cliff, covers the concave transition between the surfaces of denudation, and in its place allows a sharp nick to appear between the cliff and the detrital accumulation.

8. RISE IN THE GENERAL BASE LEVEL OF DENUDATION

Deposition by rivers brings about a relative rise in the general base level of denudation, whether it occurs in valleys or at the edges of a tectonically independent part of the crust where the general base level of denudation coincides with the immediate base level of erosion (p. 128). Similar results are brought about by a relative rise in level of standing water to which denudation surfaces are directly tributary. Processes of this kind will be termed, for short, elevation or rise of the general base level of denudation. They are changes which do not induce any alteration in the type and shape of the slope units connected with them. It is not till denudation finds a continuously changing, relatively rising, base level that these alter. The resulting features represent a special case of waning development, naturally not that of waxing or of uniform development. In this discussion reference may be made to the previously drawn profiles.

The concave nick, where the surface of the alluvium, or the water level, joins the given slope unit, is the base level of denudation. Whether it remains as such depends on the rate at which this base level rises in comparison with the rate of development of the adjoining slope unit. In the case of a cliff face, the base level of denudation must be raised at the same rate as this recedes, if it is continuously to adjoin a cliff with the same angle of inclination as before; in the time the cliff takes to retreat from t 1 to $a\ a'$ (fig. 3, p. 137), the base level must reach at least the level of point a. If it lags behind, a basal slope develops above it, the lower parts of which become buried; and even when so shortened, this separates the cliff from the general base level of denudation. Flattening of the basal slope cannot take place so long as the base level continues to rise at the same rate. Slower rising would leave proportionately larger parts of the basal slope visible; it would be possible for its normal slope of diminishing gradient to appear [at the bottom of it]; until, in the limiting case, when the general base level of denudation is no longer being raised at all, flattening continues undisturbed. When slope units develop more slowly than the rate at which deposition, or the water level, is rising, they are buried. This obviously takes place more readily and more frequently on slopes of gentle or moderate inclination than on steep or precipitous slopes.

Slope units, that are being drowned, preserve their gradient only when the rate at which the base level of denudation is rising, keeps pace with or surpasses the rate of growth of the respective slope units. This is made clear in figure 9 A. A cliff face adjoins the river t. In successive units of time it moves into the positions $a_1'a_1$, $a_2'a_2$, $t'a_3$, and a normal basal slope $t\,t'$ would develop below it. But the river is aggrading, and the level of deposition rises in the same unit of time to t_1, t_2, t_3. This, according to our premisses, is more than the basal slope can grow upwards, and more than the amount by which the cliff is receding. Under these circumstances, no normal basal slope can develop; if it has already been formed, it soon disappears under the rising floods of sediment or water, still retaining its gradient. However, the lower parts of the cliff cannot be simply buried in the same way, i.e. covered up whilst retaining their form and gradient, since denudation of the cliff face and the rise of base level are at any given moment simultaneous processes.

If, in very minute intervals of time, denudation and deposition followed one another, then, after the first unit of time, the cliff face would be in position $a_1'\,a_1$. There would be a minute basal slope $t\,a_1'$, but it would be buried under the alluvium which has meanwhile risen to $t_1$1. The upper surface of this is now the base level of denudation. At time two, the cliff would be in position $x\,a_2$, from 1 a new minute basal slope 1 x would have been formed, which again would be buried by the material that had risen to $t_2$2, etc. Below this material, therefore, there would be a slope with many steps (thick pecked line), removed from any further denudation; its mean gradient would be greater than that of the normal basal slope $t\,t'$, but less than that of the cliff. The slope which is actually formed and which is covered up at each moment of its upward development is, however, not broken when the base level of denudation is steadily rising; but because of the simultaneous working of denudation and deposition it is uniform. It is represented by the straight line t–1–2–3 which comprises all the infinite number of steps, chosen so as to be sufficiently small, of the type $t\,a_1$1. The result is valid for any slope unit of any given gradient whatsoever: *if the general base level of denudation rises more quickly than the adjoining slope unit develops, the slope unit is preserved at the base level: but below it there arises, and is drowned as it arises, a gentler slope which is more steeply inclined than that normal slope of diminishing gradient which is developed when the base level of denudation remains fixed.*

The uniform rise of the general base level of denudation, as here

assumed, occurs only in special cases and for a limited time. In its essence it is a process which is not uniform, which is accelerated at the beginning and then decelerated towards the end. Even when the causes continue to work in the same way, deceleration must take place, since the denudation surfaces of the district as a whole play the part of inclined sides to a receptacle receiving the upward growing alluvium or water. That receptacle is wider at the top—the widening being greater the flatter the average slope of the land concerned— and so, if the level is to rise by the same amount in successive units of time, there must be an unlimited increase in the supply of material filling it in. This is conceivable in parts of the crust which are sinking uniformly, or with accelerated movement, where the surface subjected to denudation becomes in the

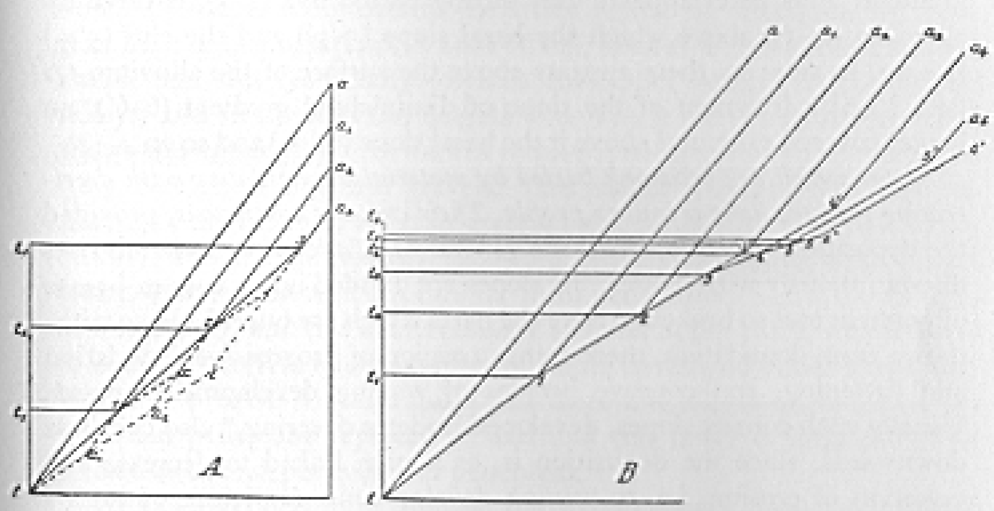

FIG. 9.

end completely covered by transgressing sediments of marine or continental origin; but it is unthinkable in regions that are in any way moving upwards, at rest, or undergoing decelerated subsidence. It may be considered normal, especially in the continental areas, for a rise in the general base level of denudation to take place with deceleration.

Fig. 9 B illustrates how this takes place. Suppose a cliff face to adjoin the general base level of denudation t. While it recedes in successive periods of time (of equal length) to a_1, a_2, a_3, the base level rises at the same time to t_1, t_2, t_3, i.e. by ever smaller amounts, or more slowly. And it has been assumed that, in time one, the base level of denudation rises more quickly than the normal basal slope can grow upwards: the buried fragment of slope t 1 is steeper than the basal slope (as shown in fig. 9 A). From the upper surface of deposition $t_1$1 there arises as before a cliff

1 a_1. In time two, the rise from t_1 to t_2 just corresponds to the rate of growth of the normal basal slope; this (1–2) is buried. Yet still there rises out of the alluvium, $t_2$2, a cliff 2 a_2. In time three, however, the rise of the base level of denudation has already slowed down: from the alluvium $t_3$3 there rises the upper part of the growing basal slope (3–3′), no longer entirely covered up, and above it the cliff (3′ a_3). In time four, because of their different individual intensities of denudation, they have reached 4–4′ and 4′ a_4. At that stage the general base level of denudation is rising more rapidly than the basal slope develops (i.e. than its normal slope of diminishing gradient grows). The part (3–4) of the slope that has been covered up during period four, when the alluvium rose to t_4, is gentler than the basal slope but steeper than its normal slope of diminishing gradient. This latter appears only during period five (4–5), covered by alluvium (t_5–5), above which the basal slope (5–5′) and the cliff (5′a_5) rise up. In time six there appears above the surface of the alluvium $t_4$6 [sic, ? $t_6$6] a fragment of the slope of diminishing gradient (6–6′), no longer covered over; and above it the basal slope (6″–6) and so on.

Slopes which are becoming buried by material accumulating with decelerating growth, have a convex profile. Their curve is continuous, provided the deposition is steady; when the general base level of denudation rises discontinuously with pauses, the slopes are divided up by convex breaks of gradient and so broken. Above the parts which are buried and so withdrawn from denudation, there comes a region of progressive denudation and flattening, and concave profiles of waning development appear. Usually such convex slopes, developed under a covering,* also continue downwards, since the deposition is, as a rule, linked to decrease and cessation of erosion, i.e. to waning development. A picture of such a complete system of slopes can be obtained by adding a concave profile at the left hand side of point *t* in fig. 9 B, as in the fourth position of the slope in fig. 3, p. 137. Such profiles are specially characteristic of the low hilly relief formed in homogeneous Devonian shales and greywacke which are overlain by Pontian and Levantine beds in the neighbourhood of Constantinople [Istambul]. The valley sides, immediately above their buried floors, are concave, passing up into continuously convex curves and then merging into the flattish slopes of the Thracian peneplane, which was formerly partly submerged by the youngest horizons [of the later beds] but only at its edges. On the peneplane, concave profiles again predominate. The buried hilly landscape[185] was thought due to the preservation of youthful forms. That is incorrect. The buried forms which appear to be entrenched in the peneplane surface cannot be those which characterised the denudation landscape before and during aggradation; it presumably had steeper mean gradients and greater relative heights, and it was only during the transgression that the buried forms originated from it. This is made plain by the convexity of the upper parts of the valley sides, which might well be regarded as slopes developed under a covering. They might, however, also be interpreted as forms of waxing development, and there would be no difficulty arising from the fact that the convex slopes change downwards into concave ones, the flanks of extremely wide trough valleys. For it will be shown that in certain parts of rising crustal segments, it is the rule for waning development to follow the waxing type. It would be desirable to have fresh investigations made in the regions of the Thracian peneplane. In that connection, attention should be drawn to the extraordinary way in which Devonian sediments in the strata below the transgressing Neogene have been worked up. A zone of soil, several metres thick, has been found, and this (especially towards the upper margin of the buried valleys, and so towards the heights over which the peneplane extends) allows the underlying greywackes to pass quite gradually into the overlying Neogene sands and gravels. This makes it improbable that the sinking of the land and the transgression associated with it occurred very quickly, and that previously produced denudation forms were buried intact. The buried land appears far from being intact [i.e. it shows signs of weathering] and this is increasingly so in its upper parts, which seems to indicate that it is really a matter of slopes developed under a covering. If that be proved, it would mean that there was hilly country before the Thracian peneplane replaced it; and that this latter is therefore to be classed as an end-peneplane or peneplain.

* *Eindeckungshänge.*

This is a general indication of the extraordinary importance which the marginal zone, between the areas of deposition and denudation, possesses for the evaluation of peneplanes. For here, if anywhere, there is a possibility of finding a part of its previous history preserved in the form of an earlier relief below the correlated* strata. If this preceding stage is another peneplane, i.e. a graded transgressional surface of continental origin, then the peneplane in question can obviously not be an end-peneplane, a peneplain, which developed from what was previously more dissected mountainous country. These most important relations will be considered in detail later.

9. INFLUENCE EXERTED BY ROCKS OF HETEROGENEOUS CHARACTER UPON THE DEVELOPMENT OF SLOPES

So far, in our investigations into the origin and development of slopes, it has been assumed that the rocks are of a homogeneous character.

[* See glossary.]

The results obtained are neither altered nor limited by the influence which has been exerted on the course of denudation by the variety found in the composition of the earth's crust. That influence is based on the different resistance of the various types of rock on which—other things being equal—the intensity of denudation depends. In each type of rock —whether of great or small resistance—the development of slopes follows the same laws. But the speed varies, and the maximum gradient for any slope unit differs according to the prevailing character of the rock. More intense denudation in a region of less resistant rocks means a swifter rate of development and growth of the slope units; and consequently more rapid flattening as compared with analogous processes in more resistant surroundings. When there occur side by side rocks, which on account of their composition, texture, structure or bedding react differently to denudation, multiform changes of slope occur: the same angles of slope occur in slope units of differing stages of development; and slope units, which have had the same duration and degree of development, have different gradients as well as different surface areas.

Structural Base Levels of Denudation

The features of an area in which there is variation in the character of the rock are well known. Earth sculpture leaves the strong parts standing out from their less resistant surroundings. In fig. 10 [p. 168] the profile illustrates the course of development and the rules that apply. It begins with a slope unit *F* 1 which at the given time just touches, at point *r*, the outcrop of a very much more resistant rock, such as an eruptive dyke *B*. For what first happens, the way in which the slope unit has developed is of no importance. Should it result from uniform development, the base level of denudation *F* would coincide with a water-course; in the case of waxing development, a steeper slope *Fβ* would follow below *F*; in the case of waning development there would be a gentler slope *Fα* below *F*.

In the region of rock *A*, the slope unit recedes in successive periods of time into positions shown by the numbers 2,3 and 2′,3′, etc.; in rock *B*, however, it would reach only $x\ a_2'$ on account of the lessened intensity of denudation here—taken as one tenth of that in *A*. The surface $a_2'\ x\ a_2$ of *B* is laid bare. It is not preserved, however, since from the moment it has been laid bare, it also is exposed to denudation. The maximum gradient a_2a_2' that can be reached by rock *B* is realised, since the position of rock $a_2'x\ a_2$ is deprived of any support, i.e. is undercut. This undercutting takes place to the same extent in any successive moment of time, so long as a slope of the gradient and of the rate of development of slope unit I adjoins it below in rock *A*. While this, in time two, reaches 3′ a_3 and then a_4, in *B* the undercut slope must keep its maximum gradient and move to a_3a_3' and a_4a_4', even if by itself it would recede, not at the same rate, but more slowly through spontaneous denudation. *The rate of development of the lower slope unit determines that of the slope above, which is steeper in the more resistant material.*

As to the slope above the outcrop of *B*: it recedes with the speed characteristic of rock *A*, but in no place can it be deepened below the outcrop of rock *B* which is being denuded more slowly. Below the slope unit that receded to 2 b_2 in time one, there appears a slope of diminishing gradient *r* b_2, which in its turn is undercut during its formation by the simultaneous shifting of the rock boundary from *r* to a_2'. It can easily be seen that the little undercut slope $a_2'\ c_2$, which actually appears in time one, is bound to have just such a gradient that denudation on it (rock *A*) works at the same rate as on the steeper slope below (rock *B*). *Above the exposed rock of greater resistance there arises a concave profile of waning development.* In these early developmental stages, however, the concave slope is convexly curved against the boundary of the rock outcropping below it, and yet still above the [actual] boundary against the more resistant rock which is giving rise to the feature as a whole. This steepening of slopes, with an approximation to steep steps following below one another, due to more resistant types of rock, can often be seen.

The slope, originally homogeneous, has been broken by the exposure of a body of more resistant rock. A number of breaks of gradient have appeared which separate the newly produced slope units and act as local base levels of denudation. In relation to these, the slope units develop independently. In the third position of the slope they are represented by the numbers I–V.

The breaks of gradient are of two types: the one set is associated with rock boundaries. In the diagram, these are labelled a_2, a_3, a_4, and so on (type *a*), and a_2', a_3', a_4', etc. (type *a′*). *They do not migrate upslope, and do not vanish in the highest parts; but they follow the shifting of the rock boundaries brought about by denudation, and every moment they are produced afresh at those places. We call them structural base levels of denudation, since they are connected not with the drainage net but with the structure of the crust. They arise wherever rocks of different resistance are being laid bare on a slope, and they are independent of the position and behaviour of the general base level of denudation.* In function they correspond exactly to local base levels of denudation in homogeneous rock. Their arrangement is always such that a convex break of gradient appears at the rock boundary on the uphill side, and a concave break of gradient on the downhill boundary, provided that the outcropping rock is more resistant than its surroundings. If not, it is the other way round.

The second type of break of gradient behaves normally: the breaks are formed at the structural base level of denudation and from there migrate upslope. If the character of the rocks does not change (differences in resistance remain unaltered, and bedding remains the same), slope unit III is produced, so long as a portion of slope of gradient I bounds rock *B* on the lower side for a sufficiently long time. When all the slope units above III have been removed in the highest parts, then only two breaks of gradient, of types *a* and *a'*, remain. These separate the three sections I, II and III of the slope, which keep their gradients unchanged. The gradient of the last named is of course steeper than that of the ori-

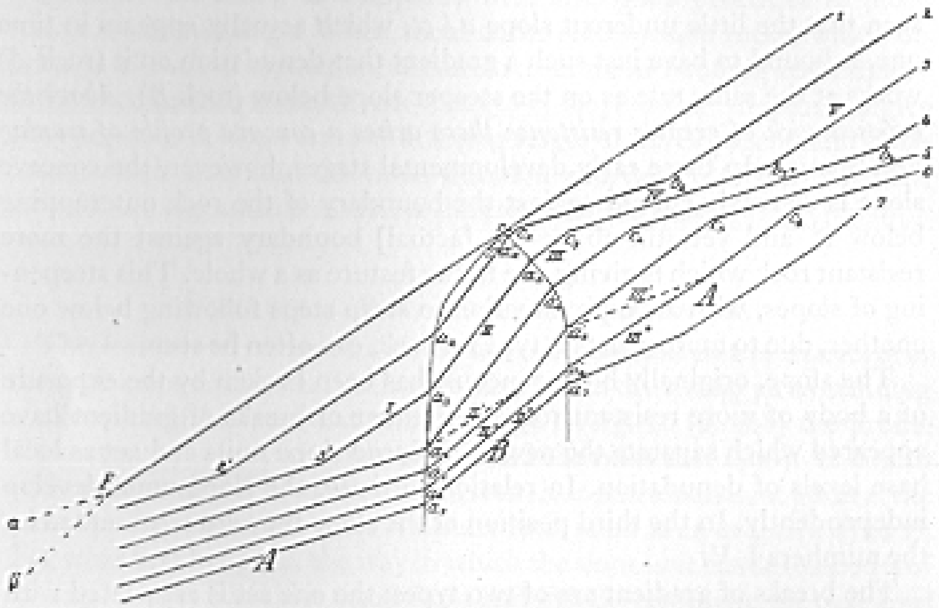

FIG. 10.

ginal unit *F* 1; steeper, too, than that of unit I which, since its development has been unaffected, has preserved the gradient of *F* 1.

The base level of denudation for III is, however, constantly being lowered, and on account of this there necessarily follows—as has been previously shown—an intensification of denudation and consequently a steepening of the gradient: the development of III is under the direct influence of the denudation on surface II, and so is influenced indirectly by the rate of development of I. In general this rule holds: *The intensity of denudation of the lower slope units is one of the factors determining the development of those parts of the slope which are situated above them in an area where the rocks are of other types and differ in resistance.*

This explains the fact that in land forms with predominantly gentle

slopes, e.g. peneplanes, the denudation forms are obviously and, within certain limits, practically completely independent of the structure of the crust. This becomes evident when we follow up the development in fig. 10, where it has been assumed that, after time three, slope unit I has been replaced by its slope of diminishing gradient, which in its turn just touches the part of the slope a_4a_4' which has the maximum gradient. If that part had its base level of denudation a_4 fixed, it would recede as far as a_5' because of its specific intensity of denudation, and in so doing leave a normal slope of diminishing gradient II' below. This, however, is being undercut during its formation by the simultaneous lowering of the local base level of denudation from a_4 to a_5; so it does not actually appear, but in its place there arises the steeper slope unit II''. After time five, this alone prevails in the region of *B*.

Also, the convex break of gradient of type *a'* moves downwards, by amounts that become smaller in successive times. This is of decisive importance for what happens on the slopes above. If the base level of denudation a_5' were fixed, the normal slope of diminishing gradient III' would be found below the slope unit receding to c_4. Its local base level of denudation, however, sinks to a_6' at the same time, and so no surface III' appears, but in its place the steeper slope of diminishing gradient III''. For the same reasons, a gentler slope section is formed below it by the end of time six, and so on. It can be seen that waning development is not fundamentally disturbed when a more resistant type of rock outcrops on a slope. The concave profile appears, but it is interrupted by a convex break of gradient at the boundary between resistant rock below and less resistant above. For waxing development an analogous statement may be added: The convex profile is interrupted by a concave break of gradient between less resistant rock below and more resistant above.

With waning development, flatter and flatter slope units approach the rock mass *B* from below. Therefore flattening progresses more and more in its neighbourhood, and so the breaks of gradient at its boundaries become ever blunter. A comparison of the slope positions 3 and 7 brings out the diminution of the feature which is interrupting the slope—caused by the exposure of rock *B*. This interruption can disappear only when the lower part of the slope (in rock *A*) has reached the smallest possible gradient and therefore has been removed from further denudation. Then the flattening in rock *B* catches up with it. But even before that, the disturbance in the slope may not be noticeable. This occurs when there is little difference in the resistance of the rock materials.

Here is an important general relation: If slope units occur in rocks of a varied nature, the difference in gradient for a given difference in rock resistance is greater, the steeper the mean gradient of the slopes. Since this mean gradient is an expression of intensity of denudation, the above statement means: the more rapidly denudation is effected, the more markedly apparent become differences in the character of the rock. *Adaptation of denudational form to crustal structure is a function not only of the duration* (p. 49) *but above all of the intensity of denudation.* Therefore the way in which the character of the rock causes subtle adaptations in individual forms as, for example, in the Alps (steep relief) is to be contrasted with the far-reaching independence of crustal structure found in peneplanes (flattish relief). This independence is by no means complete, as the above investigation shows, and as is apparent to the eye; but it causes interruptions of gradient to become imperceptible when they are due to small or moderate differences of resistance in the rocks. On the other hand, the greater differences of resistance are by no means wiped out morphologically from peneplaned landscape, but are preserved as convex prominences standing out where the most resistant types of rock occur. In American literature they are termed monadnocks; German writings use the far better expression coined by Spethmann—*Härtling*[186].

When differences in the rock are less than has been assumed for fig. 10, the structural base levels of denudation form more obtuse angles. To convince oneself of this, suppose that in fig. 10 rock *B* (but not rock *A*) possesses a slighter resistance. Then slope unit II of maximum gradient is less steep than in the figure; and so it joins the units above and below, the steepness of which is unchanged, in more obtuse angles. This is true for all the developmental stages in which flatter and flatter portions of slope approach the rock boundary *A–B*. In a more advanced stage the concave and convex breaks of gradient, which interrupt the slope at the rock boundaries, become still less noticeable than in the diagram. Taking a certain mean gradient, e.g. that in fig. 10, the structural breaks of gradient are more obtuse, the smaller the differences in rock material; and when these become nil, the breaks disappear altogether, i.e. the slope has a uniform gradient, uninterrupted by any angle on its surface, whether re-entrant or salient. *For a given gradient of medium slope, the adaptation of individual forms to crustal structure is more pronounced the greater the difference in rock resistance.*

Among the innumerable and varied combinations of rocks of differing resistance, one group has for long been specially noticed on account of the conspicuous features associated with it: the alternation of layers of different resistance in flat-bedded [i.e. unfolded] strata. They are the prerequisite for the formation of a special type of land form, *scarplands,* and seem to afford the simplest illustration of the most strict adaptation of individual forms to the character of the rock. The example of scarp-

lands which has been the most studied and commented upon is that between the Fichtelgebirge and the Black Forest. Resistant strata of Triassic and Jurassic age, mostly permeable rocks with considerable cohesion and stability, form steep escarpments of varying height and different gradients; and between them lie widely spread, flattish landscapes, peneplanes, extending over strata of less stability, usually impermeable and mobile sediments, rich in clay content. Near the step below them, these reach out on to the firm rock of the step. R. Gradmann has shown[187] that these peneplanes are no peneplains in Davis's sense; and that the steps are not tectonic formations arising from or coinciding with flexures or faults, as has often been stated, though this view is in but slight accord with the facts observed. His conception of the part which denudation plays in fashioning scarplands is an important and far-reaching step forward as compared with other less satisfactory explanations. He thought that peneplanes developed from the lowering and flattening of the ridge crests between deeply incised valleys, during a period when erosion was at a standstill.

It is only over this concept, already considered on p. 142, that we will here linger. A period when erosion is at a standstill implies a fixed position for the general base level of denudation. This has been assumed in the simplified profile of fig. 11. Above its foot *t* rises a slope *t* 1 which extends over the almost horizontally bedded strata *a* and *b*, differing in their powers of resistance. It has the greatest gradient possible. For simplicity's sake, it has been assumed that all the layers marked *a* and all those marked *b* behave in the same way with respect to each other. However, a_w is a water-bearing horizon, which the higher *a* beds are not.

The construction must once again be based upon definite quantitative assumptions as to the intensity of denudation. There can be free choice of the values, without any effect upon the qualitative result. But it must be borne in mind that, in the more resistant rocks, denudation needs a longer time to produce a slope of diminishing gradient of specific inclination than in the less resistant surroundings. Thus, within a definite period of time, the slope of diminishing gradient produced in the more resistant beds is steeper than that on the others. The greater, therefore, the difference shown in the angles of inclination of the slope units at the same stage of development, the greater are the differences in resistance that have to be assumed to exist between adjacent types of rock. A certain margin is allowable in this, but once the differences are settled, the angles of inclination within the respective zones of rock must be kept unchanged. The type of the resulting form of the slope does not depend upon that choice, but only the actual gradient of the slope units composing it at a definite moment of time. This latter does not concern us here. For the sake of clearness, the profile has been simplified in a manner which in no way affects the result: in each space between two rock boundaries, i.e. within each zone of independent development, when concave profiles appear, an infinite number of slope units has not been drawn, nor even a great many, but only a few; and thus there seems to be a greater difference of gradient between them than there is in reality. Hence the concave breaks of gradient appear relatively sharp; but in nature there is a continuous curve and not a sharp nick at these points.

The profile can now be understood. According to assumption, the original position *t* 1 has the maximum gradient in all its parts. This is steeper in rock *b* than in rock *a*. Because of its specific intensity of denudation, determined by the gradient and by the characteristics of the rock, each of these parts of the slope would be displaced upslope by a definite

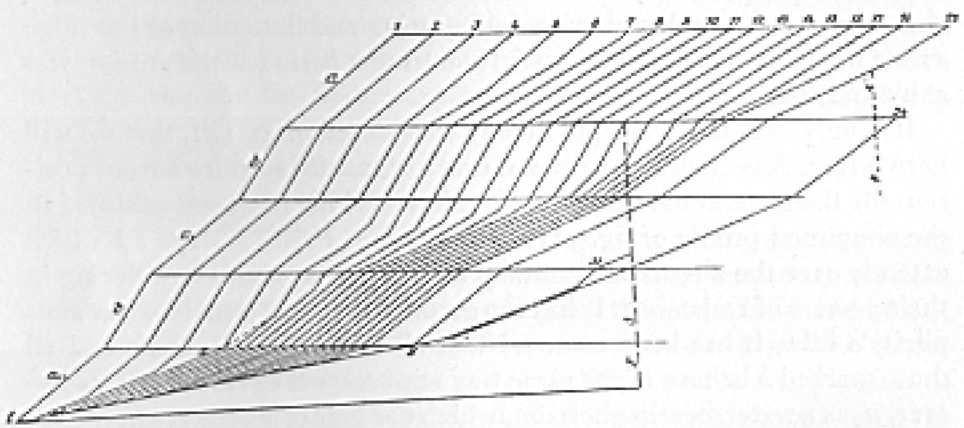

FIG. 11.

amount in unit time, leaving behind a normal slope of diminishing gradient. For the *a* layers, these amounts may be seen in the first three positions. For the assumed character of the rocks, these amounts are greater than the spontaneous recession of the maximum slope in the zones *b*. In the lower layer of *b*, this becomes visible only in positions 4–6; in the upper one, in positions 4–16 [(sic) ? 13–16]. A normal slope of diminishing gradient, however, can arise only in zone a_w, i.e. the water-bearing horizon; since, in the first place, here alone is there no undercutting through the recession of a slope unit occurring below; and, in the second place, the development is not influenced by the layer above. For the water content makes the rock mobile, in so far as it contains colloids, thus allowing it to slide away, and the layer above simply breaks off to a corresponding amount. Landslides (slumping) (p. 103) brought about in this way outstrip the spontaneous denudation occurring in the

layers above a_w, and push the whole step back while maintaining its maximum gradient. There is deceleration as soon as the slope of diminishing gradient *t x* has extended up as far as the boundary between a_w and *b*. Along its slighter inclination the material, assuming a constant water content, slides over a smaller area, moves more slowly and its migration slackens. From that time on, all the slope units of maximum gradient, occurring above, move back into the hill side, each at its own characteristic rate, which for the *b* layers is less in unit time than before (since there is now no powerful undercutting). The breaks of gradient associated with the rock boundaries are displaced at a slower rate, and so concave partial profiles appear within the individual rock horizons. Abnormal conditions may arise temporarily, if denudation works more quickly in a zone of mobile rock and maximum gradient (such as a_1) than in the more resistant layer (*b*) above it. If, however, *a* is deficient in colloidal substances or in water content, etc., it cannot slide away from under *b*. In a similar way and for the same reasons as in the relationship between rock wall and basal slope (p. 140), there arises an extension of the steep slope downwards, and the sharpest concave curve is no longer found on the rock boundary itself, but below it (zone a_1, positions 5–11). This can be observed in the pediment of cuesta scarps: the less resistant underlying beds with oversteepened surface gradient often share in their construction.

The problem here examined is a special case of waning development. In course of time the whole slope system becomes flatter[158] and acquires a concave cross section. With this, the disturbance of profile caused by petrographic differences becomes less and less. The stepping of the slope disappears, first of all in its lower parts (see position 34). Denudation reaches its goal earliest in the neighbourhood of the general base level of denudation; here the slope unit with the smallest possible gradient (*t y*) appears first. Until that has reached up to the lowest rock boundary (between a_w and *b*) and the undercutting of the upper stratum ceases, there is no possibility of its formation in *b*. The steepest slopes last longest in the highest parts, even if these consist of but slightly resistant rocks. The gradient is then smaller than if resistant types of rock formed the heights. *Consequently it is impossible for the scarpland peneplanes to have arisen, during a time when erosion was at a standstill, by the flattening of the ridge crests while the steps were preserved.* An extensive undulating landscape of the peneplane type cannot develop out of a high upstanding ridge crest by surface denudation alone. Instead, with waning development a ridge crest never becomes anything but a ridge crest, sharp-edged if steep slopes meet (see position 13; F S is the perpendicular dropped from the ridge), or rounded if gentler slopes intersect. Such would occur in a zone of but slightly resistant rock which had reached a far advanced stage of flattening: e.g. position 22, *s s'* being the perpendicular dropped from the ridge.

This brings us close to the problem offered by the cuesta landscape. The sharpness of its scarps, of the lowest as well as of the uppermost, demands continual renewal of the structural base levels of denudation, to at least the extent of remaining the same, and that *during* the peneplanation of the differences in level between the individual steps. This renewal can be brought about only by a network of eroding water-courses which are working so as at least to preserve the slopes arising from it. The very formation of peneplanes demands the existence of a drainage net on them. This takes over, or took over, the part of general base level of denudation for the denudation and development of the flattish slopes occurring where the rock had but slight resistance. But if such a drainage net exists, or has existed, there must have been from the very first the possibility of its development, even in the region of rocks of slight resistance over which the 'stepped peneplanes' extend. That presupposes an original surface on which the 'soft' strata outcropped between the resistant layers and offered places upon which a stream system could develop. R. Gradmann has derived the scarplands from such an original surface (see his profile, *loc. cit.*, p. 127), correctly, as is shown here. It is no mere construction, nor only a theoretical necessity; but fragments of it are still clearly recognisable at the present day. The previous existence of a surface, which cut across the outcropping members of the whole set of strata at an acute angle and from which the scarpland was carved out, is a fact. That surface, of course, was not a peneplain.

The existence, side by side, of scarps and of widely extending peneplanes between them presupposes the individual parts of the drainage net to possess different values as general base levels of denudation. In this respect there may be distinguished: (*a*) the main branches which could cut through the scarp ridges, i.e. which are incised below the outcrops of the resistant layers in the foundation beneath the peneplane surfaces, and possess a direct connection with the general base level of erosion for the area; (*b*) the ramifications on the peneplanes themselves, which erode more slowly, or not at all, above the outcrops of those horizons by which they were once, or are still, held up. It is in relation to them that the further modelling of the peneplanes, as well as the recession of the final upstanding scarp fragments, takes place.

Thus the character of the rock, which determines not only the surface denudation, but even more particularly the erosion, is responsible for the origin of peneplanes in the scarplands. Other things being equal, the intensity of both denudation and erosion is lessened where resistant types

of rock occur, and this lessening may have a far-reaching effect in a less resistant terrain above the outcrop of the strong rock. Flattish forms, peneplanes, are produced not only in scarplands, but also with a different arrangement of rocks provided the strong rock lies below, the less strong on top. When they are directly connected with the outcrops of resistant rock (structural base levels of denudation) they are developed only at the margins [of the less resistant beds]. Elsewhere, however, and this is the usual case, these peneplanes are related to a drainage net (general base level of denudation), the downcutting of which is retarded, or may in the end be practically stopped altogether, above the place where it meets that particular outcrop. Such structurally conditioned peneplanes may originate at any altitude. They depend only on the arrangement of the rocks and their properties, and are independent of the base level of erosion. They are not forms belonging to an earlier state of affairs, that have acquired their present altitude and general position in the surrounding landscape by some definite endogenetic movement; but they are adaptations of form to crustal material, and as such they are of the same age and have the same significance as the steeper forms, developed near by in the lower position. H. Cloos has pointed out these relationships in his description of Erongo, a South-west African inselberg[189]. Extensive flattish landscapes are found above the steep outer flanks of the mountain and the slopes of these face the source region of a stream system which originates in the heights, is impeded in its downcutting by resistant tracts of rock and, below these, leaves the massif in deep, narrow gorges.

The features of adaptation are no less characteristic when the different kinds of rock are arranged beside one another instead of one above the other. In valleys, which cross successively rocks of different resistance, a noticeable change in the valley cross section goes hand in hand with the change in rock material. The less resistant the rock bounding the valley, the less the inclination of its sides, and so the valley width seems greater. This holds even when the intensity of erosion is the same at every place. In what follows no account is taken of the inconstancy of erosional intensity which is found along all water-courses, e.g. as seen in the alternation of undercut and slip-off slopes.

For a given intensity of erosion, the sections of the slopes rising above the stream, in the less resistant rock *a*, are flatter than those in the adjoining stronger rock *b*. In both cases the slope units are at the same stage of development. The differences of gradient between them depend solely upon the differences of resistance between *a* and *b*. With increasing intensity of erosion (waxing development) slopes of maximum gradient finally appear. These are less steep in *a* than in *b*, and therefore appear in *a* sooner than in *b*[190]. If *a* has already reached its maximum gradient, whereas *b* has not yet achieved it, increasing intensity of erosion brings about increasing undercutting, and consequently the *a* slopes recede vigorously uphill. They intersect in the highest parts while, in *b*, slopes which are becoming still steeper develop above the stream. Convex profiles (in *b*) are then visible beside straight ones (in *a*). If finally the *b* slopes meet in ridge crests, these—because of their greater steepness—are relatively higher than the ridges in the region of rock *a*.

The relative height is dependent on the nature of the rock material, as has been long known and as can be observed everywhere in areas of heterogeneous structure, e.g. in the northern Limestone Alps. *When slope units at the same stage of development intersect in the highest parts of the country, then, other things being equal, the relative height in less resistant rocks is not so great as in stronger parts round about.* This is particularly clear in cases when the intersecting slopes are on the whole straight (uniform development and undercut slopes of maximum gradient).

With waning intensity of erosion, concave slopes appear first in rock *b*. They can be seen beside the straight *a* slopes until erosion has been decelerated to such an extent that even in rock *a* slopes of maximum gradient can no longer be preserved.

With the change in rock material, changes come about not only in the gradient of the slopes, but at certain stages of development in their shape also. This is true in areas where the character of the rock varies, both when the intensity of erosion is constant and when it fluctuates. Such conditions obtain when the rock boundaries do not cross the stream (which may follow a line of disturbance), or where the change of resistance to denudation over the whole surface, associated with the rock boundaries, does not also imply a change of resistance to erosion. In many instances this is not the case. Very frequently, especially if there are differences in the strength (cohesion) of rocks, the intensity of erosion is affected in a manner analogous to that of surface denudation. It is this above all which accounts for the often deep-seated difference found in the shape and inclination of the slopes along streams cutting through rocks of different strength. A short reference must suffice here.

A bank of rock, which is particularly strong as compared with its surroundings, may lessen the down-cutting of a stream in the whole reach lying above, and may have a lasting influence. The adjoining area of denudation [upstream] acquires the concave forms of waning development, and in this way differs fundamentally from the tracts lying immediately below. The less the strength of the rocks concerned, the more progress does waning development make in the area where erosion is checked (but not brought to a complete standstill). The concave slope systems then recede far back from the edges of the rivers. This effect, in

combination with the increased meandering which takes place in rivers with impeded erosion, may lead to extensive removal of readily mobile rock material. The removal of the Neogene beds from the broad synclines of western Anatolia is due chiefly to these processes. There, the hindrance to erosion starts at those spots where the rivers enter the border zone of the broad synclines, which has been uplifted by tectonic movements, and consists of strong crustal material.

In their origin, the ledge-like denudation terraces, A. Hettner's *Landterrassen*[191], also belong here; they are associated with the courses taken by running water (i.e they are in valleys) and with the boundaries between flat or horizontally bedded strata of different strength which the water has laid bare. The most famous example is that of the platform of the Colorado Canyon[192]. Such terraces occur regularly in scarplands, in close connection with the peneplanes which they continue as ledges along the side of the deeply incised valleys into the region of the next higher scarp. The necessary condition for the formation of denudational terraces is that an eroding stream should, at one and the same place, lay bare, *one after another*, rock types of different strengths. Their further independent development depends upon the way in which this stripping takes place, and on the character of the rocks. Schmitthenner[193] has recently given his attention to this in the northern part of the Black Forest, and R. Gradmann in the scarplands (see p. 171 ff.).

The importance of the adaptation of denudational forms to the character of the rocks cannot easily be overestimated; for the characteristics of the *individual forms*, as well as their arrangement, depend to a large extent, as has been shown in this section, upon the nature and distribution of the rocks exposed at the earth's surface. It will be of great importance, therefore, now and always, to examine those processes which effect the adaptation. It may also contribute to further clarification of the processes of denudation. It must be borne in mind, however, that these are matters of detail, modifications, and not the fundamental laws of denudation and land sculpture. The adaptation is only part of the feature; it obeys the general laws of denudation and presupposes the causes which make denudation possible at the surface of the crust. This fact has often been overlooked.

10. SUMMARY

It is now possible to give a complete survey of the origin and development of slopes. Above streams, to whatever extent they are incising, banks grow upwards and become valley slopes. During their formation they are subject to denudation over the whole surface; and this, in its effort to remove the slopes, works everywhere in the direction of lessening the gradient. The smaller the amount of erosion in unit time, the longer it takes for inclined surfaces to arise from the erosional tracks, and the greater the chance for the simultaneously operating denudation to come nearer to its goal. On the other hand: the quicker the downward erosion of the stream, the greater the speed with which the valley sides grow up above them, but the farther from their goal do the effects of denudation remain. *The intensity of erosion determines the gradient of the slopes rising above the drainage net; the details of their form then depend upon the character of the rocks concerned.*

In particular it has been shown that along the lines of the drainage net —the general base levels of denudation—fresh slopes of uniform gradient are always arising; their denudation is in equilibrium with the intensity of erosion and must always be so. If the latter changes, a new slope necessarily appears with a gradient such that the above-mentioned equilibrium is maintained. With increasing intensity of erosion, steeper and steeper slopes arise; with decreasing intensity, they become flatter and flatter. Between the successively formed sections of the slopes, breaks of gradient appear. They denote the levels to which the denudation of the uniformly inclined surface above each is related; they are the nearest (local) base levels of denudation. The surface of uniform gradient together with its base level of denudation make up one slope unit (i.e. form system)*.

Continuous change of erosional intensity leads to the formation every moment of a very minute slope unit. The breaks of gradient do not become visible as such, but a continuously curved slope takes the place of a slope system composed of many slope units. It is concave with decrease and halt of erosional intensity, and convex with its increase, continuously convex only so long as those breaks of gradient, which subsequently arise, have not yet appeared [see fig. 7, p. 158]. In both cases there are limits to the formation of new slope units: the slopes can become steeper only up to a maximum value which cannot be exceeded, and which is determined by the character of the rocks; the flattening (diminution of gradient) ceases with the appearance of the least possible gradient, on which further denudation can no longer take place.

The intensity of denudation which, for rocks of the given character, depends upon the gradient, is specific to each slope unit and determines its rate of development. All slope units, except those which are based upon the interruption of a slope because of a change in rock material, are produced at the edges of the streams of the drainage net, and it is here that they obtain their specific gradient. Maintaining that gradient, they shift back parallel to themselves. In addition to this, each slope unit

[* See glossary.]

grows upslope, and at the same time it is shortened and finally replaced in the highest part of the slope by the next lower slope unit which is always younger, having originated later. As a result of this behaviour the breaks of gradient which separate them, i.e. the local base levels of denudation, move in the same direction. Any slope unit which can at the present day be observed in the highest parts must—unless it belongs to the above-mentioned exception—have at one time immediately adjoined its respective erosional track in the same manner and with the same gradient.

The succession one above the other of slope units with different gradients provides a sensitive means of following up the erosional intensity at a definite place: a convex slope is proof of an increase in erosional intensity, a concave form proof of decrease. Changes in rock material may produce deviations from the normal form of slope. However, these do not obliterate the concave or convex type either everywhere, or permanently, and do not interfere with the sureness of this diagnosis. But it must be borne in mind that in many cases—always for waning and uniform development —the majority of the older slope units in the highest parts have already disappeared and been replaced by their younger successors. Even for waxing development, preservation of the oldest slope units is by no means the rule. Therefore, for a given area, the form of the slope does not always record the whole of the development up to the present day, but generally only the last phase of the erosional intensity. And so a complete investigation into the facts must take into consideration further characteristics, especially as regards the correlated deposits* and the surfaces on which they rest.

Upon investigating the conditions associated with change in erosional intensity and its causes, it becomes quite clear that the form of the slope is of outstanding importance as a means of diagnosis. It also helps in deciding the often discussed question as to how the drainage net of the German Highlands has created its present visible effect, the valleys. There is no lack of answers. The problem arises partly because of the small amount of erosion which can be proved to be taking place at the present day; partly because the changes along the drainage net since glacial times are noticeably insignificant compared with the total extent of the existing valley development. From this evidence it has, on the one hand, been deduced that erosion is working continuously but at a rate which might be considered infinitesimally slow as far as one can judge; on the other, it has been presumed that there is variability of erosion, especially in view of the way in which normal conditions are interrupted by periods of flood which occur only occasionally but are responsible for

[* See glossary.]

practically the whole of a river's work. Every river, at least in a temperate climate, first of all works rapidly towards a preliminary goal; only to continue its almost completed task by merely stagnating, as at the present day[134]. According to this view, the German Highlands should possess the forms associated with a great acceleration of erosion, i.e. they should be characterised by ridges of a flattened appearance, their flanks having sharp curves down to the valley bottom; and at their abrupt foot they should show the beginning of waning development.

Such profiles do occur. They are characteristic of the small furrows which originated in very recent times, or are now in process of formation, on the flanks of already incised valleys. But an entirely different type may be noticed along those parts of the drainage net which have shared, for a longer or shorter time, in the tectonic history of the mid-German rise. Within each drainage system, zones can be very clearly marked off according to the form of slope, which alone is being considered here. There are those in which the main amount of erosion is a thing of the past; and these are separated from others where the gradually increasing intensity of erosion has a present value that has never yet been exceeded. The multiplicity of the phenomena shows the need for specific investigations instead of incorrect generalisations.

To sum up: Any wearing away of land over its whole surface, if not due to moving air or moving ice, is connected with the action of permanent or intermittent streams. *The problem of the gradient of a slope* turns out to be a question of erosional intensity. When individual regions possess slopes with a specific mean gradient, this characterises them as zones in which the erosional intensity has a definite mean value. The question then arises as to what conditions decide this. *The problem of the form of the slope* has been traced back to the way in which the erosional intensity developed with the passage of time. What must now be investigated is why this should have increased in the one set of land regions, characterised by convex slopes, and have decreased in the other where concave slopes predominate.

On the whole, it appears that the sculpturing of land forms by denudation is fundamentally linked to the problem of intensity of erosion.