THEORETICAL GEOMORPHOLOGY

BY

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TO

MY PARENTS

Preface

The surface features of the Earth are commonly split into two categories, the first of which comprises those features that are due to processes occurring inside the solid Earth (endogenetic features) and the second those that are due to processes occurring outside the solid Earth (exogenetic features). Specifically, the endogenetic features are treated in the science of geodynamics, the exogenetic features in the science of *geomorphology*.

I have treated the theoretical aspects of the endogenetic features in my *"Principles of Geodynamics"*, and it is my aim to supplement my earlier book with a discussion of the theory of the exogenetic features. It is my hope that the two books will together present a reasonably coherent, if necessarily incomplete, account of theoretical geology.

Contrary to endogenetic phenomena, exogenetic processes can often be directly observed as they occur: the action of a river, the development of a slope and the evolution of a shore platform are all sufficiently rapid so that they can be seen as they take place. This has the result that in geomorphology one is generally on much less speculative ground regarding the mechanics of the processes at work than one is in geodynamics.

The book follows a pattern which is, *mutatis mutandis*, analogous to that of my *"Principles of Geodynamics"*. First, a brief description is given of the physiographic facts of geomorphology, after which some of the basic physics is reviewed which is necessary for the understanding of the subsequent exposition. Then, the body of the book presents in sequence the pertinent subjects which are (i) the mechanics of slope formation, (ii) river bed processes, (iii) the dynamics of valley formation, (iv) the theory of subaquatic effects (v) niveal effects and (vi) some special features.

The beginnings of the book go back to a lecture series which, under the sponsorship of Dr. Shrock, I prepared for delivery in Fall, 1958, at the Massachusetts Institute of Technology. During that time, I derived much encouragement from discussions with Dr. Orowan at that Institute. Work on the book progressed during my appointment as Visiting Professor of Geophysics at the California Institute of Technology during part of 1959. I am greatly indebted to Dr. Press for the invitation to

spend time in Pasadena and to Dr. DIX for his great interest which he took in my work. The California Institute of Technology kindly made its Burroughs Datatron computer available to me which enabled me to undertake the analysis of the development of slopes presented in Chapter 3.5. Other calculations were made through the courtesy of Imperial Oil Limited on its IBM 705 computer, under arrangements made by Dr. YOUNG of Imperial's Research laboratory in Calgary. The finishing touches were put to the book during a term as Visiting Professor of Geophysics at the University of Illinois in Urbana. I am most grateful to Professors READ and ROSE for having made this visit possible.

Some of the sections in the present book are based upon articles of my own which appeared previously in the *Bulletin of the Geological Society of America*, in the *Journal of the Alberta Society of Petroleum Geologists*, in *Geofisica Pura e Applicata* and in *Geologie und Bauwesen*; the latter published the lecture series given at the Massachusetts Institute of Technology. I am grateful to the Editors of these Journals for the permission to draw freely from my previously published articles. Professor BERNAL of the University of London kindly gave permission to quote from an unpublished letter of his, Dr. CRICKMAY of Calgary and Dr. STEKETEE of Delft have assisted me with much valuable advice and Dr. POKHSRARYAN of Erevan has patiently explained some of his theories to me. My thanks are also due to the Springer-Verlag who has again been most cooperative in effecting a speedy publication of the manuscript.

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I. Physical Geomorphology

1.1. Introduction

Geomorphology, in its widest sense, is that branch of the geosciences which concerns itself with the development of the surface features of the Earth. In a more restrictive sense, geomorphology is the science of those surface features whose shape is determined by the action of *exogenetic* processes, i.e. of processes which originate *outside* the solid Earth. It is with this latter concept of geomorphology that we shall concern ourselves.

Any discussion of the mechanical and physical processes active in the shaping of the Earth's surface features has to start with a discussion of the physiography of these features. This is what we propose to do in this first chapter of our monograph.

The basic constituents of any landscape are *slopes*. The term "slope" may refer to a mountain side, to a river bed, or to a cliff on a coast line. If the development of individual slopes is understood, the development of a landscape can be synthesized.

Some of the most striking features upon any landscape are caused by the work of *rivers*. A brief description of the physiography of river erosion, including river bed processes and meander formation, will therefore be provided.

Making the transition from one river to many rivers, one arrives at an analysis of whole *drainage basins*,—a description of which rounds out the discussion of features caused by the action of water on the land surface of the Earth.

Most of the Earth's surface (about 71 per cent) is covered by the sea. Processes connected with the motion of large bodies of water are therefore of great importance with regard to the evolution of geomorphological features. Accordingly, we shall give a brief review of coastal and submarine geomorphology.

Subsequently, we shall turn to features caused by some specific exogenetic agents: this includes niveal features caused by the action of ice and snow and aeolian features created by the direct action of wind. Finally we shall discuss some phenomena which are due to a variety of processes:—this includes karsts and caves, badland erosion and thermal effects.

The description of physical geomorphology will be held brief here as it is to serve only as a preliminary for a discussion of the exogenetic geodynamic processes at work. Many more details may be found in pertinent textbooks on geomorphology[1–18]. Treatises bearing upon specific geomorphological questions will be listed when the particular problems are under discussion.

1.2. Development of Slopes

1.21. General Remarks. Slopes are the constituent elements of mountains, river banks, coasts;—in short of all the features that are characteristic of the geography of our globe. Some of these slopes may have been formed by endogenetic processes, such as by the thrusting up of a mountain range or by the opening up of a rift valley. However, the "primary" slopes, if one whishes to call them thus, will soon be acted upon by external ("exogenetic") agents such as wind, water and ice, so that their shape will change. If it can be understood how slopes change under the influence of exogenetic processes, then it is obviously possible to explain physical geography.

1.22. Agents in Slope Formation. Let us first investigate the various agents that might cause the shapes of slopes to change. A compilation of these agents has been given, for instance, by PENCK[19]. Accordingly, the

[1] AIGNER, A.: Geomorphologie. Die Formen der Erdoberfläche. Berlin, Leipzig 1936.

[2] COTTON, C. A.: Geomorphology. 5th Ed. New York 1949.

[3] DE MARTONNE, E.: Traité de géographie physique, 2nd. vol.: Le relief du sol. 8th ed. Paris 1948.

[4] DERRUAU, M.: Précis de géomorphologie. Paris: Masson & Cie. 1956.

[5] DYLIK, J.: Dynamical Geomorphology, its Nature and Methods. Bull. Soc. Sci. Amer. Let. Lodz (Classe III, VIII, 12, p. 1–42 [1957]).

[6] HINDS, N. E. A.: Geomorphology. New York: Prentice-Hall 1943.

[7] LOBECK, A. K.: Geomorphology. New York, London 1939.

[8] LOUIS, H.: Allgemeine Geomorphologie. Berlin: W. de Gruyter 1960.

[9] MACHATSCHEK, F.: Geomorphologie. 5th Ed. Leipzig: Teubner 1952.

[10] MARKOV, K. K.: Основы проблемы геоморфологии Moscow: OGIZ 1948.

[11] MAULL, O.: Geomorphologie. Wien: Deuticke 1938.

[12] PENCK, A.: Morphologie der Erdoberfläche. 2 vols. Stuttgart 1894.

[13] ROVERETO, G.: Forme della terra, trattato di geologie morphologica. 2 vols. Milano 1924/25.

[14] SHCHUKIN, I. S.: Общая морфология сущи Moscow 1939.

[15] SPARKS, B. W.: Geomorphology. London: Longmans 1960.

[16] STRAHLER, A.: Physical Geography. John Wiley & Sons, 1st ed.: 1951; 2nd ed.: 1960.

[17] THORNBURY, W. D.: Principles of Geomorphology. New York: J. Wiley & Sons 1954.

[18] ENGELN, O. D. VON: Geomorphology. New York: Macmillan 1942.

[19] PENCK, W.: Geomorphologische Analyse. Stuttgart: Verlag von J. Engelhorn's Nachf. 1924.

processes that are effective in slope formation can be classified as follows: (i) reduction of rocks, (ii) spontaneous mass movement, (iii) corrasion, (iv) erosion, (v) transport of mass and (vi) accumulation. The terminology used by PENCK is somewhat different from that in other writings on geomorphology, but the processes considered are usually of the same general nature as those listed above.

Looking at the various processes in somewhat greater detail, we note that the *reduction* (cf. also Sec. 3.2) of rocks represents their disintegration into small pieces. It takes place by weathering due to their exposure to wind and water. It may be mechanical or chemical. Mechanical reduction is either due to the action of freezing and melting of the water in the cracks and pores of the rocks, or to the thermal expansion of the rocks themselves under temperature variations. Chemical reduction is due to the action of the water on the chemical composition of the rocks. The amount of reduction of a particular rock depends on its exposure to the elements of the weather. For given climatic conditions, the latter decreases if the weathered débris are not transported away by some other process.

The reduction of rocks alone does not produce any changes in the existing slopes. In order to produce such changes, it is necessary to have processes that can effect a transfer of mass. All such mass transfers are due to the action of gravity in some form. First of all, one has *spontaneous mass movement*. With no interference from any carrying medium, the débris produced by weathering may start to slide downhill. On steep rock walls, any loosened particles will immediately drop to the bottom and form a pile of débris. Generally, such piles of débris are steeper at the top than at the bottom, and at the same time the individual pebbles are larger at the bottom than at the top. It has been contended that the size-grading *causes* the change in steepness (cf. MACHATSCHEK[1], p. 39), but this statement would appear to require further analysis (see Sec. 3.35). The slopes vary from 25°–40°. On lesser slopes, spontaneous mass movement may express itself as a landslide, sometimes of spectacular magnitude.

The material moving over a slope by the above-mentioned process helps further wearing down the slope. This wearing-down process has been termed *corrasion*. It occurs without the intermediary of any further medium. In contrast to corrasion one has *erosion*. This process is caused by the intermediary of some moving medium such as wind, water or ice. It also causes the wearing down of the slope. The combined effect of the above agents is termed "*denudation*".

In order to achieve further slope development, the material that has been loosened and that may have slid into the lower parts of the area under consideration, must somehow be removed. This occurs by the

[1] MACHATSCHEK, F.: Geomorphologie. 5th ed. Leipzig: Teubner 1952.

various processes of *transport of mass*. In such transport processes, the appearance of a carrying medium is of prime importance. A case in point is represented by rivers. The latter, however, have only an indirect effect on slope formation by making space for more débris to form. On the slopes themselves, running water or blowing wind may directly affect the shape and thus have a far more direct effect. The end stage of transport of mass is *accumulation*. The transporting agents (water, wind, ice) may dump material in some areas which by its very presence forms a slope. This occurs not only in alluvial plains and in sheet-floods, but also in any place where the material is transported by external agents. Thus, near mountains, material might for instance be deposited in the form of alluvial fans which occur at the edge of hills and mountains. Their slopes are from 1–10 degrees, the finest deposits are always found at the periphery (Fig. 1). The opposite arrangement with regard to the grading of deposits is found in alluvial cones and talus accumulations. Here the slopes are from 10 to 50 degrees. Boulders are found at the base, sand and gravel at the top (Fig. 2). These features are caused by small intermittent streams.

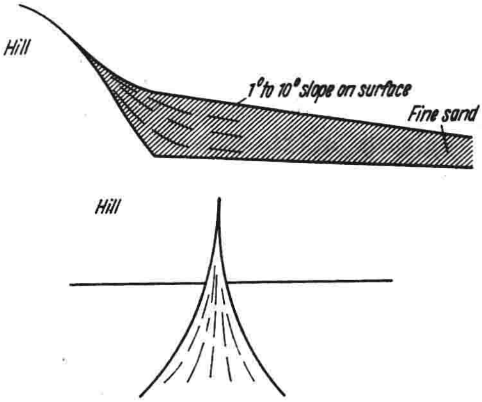

Fig. 1. Alluvial fan: top cross section; bottom: view in plan

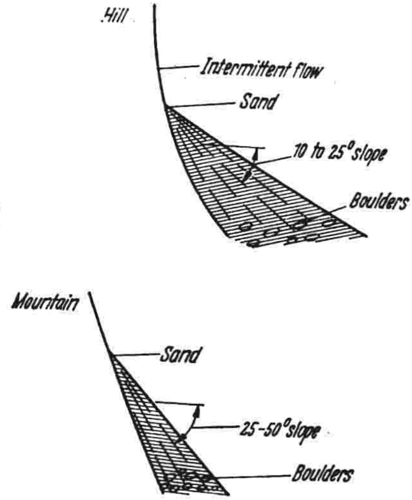

Fig. 2. Alluvial cone (top) and talus accumulation (bottom)

1.23. Differential Development of Slopes. The discussion given earlier sets the agents which act upon the shape of slopes entirely apart from those processes that caused uplifted areas on the Earth's crust in the first place. It would therefore appear that one could treat the development of a landscape in terms of a *cycle* in which uplift and planation alternate. In fact, this is the old classic view amongst geomorphologists and will be treated in detail in Sec. 1.41. However, a somewhat different point of view has been taken by PENCK[1]. Accordingly, there is little reason to believe that uplift and planation are taking place alternately; rather, uplift and planation are concurrent phenomena and should be treated as such. Thus, according to PENCK, there is little justification in speaking of a "cycle". There is no true beginning nor any end to such a cycle; slope development is a differential process in which, at best, several typical quasistationary stages can be discerned. Such stages are the following: (i) waxing development[2] in which the uplift is faster than the denudation (leading to convex slope profiles); (ii) stationary development[3] in which uplift and denudation proceed at an equal rate (leading to straight slopes and parallel slope recession) and waning development[4] in which the denudation rate exceeds the rate of uplift (leading to concave slopes).

PENCK's ideas have met with considerable opposition. However, the criticisms are directed toward PENCK's interpretation of particular slopes rather than against his endeavor to consider slopes as the outcome of a differential process. It is therefore mainly the relative importance of the various processes envisaged by PENCK which is in doubt.

1.3. River Erosion

1.31. General Remarks. Rivers are very powerful agents in shaping our globe's surface. They act in essentially two fashions: by removing material from its confines, and by transporting it.

The removal of material by flowing water from the confining channel, in turn, can occur in two ways: either the channel is being scoured out and thereby deepened, or the removal occurs on the side. The latter case is referred to as sideways erosion, the former is normally considered jointly with transportation phenomena, and the two referred to as *river bed processes.*

We shall consider the phenomenology of these various cases in their turn below.

1.32. River Bed Processes. Turning first to river bed processes, we note that this includes every kind of interaction of a river with its bed, such as the entrainment of particles of which the river bed is composed, the formation of bottom ripples, the silting up and scouring out of a channel, the contrition of bed particles, the gradation of pebbles and so on. Erosional processes proper, however, are usually dealt with separately.

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[1] PENCK, W.: Die geomorphologische Analyse. Stuttgart: J. Engelhorn's Nachf. 1929. English translation by H. CZECH and K. C. BOSWELL. London: Macmillan 1953.

[2] Aufsteigende Entwicklung.

[3] Gleichförmige Entwicklung.

[4] Absteigende Entwicklung.

Many field measurements have been made of various typical river bed processes. However, these were usually made in connection with special mechanical investigations and it is therefore difficult to give a meaningful summary in connection with a general discussion of physiography. These investigations will be referred to when the appropriate mechanical theories will be discussed.

1.33. Total Material Transport. As we have seen earlier, mass may be transported over the Earth's surface by a variety of means, However, it is only the *rivers* which are able to transport material over large distances. Thus, if one would like to know the total denudation rate in any one area, he has to look towards the rivers as the main removing agents.

It is to be expected that the fact of mountain ranges being worn down has an effect on the equilibrium of geodynamic forces; therefore the problem of determining the *total* amount of material that is being carried away from any given area per unit of time, is of major importance. The method of attacking this problem is by measuring the total mass flux in a river at successive points. The increase in mass flux between two points must be due to the denudation of the area drained between those two points. In making the appropriate measurements, it must be noted that a large part of the material is being transported in *solution*.

Analyses of the pertinent mass transport data for various rivers have been reported on many occasions, for instance by LOPATIN[1], BOURCART[2], WEGMANN[3] and by CORBEL[4]. Particularly the last author has given a convenient summary of the pertinent denudation rates. His results are given in Table 1. In this table, the first column of numbers represents the denudation in millimeters per thousand years, the second column the percentage that is being carried off in *solution*. From this table one may see that the denudation rates in mountainous areas are very substantial indeed. This, in turn, signifies that the sum total of the exogenetic processes in geodynamics is anything but negligible and that there might even be an interaction of the latter with endogenetic processes. Under certain circumstances, the two types of processes may be of the same order of magnitude.

An estimate of the total material lost by erosion from the entirety of the non-submerged areas of the world has been made by FOURNIER[5] who arrived at a value of 400 mm per thousand years.

[1] LOPATIN, G. V.: Dokl. Akad. Nauk SSSR **73**, 161 (1950).

[2] BOURCART, J.: L'érosion des continents. Paris: Librarie Armand Colin. 1957.

[3] WEGMANN, E.: Rev. de Géol. et de Géologie Dynamique (2), **1**, 3 (1957).

[4] CORBEL, J.: Z. Geomorphol. **3**, 1 (1959).

[5] FOURNIER, F.: Débit solide des cours d'eau. Paper presented at the 12th General Assembly, Association of Scientific Hydrology, U.G.G.I., Helsinki, 1960