A GEOLOGY FOR ENGINEERS

BY

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PREFACE TO SECOND EDITION

In preparing the revision for a second edition I have taken the opportunity of inserting some additional material, mainly in the first chapter, and of making a number of minor corrections in the text. In this connection I am grateful to colleagues and reviewers who have suggested improvements. The new matter relates chiefly to rivers and alluvium, marine action and coastal works, and glacial deposits. Mr. Skempton and Dr. Bruckshaw have kindly revised the Appendixes on Soil Mechanics and Geophysical Prospecting. Apart from the alterations mentioned the book remains substantially the same and will, I hope, continue to be of service.

F. G. H. B.

June 1945.

PREFACE TO FIRST EDITION

The art of engineering and the science of geology meet over a wide field, and the civil engineer in his handling of rocks and soils during most kinds of construction comes into contact with problems which are essentially of a geological nature. If he has some knowledge of geology he is in a position to carry out the simpler and more routine geological investigations encountered in his daily work and, when conditions are less straightforward, he is able to decide when to call in expert geological advice.

Geology is now a subject included in the training of civil engineers, though to a different extent in different centres. The object of such a course should be to present to the student the broad content of the science, viewed from the geologist's standpoint, and this should be supplemented by discussion of selected cases from engineering practice which illustrate the applications of the science to the art. A course of field-work should also be included, since rocks are best studied in their natural environment.

My experience in teaching geology to engineers leads me to believe that an approach such as that outlined above enables the student to acquire the necessary grounding in the fundamentals of the subject (and its rather complicated terminology), and helps him to appreciate something of the nature of the materials with which he will be concerned in practice. In writing this book, therefore, I have attempted to produce a concise account of geological science at the present day and some of its applications to engineering.

The use of the petrological microscope is becoming more extensive in certain branches of engineering practice, together with a recognition of the value of the information that it can yield about a rock. From a teacher's point of view, also, the texture and components of a rock are best demonstrated by the study of thin sections. For these reasons, brief descriptions of the optical properties of the commoner rock-forming minerals have been included; they are printed in small type and if not required can be omitted on reading.

Applications of geology to engineering problems are discussed in the later chapters, but no claim is made to an exhaustive treatment as these aspects are covered by larger works on the various topics concerned, to which references are included. My thanks are specially due to the writers of the Appendixes on Soil Mechanics and Applied Geophysics, Mr. A. W. Skempton and Dr. J. McG. Bruckshaw, for contributing these statements on two modern branches of investigation which have an important bearing on engineering construction, notably in the matter of foundations.

The book covers the courses in Geology for Civil Engineering students at the Imperial College of Science and Technology. It is hoped that it will also be of value to other students of Geology and to candidates who are taking the subject in the examinations of professional institutions.

I gratefully acknowledge the help received from colleagues in criticizing the manuscript and reading proofs and, in particular, would express my thanks to Dr. Gilbert Wilson for supporting many discussions, and to Professor H. H. Read for much helpful criticism and advice. Dr. G. Slater first suggested to me that this book should be written.

For permission to reproduce the following illustrations, my thanks are due to Professor P. G. H. Boswell and the Council of the Liverpool Geological Society (Figs. 127, 128); to Mr. C. Barrington Brown and Professor F. Debenham for Figs. 7, 33, 64 and 66 from "Structure and Surface"; to the Editor of the *Belfast News-Letter* (Plate XV); to the Council of the Geologists' Association (Plates IA, IB, IIA, IXA, XA, and XIIB); to the British Association for the Advancement of Science (Plate IVA); and to the Director of H.M. Geological Survey (Plates VIA, XB, XIA, and XIIIA). I also acknowledge the permission of the Director of H.M. Stationery Office to use the photographs of Plates IVB and VB.

Lastly, I would pay a tribute to my old teacher, Dr. A. Brammall, whose enthusiasm for his subject and skill in transmitting some of that enthusiasm to his students were first responsible for awakening my interest in the world of rocks and minerals.

F. G. H. B.

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CHAPTER 1

PHYSICAL GEOLOGY

Introduction. It is a matter of common observation that changes are constantly in progress on the earth's surface. Rivers, fed by rain, carry their loads of sediment and dissolved matter to the sea ; coast-lines are continually being modified by the combined forces of waves and currents ; fragments produced by the breakdown of the rocks are rounded into pebbles and sand, and are deposited along shore-lines, while in the river estuaries and farther out to sea the finer particles are built up into deposits of silt and mud. Water is the active agent here, but the work done by wind is also seen in the formation of sand-dunes and in the dust-storms of more arid climates. In colder regions frost, snow and ice play their part in modelling the landscape. Conditions are not static, but everywhere there is movement and change, and with the results of these geological processes the civil engineer is constantly concerned. Coast erosion, the littoral drift of shingle, shifting sand-dunes, the silting up of rivers, the regulation of river courses and the disposal of flood waters—these are a few of the problems with which he is confronted, quite apart from the geological conditions met with in excavation, tunnelling and boring operations in engineering construction.

Denudation is the general term used for the wearing down of land areas, by processes originating and acting at the earth's surface. All rocks, when exposed for a sufficient length of time to the atmosphere, undergo decay from disintegration and decomposition, together referred to as *weathering*. Disintegration is the breakdown into small particles by the action of the mechanical agents of denudation, such as rain, frost, wind and waves, all of which are helped by gravity. Decomposition is the breakdown of mineral particles into new compounds by the action of chemical agents, such as the acids in the air and in rain and river water. By all these processes a covering layer of weathered rock is formed on a land surface ; as parts of this are continually being removed, fresh material comes under the influence of weathering. This chapter reviews some of the distinctive results of denudation and deposition produced by the various geological agents, and their bearing on the work of the engineer.

WEATHERING BY ATMOSPHERIC AGENTS

1. **Rain.** The mechanical action of rain consists mainly in the washing of loose particles of soil and rock to lower levels, a phenomenon known as *rain-wash* ; it is the means by which rivers receive much of the sediment they carry in suspension. The denuding effects of heavy showers and

rain-storms may be very severe, especially in regions where a covering of vegetation is lacking. Wash-outs resulting from cloud-bursts and heavy storms cut gullies in the surface of the ground, some of considerable size, and may cause great damage by the destruction of roads and live stock. Such gullies are common in tropical and sub-tropical countries, such as South Africa. Heavy rains also promote landslides (p. 19) under certain geological conditions. Rain denudation is most effective in tropical climates.

Vegetation protects the ground from the immediate disintegrating effects of rainfall, and the clearing of wooded areas has been followed in many cases by considerable denudation of the bare ground surface. If this proceeds for a length of time, the entire covering of soil may be removed and the ground rendered useless for cultivation. Of recent years the question of *soil erosion* has come to the fore, with the realization of the dangers of haphazard de-forestation and of over-cultivation of an area. (See also under *Wind*, p. 4.)

An interesting structure produced by rain denudation is the "earth pillar," a more or less slender column of soil capped by a stone or boulder which has preserved the material below it from being washed away. Groups of earth pillars are developed on valley slopes from earthy or clayey deposits containing boulders, as in parts of Scotland, the Tyrol, and elsewhere. All stages in their formation have been traced in the denudation of soft deposits in the Durance valley in southern France.

The chemical weathering effects of rain are seen in its solvent action on some rocks, notably limestones; the process depends on the presence of feeble acids, derived from gases such as CO_2 and SO_2, which are present in the air in small quantities and which enter into solution in rain-water. An economic aspect of chemical weathering, discussed in a later chapter (p. 126), is the decay of building stones, especially under the atmospheric conditions which prevail in cities, where a much higher content of impurities is present in the air than in country districts.

While other rocks are susceptible in some small degree to the solvent action of rain-water, limestones frequently show marked solution effects. The calcium carbonate of the limestone is dissolved by rain-water containing carbon dioxide, and is held in solution as calcium bicarbonate. The surface of the Chalk (an earthy limestone), for example, commonly holds solution hollows and elongated channels or "pipes," which are filled with sand or clay from overlying deposits (Plate IVB). In bare limestone districts, such as areas of the Carboniferous Limestone of Lancashire and Yorkshire, the surface of the rock is channelled by "runlets" along which rain has trickled, and presents a very irregular appearance. Joints in the rocks are widened by solution as the rain passes down over their walls, and are then known as *grikes*; the widening of joints leads to the formation of *swallow holes*, rough shafts which may communicate downwards with underground caverns, also formed by solution aided by the fall of loosened blocks of limestone. Gaping Ghyll, on the slopes of Ingleborough in Yorkshire, is a well-known swallow hole with a depth of 365 feet, leading to a cavern below.

The circulation of underground water helps to extend such caverns and channels, particularly in hard limestone formations; streams which once flowed on the surface now flow along bedding planes and joints below ground. The famous Cheddar Caves of the Mendips are a good example out of many which might be given, and Cheddar Gorge itself, 420 feet deep at one point, is thought to have been a cavern cut by an underground stream and now exposed by the collapse of its roof. As water, charged with calcium bicarbonate, trickles over the walls and drips from the roofs of caves, part of each drop evaporates and calcium carbonate is slowly re-deposited through loss of carbon dioxide from solution. In this way masses of *stalactite*, hanging from the roof or coating the walls of a cave, are formed, sometimes making beautiful slender columns where they have become united with *stalagmites* which have been slowly built up from the floor of the cave, on to which water has dripped over a long period of time.

2. **Frost.** Briefly stated, frost action breaks up a rock surface into loose angular fragments, a process sometimes referred to as the operation of the "ice wedge." It is this which produces the serrated appearance in a high mountain sky-line, and aids in the formation of screes on mountain slopes. Water enters rocks along pores, cracks, and fissures; on freezing it expands and occupies about 10 per cent greater volume, exerting a pressure of about 2000 pounds per square inch during the freezing process, which is therefore like a miniature blasting action, and brings about the disintegration of the rock. The loosened particles fall from the mass and accumulate as heaps of *scree* or *talus* at lower levels, and this material may later be consolidated into a deposit known as *breccia*. By the removal of the fragments the surface of the rock is left open to further frost action, and so the process goes on. Some of the most famous screes in England are those in the Lake District, along the eastern side of Wastwater, where the mountain slopes fall steeply to the water's edge. Joints and cleavage planes in rocks assist the action of frost and to some extent control the shape of the fragments produced.

3. **Wind.** Wind is one of the two natural agents which transport rock material against gravity, and its denuding action is seen most prominently in regions which have a desert climate. Its effects are three-fold: first, it removes loose particles of rock decay as it blows over a surface; then, charged with these grains, the wind acts as an abrading sand-blast, driving the grains against other rocks which become worn and polished in course of time. Thirdly, the blown grains are accumulated to form sand-dunes. The principle of abrasion by sand-blast is used in commercial processes for etching glass. Ancient monuments in desert countries like Egypt, as well as natural rock-faces, show the effects of centuries of battering by wind-blown sand; their corners have been rounded and soft bands of rock have become more deeply etched than the harder layers. Vertical rock-faces are undercut by eddying sand near the ground and left with their upper part overhanging; where the wind blows from several directions in turn, stacks of rock may be eroded so that their base is narrower than their top. Evidences of wind action in an earlier geological age are sometimes seen, as at Mountsorrel near Leicester, where granite is covered by Triassic red marl; when excavated,

the surface of the granite was found to be smoothed and to show unmistakable signs of wind erosion, pointing to a former desert climate.

Wind-blown sand grains become worn down to well-rounded, nearly spherical forms with frosted surfaces, and from their shape are sometimes called " millet seed " grains. This rounding is more perfect than in the case of water-worn sand, and the grains are also well graded (i.e. nearly of a uniform size), since wind exerts a winnowing action. The finer particles of dust are separated from the sand and carried over larger distances, to be deposited far away from their source (see *loess*, below). The sand is swept along until it accumulates against obstacles to form dunes. Pebbles and boulders lying on the floor of a desert and not lifted by the wind become smoothed and faceted by exposure to sand-storms, and frequently present three-cornered shapes, whence they are known as *dreikanter*. The surface of a desert may be worn down by the wind until a level is reached where water is present in the rocks (groundwater, p. 237). Many hollows in which oases are situated have been formed in this way.

Lines of communication may be seriously affected by wind-blown sand in arid countries. It is on record that the telegraph wire on the Trans-Caspian railway was worn down to half its diameter in 11 years, and renewal was then made. To avoid the accumulation of sand alongside railway

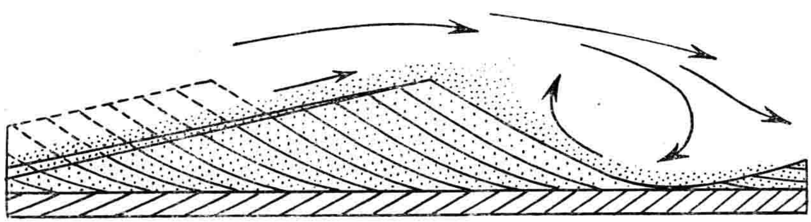

FIG. 1.—MOVEMENT OF SAND-DUNES.
Arrows show direction of wind currents, and broken lines indicate successive positions of sand-slopes. The leeward slope is steeper than the windward.

embankments in the Sudan, culverts have been constructed to allow for easy passage of the wind and its load of sediment. But probably the most serious of all the damage caused by the action of wind is the removal of vast quantities of soil in many regions of the world. The " Dust Bowl " areas of Kansas and Nebraska are an example of widespread *soil erosion* in a district of low rainfall. A century ago, this region of the Great Plains of America, between the Missouri River and the Rocky Mountains, was a short grass country supporting vast herds of buffalo, whose bones remain to-day as evidence of their former numbers. Settlers used the country as a cattle-belt, and later (about 1915) ploughed it up for wheat, obtaining wonderful crops which gave rise to popular names like " The Golden West." In their desire to make quick fortunes, the farmers abandoned the principle of the rotation of crops ; the land was ploughed persistently without proper periods of rest, trees were cut down and the hillsides ploughed, and swamps were drained. After twenty years of bad farming the soil had become exhausted and the subsoil disturbed; drought followed, and the wind began to scatter the loose dusty soil, reducing vast areas to desert. The district is now a barren, wind-eroded, sandy waste, bare of vegetation and useless for cultivation until sufficient time has elapsed for new soil to be formed. Measures have been taken to promote the accumulation of soil and reduce the effects of wind.

This is not an isolated instance; the encroachment of desert conditions is proceeding, for example, in Kenya and Nigeria, largely owing to the overstocking of sparse grasslands with cattle and sheep, which is another contributory cause of soil erosion. Depletion of the scanty cover of grass soon follows and erosion of the soil begins. It is estimated that the Sahara Desert is advancing southward at the rate of a kilometre a year.

Mounds of blown sand, or *dunes*, are piled up by the wind in certain coastal regions of more humid climate as well as in desert countries. The western coasts of Europe, for example, are liable to dune formation because of the prevailing south-west wind. Accumulations of blown sand occur on the East Anglian coast and in other parts of Britain. Dunes are not stationary, but move continually and may overwhelm land areas; stages in the advance of a sand-dune in relation to the direction of the prevailing wind are shown in Fig. 1. Sand is blown from the back of the dune over the crest and dropped on the leeward slope at its natural angle of repose of some 30° to 35°. The dune thus migrates in the direction of the prevailing wind until arrested by some obstruction. It has a bedded structure, due to the deposition of successive layers of sand (*dune-bedding*, *cf.* current-bedding, p. 14). Dune-bedding may be seen in sandstones formed during past geological ages, as at the Ballochmyle quarries in Ayrshire (p. 201); the sand grains in these rocks are well rounded and polished.

The dunes of desert regions often show crescentic shapes in plan (*barchans*), and occur in groups in areas where the wind blows from a constant direction. Other desert dunes are in the form of long ridges of coarser sand, several hundred feet high, surmounted by crests of finer sand at regular intervals. These ridges may extend in straight lines for great distances, sometimes a hundred miles or more, as in the region south-east of the Qattara Depression in North Africa. They are described by R. A. Bagnold as resembling gigantic "notched caterpillars end to end in continuous chains."[1]

Evidence for the movement of dunes in England is provided by old records, as in the case of Eccles Church, on the coast of Norfolk. This building was almost completely buried by sand in 1839; twenty-three years later the tower was uncovered as the dunes moved inland, and to-day the foundations of the tower are seen on the shore, the line of dunes having advanced still farther. The rate of movement can be estimated in such instances; it varies in different localities and at times may be rapid enough to warrant steps being taken to arrest the process, if valuable land areas

[1] "Libyan Sands," by R. A. Bagnold (Hodder & Stoughton, 1935), an account of desert travel; the same author has published the results of his researches in "The Physics of Blown Sand and Desert Dunes" (Methuen, 1941).

are threatened. The stabilization of dunes is frequently effected by the planting of marram grass, the roots of which bind the surface sand and so prevent its removal by wind. Afforestation is a larger-scale method of dealing with the same problem, as, for example, the planting of pines at parts of the Norfolk coast. In Wallasey, Cheshire, rubbish was dumped on an area of blown sand ; the whole became stabilized in a short time and provided land for a recreation ground.

The wind-blown deposit known as *loess*, a fine calcareous clay or loam, extends from Central Europe through Russia into Asia and covers large areas in China, where it reaches its greatest thickness. It represents the finer particles which are blown from the deserts to distant regions, as mentioned above. Thus the deserts of North Africa contribute much of this material to the Russian steppes. Generally of buff colour, it is darkened by mixture with vegetable matter, and in this condition forms the " black earth " of Russia. Loess is a porous deposit, and is often traversed by a network of narrow tubes which once enclosed the roots of grasses, which during growth have bound the particles of dust and silt in their grip. It resists weathering and stands in steep, sometimes vertical cliffs where, for example, it has been dissected by the action of streams.

4. **Insolation.** When a rock-surface is exposed to a considerable daily range of temperature, as in arid and semi-arid regions, the expansion which occurs during the day and the contraction at night, constantly repeated, have a weakening effect on the rock over a period of time. The outer heated layer of rock tends to pull away from the cooler rock underneath (*exfoliation*). This is particularly noticeable on surfaces which face south (in the northern hemisphere), since they are subjected to the hot rays of the sun to a greater degree than would be the case for any other direction. Strain is set up in the rock by the unequal expansion and contraction of its mineral constituents. Granite, for example, is mainly composed of two minerals which expand at very different rates. They are quartz, which has a coefficient of cubical expansion of 0·000036 per degree Fahrenheit, and orthoclase, whose coefficient is 0·000017. The result is that when the rock is heated its texture is loosened owing to the different behaviour of the two minerals. For this reason, granite employed in building construction may flake badly if subjected to fire, while a more homogeneous rock would not be at the same disadvantage in this respect. Under natural conditions, insolation of rock-faces results in the opening of many small cracks (of hair-like fineness) into which water enters, and so both the decomposition of the rock and its disintegration by the help of frost are promoted. This kind of weathering is prominent in climates where high day and low night temperatures are prevalent, but it may also be observed in more temperate lands.

Weathering by Organic Agents

Effects which are small in themselves, but noticeable in the aggregate, are due to plants and animals. Plants retain moisture, and any rock-surface on which they grow is kept damp, thus aiding the solvent action of the water. The chemical decay of rock is also promoted by the formation of vegetable humus, an organic product of the decay of plants, which is assisted by the action of bacteria and fungi ; thus organic acids are added to percolating rain-water and increase its solvent power. The mechanical break-up of rock is helped by the roots of plants, which penetrate into cracks and crevices and tend to wedge apart the rock. The general result of these processes is the production of a surface cover of *soil*, which passes down through broken rock mixed with soil into the solid rock at no great depth (Plate 1B). Earth-worms and other burrowing animals bring to the surface large quantities of finely divided soil, which is readily removed by transporting agents, such as rain-wash, running water, and wind.

The Work of Rivers

The work performed by rivers may be placed under three heads : erosion, transport, and deposition. Rivers are active agents of erosion and are always attempting to lower their courses. They carry away material and re-deposit some part of it farther downstream, the rest being transported to the sea ; some matter goes into solution in the river water and ultimately helps to increase the salinity of the oceans. The energy which is imparted to sediment held in suspension by the turbulence of the stream, and to coarser material which is rolled along by it, performs the work of abrading the bottom and sides of the river-bed.

The initiation of a drainage system takes place when, for example, a new land surface has been uplifted from beneath the sea, and youthful streams begin to flow over it and carve their valleys. Their courses are mainly directed by the general slope of the surface but are also controlled by any irregularities which it possesses. In the majority of cases present-day valleys have been cut by the streams which occupy them, except in so far as they have been modified by the action of ice or other agents. Stages of *youth*, *maturity*, and *old age* may be distinguished in the history of a river, and topographical forms characteristic of these stages may be recognized in modern landscapes. Thus there is the steep-sided valley of the youthful stream ; the broader valley and deeply dissected landscape of the more mature river system ; and the flat, meandering course of a stream in old age.

Valley Erosion. Young streams cut gorges in hard rocks and **V**-shaped valleys in softer rocks (profile 1, Fig. 2*a*), and are characteristic of many mountainous regions. Debris falls from the valley sides as it is loosened by rain and frost, to be carried away by the stream and assist in its work of abrasion. Rain-wash and soil-creep (p. 20) also contribute much material from the slopes ; this is especially the case in the more mature stages of valley development, when a mantle of soil has been formed on the land surface. Gradually as the headwaters of a river cut back into the land, its valley is deepened and widened into a broader **V**, and small scree-slopes form at the bottom of the valley sides (the flatter inner slopes of profile 2). The deepening and widening, if uninterrupted, continue as shown by successive profiles in the figure, until a stage is reached in old age when the valley has a wide flat floor and its upper slopes are convex (profile 5). Under other conditions of valley widening the slopes are cut back so that they keep their steep gradient, and the ridges between valleys are sharp instead of flat-topped.

The shape of a valley depends on the nature of the rocks in which it is excavated. The forms illustrated in Fig. 2*a* would be developed in rocks of uniform character throughout. When alternate hard and soft layers are present, erosion of the softer rock is more rapid than of the harder, and terraced forms are developed as shown in Fig. 2*b*. If the rock layers are inclined and the river flows parallel to their upturned edges, instead of across

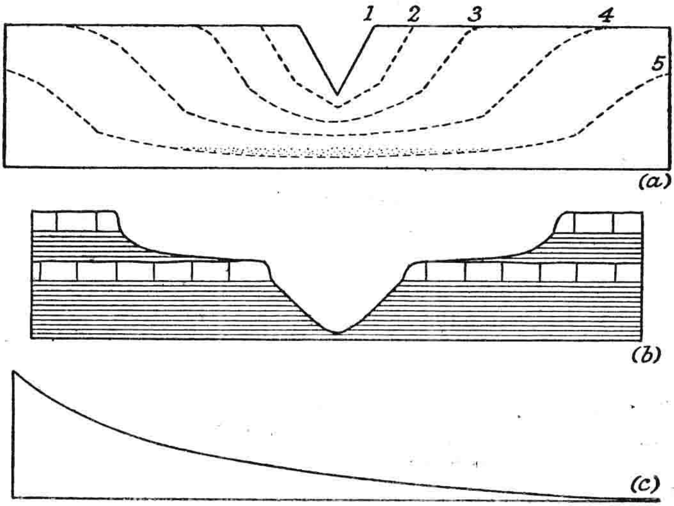

FIG. 2.—VALLEY PROFILES.
(*a*) Successive valley profiles during widening. (*b*) Valley eroded in hard and soft beds. (*c*) Profile along the course of a mature (graded) river.

them, the land surface will be carved into long hollows or vales along the softer beds, separated by ridges of harder rock which form escarpments (see Fig. 60, p. 159).

Grading and Rejuvenation. The profile taken *along* the course of a river also changes during the stream's evolution. For a young stream, actively eroding, this profile is an irregular curve, which is steeper where the river crosses more resistant rocks and perhaps forms rapids or waterfalls, and flatter where it flows over more easily eroded material. If left undisturbed by earth-movements (e.g., uplift) or other factors causing change, the river continues to reduce irregularities of gradient and to smooth out its bed until in maturity it is said to be *graded.* Its longitudinal profile is then independent of the kind of rock over which it passes, and tends towards a smooth curve (Fig. 2*c*) of the type expressed by the equation :

$$y = a - k.\log (p - x),$$

where y is the height of a point above datum, x its distance from the river's mouth, p the total length of the stream, and a and k are constants.

For the upper course of the River Mole in Surrey, it has been shown that a curve closely fitting the longitudinal profile of the river is given by the above formula when $a = 241{\cdot}5$ and $k = 65$, y being measured in feet and x and p in miles.[1] It has also been found that similar curves fit the rivers Towy,[2] Dart, and Otter.

The *base-level* of a river is the level of the sea or lake into which it discharges, for clearly it cannot cut down below this. For tributaries, base-level is the level of the main stream at their various points of entry, and as this changes in the course of time the tributaries are constantly attempting to adjust their grade to new levels. The cutting power of a river which has reached maturity or old age may, however, be revived by uplift or tilting of the land, by recession of the coast-line due to marine erosion (p. 25), or by other causes, any of which will give the stream a new fall to the sea. It begins cutting back again and lowering its bed by the newly acquired energy, and is said to be *rejuvenated.* Owing to such interruptions in their cycle of activity, not all streams becomes completely graded.

A good example of rejuvenation, probably due to uplift, is to be seen in the valley of the River Greta near Ingleton in Yorkshire. In its upper course this stream has a wide, mature valley; but about $1\frac{1}{4}$ miles above Ingleton the river begins to plunge downwards in a series of waterfalls, cutting into hard rocks and displaying the energy of youth in striking contrast to the placid flow of middle age which is evident only a short distance upstream. Below Ingleton the river again assumes a meandering course.

As a river grows older it remains vigorous only in its upper reaches, where the flow is swiftest and the gradient steepest (Fig. 2*c*). In its lower course the speed and carrying power are reduced, and the river begins to meander from side to side of its valley. It becomes subject to seasonal floods, and under these conditions much sediment in suspension is deposited, as described later.

Waterfalls and Gorges. Waterfalls and rapids are formed where a stream in a youthful stage flows over rocks of different hardness. A hard layer is worn away less rapidly than a soft, with the result that a river's gradient is increased where it crosses a ledge of harder rock; softer material below the resistant layer is undercut by the eddying and splashing of the water, leaving an overhanging ledge over which the stream falls (Fig. 3). As the overhang becomes greater than the strength of the rock can support, the ledge breaks away and the fall gradually recedes upstream. The Whin Sill, in the north of England, is a layer of jointed igneous rock which frequently gives rise to waterfalls in this way, two well-known falls being High Force in Teesdale and High Cup Nick in Westmorland. At Niagara the waters of Lake Erie, which flow down to Lake Ontario, cross a hard limestone formation (the Niagara Limestone) which lies above softer rocks,

[1] J. F. N. Green and others, "The River Mole," *Proc. Geologists' Association.* Vol. 45, 1934, pp. 35–69.

[2] O. T. Jones, "The Upper Towy Drainage System," *Q.J.G.S.*, Vol. lxxx, 1924, pp. 568–609.

and here the river makes the world-famous falls with a drop of 180 feet. The limestone forms a broad ledge which is undercut by the river, and the falls retreat upstream as the ledge collapses from time to time. Below the falls the river flows through a gorge 7 miles long. In 63 years their position changed by 265 feet, and at this rate the time taken to cut the gorge has been about 9000 years—i.e. the cut has been made since the end of the Pleistocene glaciation (p. 215). The rate of recession of the falls is now reduced to 12 or 15 inches per year, because much energy is taken from the river at this point for hydro-electric power generation, affording a good example of the effect of man's interference with natural agents. The 360-feet high Victoria Falls on the Zambesi River, Rhodesia, are situated at a point where the river leaves the gently undulating surface of a lava plateau

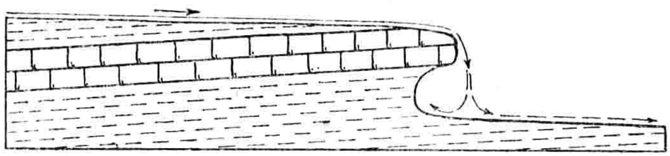

FIG. 3.—WATERFALL FORMED OVER A HARD STRATUM.
The softer beds beneath are undercut, leaving an overhanging ledge.

and plunges into a youthful gorge. This gorge is cut in basaltic lavas and has been eroded along lines of weakness formed by intersecting joint and fracture planes, which cause it to have a pronounced zig-zag course.

Hollows, known as *pot-holes*, may be worn in the hard rock of a river-bed by the motion of pebbles which are swirled round by eddies, especially in the neighbourhood of waterfalls. Such a water-worn rock surface is easily recognized, and if observed near but above an existing stream, it marks a former course at a higher level.

Gorges are cut by young streams which erode mainly downwards, the cutting being assisted in some cases by uplift of the area while the deepening of the gorge proceeds. Where prominent joint directions or other lines of weakness in the rocks are present, these are often followed during the rapid erosion of the steep-sided gorge-like valley. If the rock is sufficiently strong to stand with steep or vertical walls, or is capped by a hard layer, a narrow gorge is made ; with a weaker or softer rock the gorge will become widened out after a time, particularly if erosion is aided by solution, as in the case of Dovedale, Derbyshire, a gorge cut in the Carboniferous Limestone.

The Grand Canyon of the Colorado, 300 miles long and with a maximum depth of 6000 feet, is a remarkable vertical cut which has been made by a young river flowing from the Rockies, on entering an arid region. Rapid downward erosion, probably assisted by a rising land surface, has produced in comparatively soft rocks this steep-sided canyon, whose walls have been only slowly denuded by atmospheric agents on account of the arid climatic conditions and low rainfall prevailing.

River Capture. It sometimes happens that a river which is cutting back vigorously in an easily eroded formation may approach the course of a neighbouring stream, and meet and divert the headwaters of the latter into its own channel. This process is known as *river capture*; the stream which has lost its headwaters is said to be beheaded, and dwindles in size until it has become obviously too small for the valley in which it flows, and is called a "misfit." An example is provided by the River Blackwater near Farnham, Surrey, a tributary of the Thames. The course of this now small stream once extended much farther to the south-west, whence it transported distinctive gravels containing chert, to deposit them north of the gap in the Chalk ridge at Farnham. The source rocks of the gravels prove the former extent of the river. An eastward flowing stream, the Wey, cutting back rapidly from Godalming in soft strata, tapped the upper reaches of the Blackwater and diverted the flow into its own channel. The point of the capture is marked by a right-angle bend which the river makes just east of Farnham.

Meanders. When a river has cut down nearly to base-level it flows more slowly with a reduced gradient and begins to swing from side to side

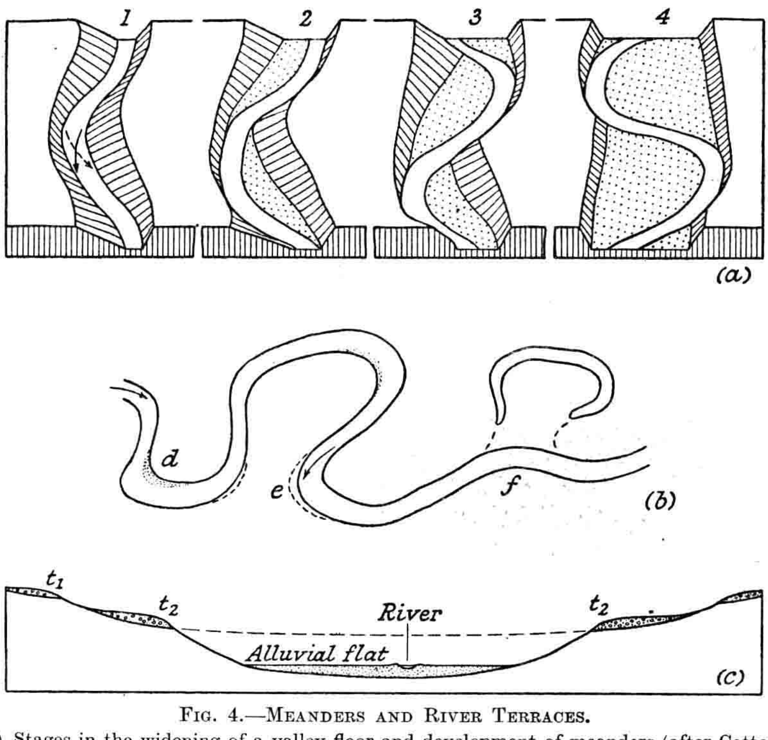

FIG. 4.—MEANDERS AND RIVER TERRACES.

(*a*) Stages in the widening of a valley floor and development of meanders (after Cotton). (*b*) Fully developed meanders, showing deposition (*d*) and erosion (*e*) at bends. (*c*) Section across a valley to show alluvial flat and older river terrace deposits at $t_1 t_2$.

of its valley. The energy imparted to the load of sediment which it carries is expended in the widening of the valley by lateral erosion, and the course of the river develops a series of big looped curves called *meanders* (Fig. 4*a*).