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PLAINS OF MARINE AND SUBAERIAL DENUDATION

BY

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INTRODUCTION.

Geologists today may be divided into two schools regarding the origin of regions of comparatively smooth surface from which a large volume of overlying rocks have been removed. These regions occur under two conditions: First, as buried "oldlands" on which an unconformable cover of later formations has been deposited, the oldlands being now more or less locally revealed by the dissection or stripping of the cover; second, as uplands or plateaus whose once even surface is now more or less roughened by the erosion of valleys.

The older school, now represented chiefly by English geologists, follows the theory of Ramsay, and regards these even oldlands as plains of marine denudation. The newer school, represented chiefly by American geologists, but also by a number of continental European geologists, may be said to follow Powell, who first emphatically called attention to the possibility of producing plains by long continued subaerial denudation. The present review of the question first cites a number of extracts from various representatives of the two schools, and then seeks for a test by

which the rival conclusions may be distinguished, the test being developed from a study of the natural history of rivers.

The English School.

Ramsay is believed to have been the first advocate of marine erosion as an agency for the production of broad plains of denudation. In describing the action of the sea on the land he wrote:

"The line of greatest waste on any coast is the average level of the breakers. The effect of such waste is obviously to wear back the coast, the line of denudation being a level corresponding to the average height of the sea. Taking *unlimited* time into account, we can conceive that any extent of land might be so destroyed, for though shingle beaches and other coast formations will apparently for almost any ordinary length of time protect the country from the further encroachments of the sea, yet the protections to such beaches being at last themselves worn away, the beaches are in the course of time destroyed, and so, unless checked by elevation, the waste being carried on forever, a whole country might gradually disappear.

"If to this be added an *exceedingly slow depression* of the land and sea bottom, the wasting process would be materially assisted by this depression, bringing the land more uniformly within the reach of the sea, and enabling the latter more rapidly to overcome obstacles to further encroachments, created by itself in the shape of beaches. By further gradually increasing the depth of the surrounding water, ample space would also be afforded for the outspreading of the denuded matter. To such combined forces, namely, the *shaving away* of coasts by the sea, and the spreading abroad of the material thus obtained, the great *plain* of shallow soundings which generally surrounds our islands is in all probability attributable."*

At this early date Ramsay attributed not only the plains themselves, but also the valleys which now interrupt ancient and uplifted plains of denudation, in greatest part to marine action, and allowed but little effect to subaerial denudation. On this topic he said:

"The power of running water has also considerably modified the surface, but the part it has played is trifling compared with the effects that have sometimes been attributed to its agency. . . . In the larger valleys, where the streams are sluggish, instead of assisting in further excavations, the general tendency is often rather to fill up the hollow with alluvial accumulations, and so help to smooth the original irregularities of the surface." †

Thirty years later Ramsay ascribed greater results to subaerial agents. Referring to the generally even sky-line of South Wales, he wrote:

"The inclined line that touches the hilltops must have represented a great plain of marine denudation. Atmospheric degradation, aided by sea waves on the cliffs by the shore, are the only powers I know of that can denude a country so as to

* Denudation of South Wales. Mem. Geol. Surv. Great Britain, vol. 1, 1846, p. 327.
† Ibid., pp. 332, 333.

shave it across and make a plain surface either horizontal or gently inclined. If a country be sinking very gradually and the rate of waste by all causes be proportionate to the rate of sinking, this will greatly assist in the production of the phenomena we are now considering."

When raised out of the water—

"The streams made by its drainage immediately began to scoop out valleys, and, though some inequalities of contour forming mere bays may have been begun by marine denudation during emergence, yet in the main I believe that the inequalities below the [level of the plain] have been made by the influence of rain and running water." *

Greenwood, an early advocate of the efficacy of "rain and rivers," (1857), directed his arguments against the prevailing belief of the time that valleys were carved by marine currents, but does not seem to have considered the possibility of producing plains by the long continued weathering and washing of the land.

The important paper by Jukes, on the "Formation of . . . river valleys in the south of Ireland," † still finds many followers among English geologists. Like Ramsay, Jukes assumed an uplifted plain of marine denudation on which the rivers of today began their erosive work (page 399), but he did not specify slow depression during the marine denudation.

Lyell said little on the problem before us. His "Principles" do not discuss plains of denudation. His "Elements of Geology" ‡ allow only small valleys to stream work, and ascribe the larger valleys "to other causes besides the mere excavating power of rivers" (page 70). It is said that "denudation has had a leveling influence on some countries of shattered and disturbed strata" (page 71). Again, "in the same manner as a mountain mass may, in the course of ages, be formed by sedimentary deposition, layer after layer, so masses equally voluminous may in time waste away by inches; as, for example, if beds of incoherent materials are raised slowly in an open sea where a strong current prevails" (page 70). The problem of subaerial denudation here discussed was not then formulated.

The writings of Sir A. Geikie offer several interesting quotations. When describing the general uniformity of the sky-line over the Scotch Highlands in the first edition (1865) of the "Scenery of Scotland," he writes:

"In other words, these mountain tops are parts of a great undulating plain or table-land of marine denudation. . . . The marine denudation probably went

* Phys. Geol. and Geogr. Great Britain, 5th ed., 1878, pp. 497, 498.
† Quart. Journ. Geol. Soc., vol. xviii, 1862, pp. 378–403.
‡ 6th edition, 1868.

on during many oscillations of level, and the general result would hence be the production of a great table-land, some parts rising gently to a height of many hundred feet above other portions, yet the whole wearing that general tameness and uniformity of surface characteristic of a table-land where there are neither any conspicuous hills towering sharply above the average level nor any valleys sinking abruptly below it. . . . The valleys which now intersect it . . . have probably been dug out of it by the agencies of denudation. If therefore it were possible to replace the rock which has been removed in the excavation of these hollows the Highlands would be turned into a wide undulating table-land, sloping up here and there into long central heights and stretching out between them league after league with a tolerable uniformity of level. And in this rolling plain we should find a restoration of a very ancient sea" (pages 106–108).

On earlier pages, subaerial agents are described as producing valleys and cliffs, while the sea, aided by the atmosphere, produces a plain of marine denudation.

An essay "On modern denudation"* by the same author recognizes that plains of denudation are reduced mainly by subaërial forces, but concludes that "undoubtedly the last touches in the long processes of sculpturing were given by waves and currents, and the surface of the plain corresponds with the lower limit of the action of these forces" (page 186).

In the second edition (1887) of this delightful book on the Scenery of Scotland, argument is still directed against the prejudice that mountains are due to local upheaval; in a word, against the prepossession that mountainous districts like the Scotch Highlands are constructional forms not significantly modified by denudation; but greater value is given to subaerial agencies than before:

"The more we consider the present operations of subaërial denuding agents, the more we shall be convinced that a system of hills and valleys, with all the local varieties of scenic feature that now diversify the surface of the earth, may be entirely produced by denudation, without further help from underground forces than the initial uplift into land. No matter what may be the original configuration of the mass of land, the flow of water across its surface will inevitably carve out a system of valleys and leave ridges and hills between them" (page 94).

The possibility of producing a plain by a continuance of this process is not here alluded to, but on an earlier page the aid of shore waves is called on:

"The limit beneath which there is little effective erosion by waves and tidal currents probably does not exceed a very few hundred feet. Worn down to that limit, the degraded land would become a submarine plain, across the surface of which younger deposits might afterward be strewn" (page 92).

* Trans. Geol. Soc. Glasgow, vol. iii, 1868, p. 153.

On later pages (137 and 138) the author continues:

"The table-land of the Highlands has been the work not of subterranean action, but of superficial waste. The long flat surfaces of the Highland ridges, cut across the edges of the vertical strata, mark, I believe, fragments of a former baselevel of erosion. In other words, they represent the general submarine level to which the Highland region was reduced after protracted exposure to subaerial and marine denudation. The valleys which now intersect the table-land . . . have been eroded out of it. If, therefore, it were possible to replace the rock which has been removed in the excavation of these hollows, the Highlands would be turned into a wide, undulating table-land; . . . and in this rolling plain we should find a restoration of the bottom of a very ancient sea. . . . Its mountains were levelled; its valleys were planed down; and finally the region was reduced to a baselevel of erosion beneath the waves. . . . Some central tracts of higher ground may have been left as islands." *

In Geikie's "Text-book of Geology" subaerial denudation is regarded as providing a greater amount of detritus than marine denudation, and a significant modification is made of Ramsay's interpretation of plains of marine denudation. In the actual production of such plains—

"The sea has really had less to do than the meteoric agents. A 'plain of marine denudation' is that sea-level to which a mass of land had been reduced mainly by the subaerial forces, the line below which further degradation became impossible, because the land was thereafter protected by being covered by the sea. Undoubtedly the last touches in the long process of sculpturing were given by marine waves and currents, and the surface of the plain, save where it has subsided, may correspond generally with the lower limit of wave action." †

Plains or peneplains of subaerial denudation, elevated into a new cycle of erosion without waiting to be planed off by the sea, are not explicitly considered. Under "terrestrial features due to denudation" it is stated that—

"Table-lands may sometimes arise from the abrasion of hard rocks and the production of a level plain by the action of the sea, or rather of that action combined with the previous degradation of the land by subaerial waste. Such a form of surface may be termed a *table-land of erosion*" (page 939).

*I have elsewhere (London Geographic Journal, vol. v, 1895, p. 139) taken the liberty of questioning the geological date assigned by Geikie to this baseleveling. He states that "the great denudation which leveled the old Highland table-land was far advanced before the close of the Old Red Sandstone period" (page 144). Undoubtedly a vast denudation was accomplished before and during that time, for the heavy strata of the Old Red lie on the greatly denuded edges of more ancient rocks; but the even table-land, restorable from the summits of the mountains and ridges of today, seems to be of more modern date, because, since the deposition of the Old Red, significant deformation has taken place, whereby a peneplain of earlier date must have been here elevated, there depressed. The table-land now recognizable appears to be the result of denudation on the deformed Old Red peneplain. There has been plenty of time for its production.

†Second edition, 1885, pp. 434, 435.

That an author who has so ably discussed the relative competence of marine and subaerial denudation should not give explicit account of plains worn down under the air and afterward uplifted and dissected, illustrates how strongly the doctrine of marine denudation has been impressed on the geologists of today.

Brief citation may be made from a number of other books and essays.

The able article, "The Denudation of the Weald,"* in which Foster and Topley did so much to advance the modern understanding of the subaerial origin of valleys, assumed that the streams of southern England began to act on an uplifted plain of marine denudation, and from this arbitrary beginning explained the transverse valleys by which the chalk escarpments around the Weald are trenched (page 473).

Maw in his essay, "Notes on the comparative structure of surfaces produced by subaerial and marine denudation,"† contrasts hills and valleys carved by rain and rivers with plains of denudation carved by the sea.

In the same way Wynne wrote "On denudation with reference to the configuration of the ground"‡ and concluded that—

> "Rain seems to act vertically, its tendency always being to produce steep ground where it is not accumulating materials. Thus we are obliged, in the absence of anything more likely to produce them, to attribute the formation of plains to the action of the sea" (page 10).

A little later Whitaker, when advocating the origin of cliffs and escarpments by subaerial denudation, said that nature "uses the sea to carve out continents and islands; rain and rivers to cut out hills and valleys."§

Mackintosh in his "Scenery of England and Wales" (1869) carries the doctrine of marine erosion to an extreme and allows hardly anything to subaerial agencies. Even the inner Triassic lowlands of England, inside of the oölitic escarpment, are ascribed to marine denudation. "The sea must have mainly given rise to the inequalities of the earth's surface, so far as they are the result of denudation" (page 292).

It appears, therefore, that the active discussion in England, of which the above extracts give some indication, did not consider the possibility of subaerial baseleveling, but was concerned chiefly with the origin of valleys by rain and rivers. Since the settlement of this question, land sculpture has not received much attention from English geologists, as the following extracts from a later period will show.

Green says, "the even surface that would result from the action of

* Quart. Journ. Geol. Soc., vol. xxi, 1865, pp. 443–474.
† Geol. Magazine, vol. iii, 1866, pp. 439–451.
‡ Geol. Magazine, vol. iv, 1867, pp. 3–10.
§ Geol. Magazine, vol. iv, 1867, p. 454.

marine denudation is called a 'plain of marine denudation.'"* No appreciable wearing takes place below the level of the lowest tides. No mention is made of a cover of sediments as a characteristic accompaniment of the plain of denudation, and no consideration is given to the plains of subaerial denudation; only the lesser inequalities of land form are ascribed to subaerial agencies.

The edition of "Phillips' Manual of Geology," by Etheridge and Seeley (1885), briefly describes plains of marine denudation (page 131), and under subaerial denudation goes no further than to explain the origin of valleys.

Woodward, in his valuable summary of the "Geology of England and Wales,"† follows his predecessors in adopting the idea of marine denudation for the production of plains.

Jukes-Brown writes:

"Plains of erosion are those which have been formed by marine erosion across the edges and outcrops of strata without reference to their inclination, flexures, or fractures. They are surfaces of planation formed by the march of the sea across the country. The limestone plains of central Ireland may be cited as an instance."‡

Subaerial agencies are not considered beyond the formation of valleys. For example:

"As soon as this surface produced by marine erosion is elevated into dry land, it is subjected to the detritive action of the subaerial agencies already described, and is ultimately carved out into new forms of hill and valley" (page 565).

Detritive and erosive agencies are grouped under two heads:

"1. Marine agencies, which act along the margin of the land, and tend to produce an approximate level surface or plain. 2. Subaerial agencies, which act over the whole surface of the land, and tend to produce a system of valleys and watersheds, hollows and relative eminences" (page 564).

In discussing breaches in the escarpments and hill ranges of the Wealden district, the same author says:

"The only explanation of these facts is . . . marine erosion first produced a surface of planation across the whole district while it was being slowly elevated, so that this original surface sloped gently from a central line toward the north and south. The primary streams naturally followed these slopes, . . . forming the transverse valleys" (page 581).

Richthofen is the leading advocate of marine erosion among continental geologists. He treated the origin of plains of denudation, inde-

* Physical Geology, 1882, p. 577.
† Second edition, 1887.
‡ Handbook of Physical Geology, 1892, p. 620.

pendently of Ramsay's writings, in his great work on China, attention being led to the problem by the occurrence of unconformable marine strata lying on smooth foundations, as observed in his eastern travels. He concludes that the "oldland" platform cannot have been produced by atmospheric wasting or by running water; these agencies produce valleys separated by ridges. Truly the valleys multiply and widen and the ridges weaken, but reduction to a lowland can be reached only locally and in small dimensions. Moreover, change in the altitude of land works against complete denudation; yet, although such a result is unattainable by subaerial agencies, it may be accomplished by the waves of the sea beating on the coast. Three cases are considered: a still-stand of the land for an indefinite period, a slow elevation and a slow depression. The still-standing land would be cut inward to a limited distance, after which the waves would be exhausted on the platform of their own carving. During elevation slight effect could result, for the work would always be beginning anew. Slow depression alone can produce regional abrasion, for then the power of the waves is maintained by the continued sinking of the bottom, while detritus accumulates on it. In contrast to structural plateaus (Schichtungsplateaus), plateaus of denudation have no relation to the structures across which they are cut or to the valleys which are sunk beneath their level after general elevation. As examples, the Ardennes and the uplands of the middle Rhine are first mentioned, these being explained as producible only by sea waves; never by flowing water or other subaerial agents. Another example given is the western slope of the Sierra Nevada of California, now uplifted and dissected.*

The substance of the above is repeated in Richthofen's "Führer fur Forschungsreisende," † emphasis being given to the association of plains of denudation with unconformably overlying sediments, to which the English school directs insufficient attention. Subaerial agents are described as excavating valleys in uplifted plains of denudation, but not in producing the plains (pages 171–173, 670, 671). The prevalence of superposed streams in certain dissected uplands of abrasion is noted (pages 671, 672), but no contrast drawn between these examples and others in which the streams are systematically adjusted to the structures.

Cornet and Briart have made special study of the greatly deformed Paleozoic rocks of Belgium, which they believe once rose in lofty mountains. Although they regard subaerial agencies competent to produce the "complete ablation" of a land surface, they conclude that it was probably the waves of an encroaching sea that contributed largely to destroy what remained of their ancient mountains in Cretaceous time.‡

* China, 1882, vol. ii, chap. xiv, sec. 3. † Berlin, 1886, pp. 353–361.
‡ Le relief du sol en Belgique. Ann. Soc. Geol., Belg., iv, 1877, pp. 72–113.

Philippson follows Richthofen in treating plains of denudation—"abrasionsflächen"—as the result of wave action.*

The American School.

Few American writers accept the belief of the English school. The first clear recognition of the importance of subaerial baseleveling should, I believe, be credited to our geologists in the western surveys.†

Powell's "Exploration of the Colorado river" (1875) brought the American view of the capabilities of subaerial erosion more prominently forward, yet the text does not furnish brief explicit statement directly to the effect that lowlands of denudation may be produced by subaerial agencies. Extracts would lose their flavor apart from their context, but in figuring a section of the wall in the Grand canyon the beveled surface of the tilted older strata on which the horizontal Carboniferous strata lie is drawn smooth and even. The overlying beds "are records of the invasion of the sea; the line of separation the record of a long time when the region was dry land" (page 212). Here the implication is that the sea gained entrance by depression of the baseleveled land. The overlying strata are regarded as the ruins of some unrepresented land, not of the locally buried land. The explanation is precisely opposite to that given to similar structures by Richthofen.

In Powell's "Geology of the Uinta mountains" (1876) there is a similar absence of explicit account of baseleveled plains, apparently because it was not necessary to expand truisms so simple; but the chapter on degradation very clearly implies the capacity of subaerial forces to wear down mountains, however high; indeed, its burden is to show that the destruction of a lofty range is so much accelerated by steep declivity that its life cannot be much longer than that of a low range. Mountains are "ephemeral topographic forms;" all existing mountains are geologically recent (page 197). All this without once calling on the aid of sea waves.

Dutton's monograph on the "Tertiary History of the Grand Canyon district" (1882) is most characteristically American in treatment as in theme. Referring to the great unconformity near the base of the canyon walls in the Kaibab and Sheavwits plateaus, he says, on page 207, that—

"The horizontal Carboniferous beds appear to have been laid down upon the surface of a country which had been enormously eroded and afterward submerged."

*Studien über Wasserscheiden, 1886, p. 100.

†Marvine briefly presented the essence of the idea in 1873, but he made mention of marine action in a late stage of the process, somewhat after the fashion of the English school. Describing the east slope of the Rocky mountain front range, he wrote: "The ancient erosion gradually wore down the mass of Archean rocks to the surface of the sea, . . . the mass was finally leveled off irrespective of structure or relative hardnesses of its beds, by the encroaching ocean, which worked over its ruins and laid them down upon the smoothed surface in the form of the Triassic and other beds" (Hayden's Survey, Rept. for 1873, p. 144).

The erosion followed uplift, the deposition followed submergence when the erosion was essentially completed. Along the surface of contact there are—

"A few bosses of Silurian strata rising higher than the hard quartzitic sandstone which forms the base of the Carboniferous. These are Paleozoic hills, which were buried by the growing mass of sediment. But they are of insignificant mass, rarely exceeding two or three hundred feet in height, and do not appear to have ruffled the parallelism of the sandstones and limestones of the massive Red Wall group above them" (page 209).

On another page (181) Dutton says:

"The meaning of this great unconformity obviously is that after a vast body of early Paleozoic strata had been laid down they were distorted by differential vertical movements, were flexed and faulted, and were elevated above the sea. They were then enormously eroded. . . Still later the region was again submerged."

Over the rugged country thus ravaged, the later strata, perhaps 15,000 feet thick, were laid down.

Many other examples of the American view may be given. Most of them, as in the cases already cited, take no account of the possibility that the evenly abraded surface of the older terrane might be essentially the product of wave work, but tacitly assume that it resulted from subaerial erosion, followed by depression, with more or less tilting, so that the submerged area comes to be sheeted over with waste derived from some non-submerged area.

Irving concludes that in Wisconsin—

"An amount of material vast beyond computation was removed from this ancient land before the encroachment upon it of the sea within which the [Potsdam] sandstone was deposited."*

The buried oldland is referred to as a "sub-Potsdam land surface."†

Van Hise, writing of the great unconformities below and above the Penokee series of Wisconsin and upper Michigan, implies great subaerial erosion, by which an uplifted region was reduced to a peneplain; depression, submergence and deposition of material eroded elsewhere then followed. The essentials of the explanation are that the Penokee series rests upon an ancient land surface, more or less modified by wave action at the time of submergence, but worn down from its constructional form almost entirely by subaerial agents.‡

Walcott, recognizing wave work at the margin of an encroaching sea as contributing to the formation of basal conglomerates, nevertheless explains the great pre-Cambrian land area of our country as "approaching

*Seventh Ann. Rep. U. S. Geol. Survey, 1888, p. 402. † Ibid., p. 409.
‡ U. S. Geol. Survey, monograph xix, 1892, pp. 454–466.

the baselevel of erosion over large portions of its surface."* Moreover, it was a result of continental depression and not of erosive encroachment of the waves that the upper Cambrian sea gained its extension over the great interior of the continent (page 565). The relation of subaerial and marine agencies are here, as in so many instances, just reversed from their proportionate activities in Richthofen's scheme.

McGee was the first to present a clear statement of the vast subaerial denudation of our Atlantic slope in Mesozoic time:

"Before the initiation of Potomac deposition, but subsequent to the accumulation of the Triassic and Rhaetic deposits and to the displacement and diking by which they are affected, there was an eon of degradation during which a grand mountain system was obliterated and its base reduced to a plain which, as its topography tells us, was slightly inclined seaward and little elevated above tide. . . . There followed a slight elevation of the land, when the rivers attacked their beds and excavated valleys as deep as those today intersecting the Piedmont plain. . . . Then came the movement by which the deposition of the Potomac formation was initiated; the deeply ravined baselevel plain was at the same time submerged and tilted oceanward." †

It appears from the foregoing examples that, in denuded plains over which unconformable sediments have been deposited, some late and small share in the work of denudation may be allowed to the shore waves as they advance over an already prepared peneplain when depression occurs; but it is otherwise with those uplifted and dissected plains of denudation upon which there is no reason to think that unconformable sediments have ever been deposited. The plateau in which the Grand canyon of the Colorado is cut is an extraordinary example of this kind. It is, moreover, notable from consisting of nearly horizontal strata, where acute observation has been needed to detect evidence of the long cycle of erosion passed through before the region was uplifted to its present altitude.

The great plateau is beveled obliquely across the Carboniferous and Permian strata, so that the undulating surface of the upland in its medial part presents Permian beds on the hills and Carboniferous beds in the hollows; but to the south, where the strata gently rise, the whole surface is Carboniferous; to the north, where the strata sink, the surface is entirely Permian.

"We may suppose that this entire region, at the epoch at which the great denudation of the Mesozoic system approached completion, occupied a level not much above the sea. Under such circumstances it would have been at what Powell terms baselevel of erosion. The rivers and tributaries would no longer corrade their channels. The inequalities which are due to land sculpture and the general process of erosion would then no longer increase, and the total energy of erosion would be

* Twelfth Ann. Rep. U. S. Geol. Survey, 1891, p. 562.

† Three formations of the middle Atlantic slope. Am. Jour. Sci., vol. xxxv, 1888, p. 142.

occupied in reducing such inequalities as had been previously generated. During periods of upheaval, and for a considerable time thereafter, the streams are cutting down their channels, and weathering widens them into broad valleys with ridges between. The diversification so produced reaches a maximum when the streams have nearly reached their baselevels; but when the streams can no longer corrade, and if the uplifting ceases, these diversifications are reduced and finally obliterated. Such, I conceive, was the case here. . . . The entire region was planed down to a comparatively smooth surface." *

Willis first called attention to the occurrence of an uplifted and dissected peneplain of subaerial denudation in the mountains of North Carolina,† and Hayes and Campbell have since then shown the great extent and area of this ancient land surface. ‡ Willis and Hayes have lately described the northern and southern Appalachians, § giving much attention to the essential extinction of the mountains, except in the Carolina highlands, in late Cretaceous time. The first author writes of the lowland thus produced: "The land was flat, featureless and very slightly elevated above the sea" (page 189). The second author writes: "The whole region was reduced to a nearly featureless plain, relieved only by a few groups of monadnocks where the highest mountains now stand" (page 330).

Emerson writes of the Berkshire hills in western Massachusetts:

"Erosion planed away the mountains to the general level, which can still be seen in the average level of the plateau, pitching slightly east. * * * When this peneplain was formed it was doubtless horizontal and near the sealevel, and was what is called a baselevel." ‖

Salisbury says that the even crest-lines of the New Jersey highlands tell of "mountainous elevations reduced to a peneplain near the level of the sea." ¶

Not only the tilted rocks of the Alleghenies and of the older Appalachian belt, but the horizontal strata of the Allegheny plateau are regarded as having been baseleveled, or almost so, before their present uplift and dissection was gained. See, for example, the account of the Cumberland plateau in Tennessee by Hayes.**

Griswold has recognized a greatly dissected peneplain in the even crested ridges of the Arkansas novaculites, and has associated the warping of the great peneplain of which his special district was a part with the origin of the lower course of the Mississippi in late Mesozoic time.††

* Grand Canyon District. U. S. Geol. Survey Monogr., II, 1882. p. 119.
† Round about Asheville, Nat. Geog. Magazine, vol. i, 1889, p. 297.
‡ Geomorphology of the southern Appalachians, ibid., vol. vi, 1894, p. 69.
§ Nat. Geog. Monographs, vol. i, 1895, nos. 6 and 10.
‖ Hawley sheet, Geol. Atlas U. S., 1894.
¶ Geol. Survey New Jersey, 1894 (1895), p. 8.
** Sewanee sheet, Geol. Atlas U. S., 1895.
†† Geol. Surv. Arkansas, 1890, vol. iii, p. 222; Proc. Bost. Soc. Nat. Hist., vol. xxvi, 1895, p. 478.

Keyes * and Hershey † have recently described the upland of the Ozark plateau in Missouri as an uplifted and dissected peneplain. The region has an essentially horizontal structure, like the Allegheny plateau, with which it is in many ways homologous. The latter author tells of residual hills or monadnocks which still surmount the upland plain, and of faint inequalities of form that seem to mark "the hydrographic basins of the streams which flowed on the Cretaceous lowland plain;" but as a whole the region was "a low, marshy plain of very slight relief, probably nearly at sealevel."

Darton describes the Piedmont area of Virginia as—

"An undulating plateau carved in greater part in crystalline rocks . . traversed by rivers which flow in gorges. . . It is now very clearly recognized that the Piedmont plateau is a peneplain of Tertiary age. . . There is a system of very low, flat divides coincident with those of the present drainage system." ‡

Keith also describes the formerly even surface of the Piedmont belt in which the valleys of today are incised, as a Tertiary baselevel of subaerial origin. §

The bevelled western slope of the Sierra Nevada, regarded as an upturned plain of marine abrasion by Richthofen, is ascribed by Gilbert, || Leconte, ¶ Lindgren, ** Diller †† and others to subaërial denudation; but Lindgren makes it clear that when the region stood lower it was not worn smooth enough to be called a peneplain; "the declivities and irregularities of the old surface are too considerable for that."

Diller describes a peneplain formed on the upturned Cretaceous rocks of northern California and now dissected by various streams:

"The production of such a broad, uniform plain by the erosion of rocks varying greatly in hardness could only be accomplished on a very gentle slope near the level of the controlling water body, and we may therefore properly consider this plain a baselevel of erosion." ‡‡

Lawson presents an instructive account of an uplifted and dissected peneplain beveled across upturned strata in northern California. Waterworn gravels occur on the ridges of the dissected upland. They "can only be interpreted as remnants of the stream gravels of the ancient peneplain." §§

* Geol. Surv. Missouri, vol. viii, 1894, pp. 330, 352.
† American Geologist, vol. xvi, 1895, p. 338.
‡ Chicago Jour. Geology, 1894, vol. ii, pp. 568–570.
§ Fourteenth Ann. Rept. U. S. Geol. Survey, 1894, p. 369.
|| Science, vol. i, 1883, p. 195.
¶ Bull. Geol. Soc. Am., vol. 2, 1891, p. 327.
** Ibid., vol. 4, 1893, p. 298.
†† Chicago Jour. Geol., vol. ii, 1894, p. 34.
‡‡ Fourteenth Ann. Rept. U. S. Geol. Survey, 1894, p. 405.
§§ University of California; Bull. Dept. Geol., vol. i, 1894, p. 244.

G. M. Dawson describes an ancient peneplain, now an elevated and dissected plateau, in the Rocky Mountain region of Canada:

"Climbing to the level of this old plateau, or to that of some slightly more elevated point about the fiftieth or fifty-first parallel of latitude, the deep valleys of modern rivers with other low tracts are lost sight of, and the eye appears to range across an unbroken or but slightly diversified plain, which, on a clear day, may be observed to be bounded to the northeast, southwest and south by mountain ranges with rugged forms, and above which in a few places isolated higher points rise, either as outstanding monuments of the denudation by which the plateau was produced, or as accumulations due to volcanic action of the Miocene or middle Tertiary period." *

After explicitly considering the alternatives of marine and subaerial erosion, the author decides against the former, because the plateau district is not accessible to the sea, and because there are no marine strata thereabouts referable to the period when the peneplain was formed. The river system of the region—

"aided by other subaerial agencies, cut down almost its entire drainage basin till this became a nearly uniform plain, with some slight slope in the main direction of the river's flow, but of which the lowest part approximately coincided with the sea-level of the time. . . . After reaching this baselevel of erosion the rivers would, of course, be unable to do more than serve as channels for the conveyance of material brought into them from the surrounding country, which, wherever it stood above the general level, was still subject to waste. The valleys became wide and shallow, and the surface as a whole assumed permanent characters." †

My own studies lead me to believe that subaerial denudation has reduced various mountainous or plateau-like uplifts to lowland peneplains. ‡

A considerable number of extracts might be presented from the works of foreign writers to show that the idea of marine denudation is on the whole less favorably received by continental than by English geologists; but the features of land form and the processes of land sculpture have not been studied in Europe with the attention that has been given to stratigraphic succession or to the problems of paleontology and petrography. Regions that are known to be uplands of denudation are often described with abundant detail as to their structure, but with the scantiest reference to the conditions of their topographic development.

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* . . . The Rocky Mountain region in Canada . . . , Trans. Roy. Soc. Can., viii, 1890, p. 11.

† Loc. cit., p. 13.

‡ The following articles may be referred to: Relation of the coal of Montana to the older rocks (Tenth Census U. S, vol. xv, 1886, p. 710); Topographic development . . . of the Connecticut valley (Am. Jour. Sci., vol. xxxvii, 1889, p. 430); Geographic development of northern New Jersey (with J. W. Wood, Proc. Boston Soc. Nat. Hist., vol. xxiv, 1889, p. 373); Rivers of northern New Jersey (Nat. Geog. Mag., vol. ii, 1890, p. 6); Topographic forms of the Atlantic slope (Bull. Geol. Soc. Am., vol. 2, 1891, p. 557); Physical geography of southern New England (Nat. Geog. Monogr., vol. i, 1895, p. 276); Development of certain English rivers (London Geog. Jour., vol. v, 1895, p. 140).

A characteristic example of this manner of treatment is found in the valuable works by Lepsius on the mountains of the upper and middle Rhine,* in which the Schiefergebirge and other ancient mountains are fully treated as to structure, although little is said of their form and still less of the origin of their form.

The following citations are from works in which land form and sculpture are more fully considered.

The increasing importance attributed by Sir A. Geikie to subaerial agencies in his later writings has already been noted. Professor James Geikie goes further in this direction and says:

"Valleys continue to be deepened and widened, while the intervening mountains, eaten into by the rivers and their countless feeders and shattered and pulverized by springs and frosts, are gradually narrowed, interrupted and reduced until eventually what was formerly a great mountain chain becomes converted into a low-lying undulating plain." †

Gosselet, in his comprehensive monograph on the Ardennes, says that the tilted, folded and faulted strata of their uplands have been, as it were, planed down by the combined action of atmospheric disintegration and pluvial wearing. Both the Jurassic and Cretaceous formations are described as lying on oldland soils, where they overlap the Paleozoic strata.‡

The elaborate treatise on "Les formes du terrain" (1888), by de la Noë and de Margerie, clearly maintains that pluvial denudation may not only produce valleys, but it may wear down the divides between the valleys (page 106). The escarpments or cross-valleys of the Weald in southern England may be explained without calling on marine erosion, as most of the English geologists have done (pages 135, 136). Plateaus of abrasion, without a cover of unconformable strata, may be "simply the result of prolonged subaerial erosion." If unconformably covered, it still remains to be seen how far the abraded surface is—

"The modification by wave action of a hardly different surface, produced by the prolonged work of streams which had long before attained faintly graded slopes, and which had by the aid of atmospheric agents almost completely destroyed pre-existing inequalities of form" (page 188).

Penck concludes that the final aim of subaerial denuding agents is to reduce a land almost completely to a plain,§ but his account of the Schiefergebirge of the middle Rhine does not explicitly state whether the "abrasionsplateau" of their uplands is of marine or subaerial origin.‖

* Die Oberrheinische Tiefebene und ihre Randgebirge, Forschungen zur deut. Landeskunde, i, 1885, 35–91; Geologievon Deutschland, 1887.

† Mountains, their origin, growth and decay: Scot. Geog. Mag., vol. ii, 1886, p. 160.

‡ L'Ardenne. Mém. Carte géol., France, 1888, pp. 802, 808, 837.

§ Das Endziel der Erosion und Denudation, Verh. viii deut. Geographentag, 1889, pp. 91–100.

‖ Landerkunde des Erdtheils Europa, i, 1887, p. 316.

In his compendious volumes on the "Morphologie der Erdoberfläche" (1894), he considers plains of marine and of subaerial denudation, both as to process of origin and as to derivative forms, after elevation and dissection, but criteria for their discrimination are not discussed.*

De Lapparent, president of the French Geographical Society, has advocated subaerial erosion as the means of denuding the Ardennes and the Central plateau of France, † and later says:

"La notion des pénéplaines est extremement féconde, et ce n'est pas un de ses moindres mérites d'avoir porté le coup de grâce à la théorie des plaines de dénudation marine, si fort en honneur de l'autre coté du détroit." ‡

Comparison of the two Schools.

It is noteworthy that, with few exceptions, the more recent writers here quoted do not discuss both processes by which smoothly abraded plains, whether buried or bare, may be produced, but directly announce their conclusion as to the origin—by marine or by subaerial agencies—of the surface under consideration. This, of course, implies that they regard the question as settled, just as for some time back it has been the habit of geologists on finding marine shells in stratified rocks to conclude, without reviving the discussions of earlier centuries, that the strata are of marine origin, and that their present position indicates a change in the relative attitude of the land and sea. But in this latter example all geologists are today agreed, while in the problem of the origin of plains of denudation each writer follows only the conclusion of his own school, not the conviction of the world. *It is chiefly to arouse attention to this aspect of the problem that the present review is undertaken.*

It is further noteworthy that, with few exceptions, the authors who discuss the matter at all do not attempt to discriminate between the two possible classes of denuded surfaces by searching for features peculiar to one or the other, but content themselves with *a priori* argument as to the possibility of producing plains by marine or subaerial agencies.

There is, however, a certain difference of attitude in the two schools regarding the doctrine of the other. The English school hardly considers at all the ability of subaerial agencies to produce smooth plains of denudation; their discussion of the question turned really on the possible origin of valleys by subaerial agencies. The American school does not, as far as I have read, deny the ability of marine agencies, but attributes greater ability, especially far in continental interiors, to subaerial agencies; their discussion of the question postulates the subaerial origin of ordinary

* Vol. ii, pp. 145, 181, 489.

† L'age des formes topographiques, Rev. des quest. scient., Oct., 1894.

‡ La géomorphogénie, ibid., April, 1895.

valleys as a matter already proved, and goes on from this to the possible ultimate result of the valley-making processes. Again, the English school denies, tacitly or directly, the probability or even the possibility of a period of still-stand long enough for essentially complete subaerial denudation close to sealevel, but assumes the possibility of a period of still-stand or of slight depression continuous and long enough to allow the sea waves to plane off the sinking lands. The American school tacitly questions the occurrence of great erosive transgressions of the sea during either a still-stand or a slow depression of the land, but admits the possibility of essentially complete subaerial denudation to an average sealevel, above and below which the land long hovers in many minor oscillations before a new attitude is assumed by great depression, elevation or deformation. It should be borne in mind that the depressed and buried or the uplifted and dissected plains of denudation whose origin is in question are in no cases geometrical planes; they nearly always possess perceptible inequalities, amounting frequently to two or three hundred feet; but these measures are small compared to the inferred constructional relief of earlier date, or compared to the deep valleys often eroded beneath the plain if it has been uplifted. By whatever process the so-called "plain of denudation" was produced, an explanation that will account for a peneplain of moderate or slight relief is all that is necessary. Absolute planation is so rare as hardly to need consideration here.

In no respect is the contrast between the two schools more strikingly shown than in the beliefs concerning the cover of unconformable strata that lie or are supposed to have lain upon an oldland. The continental members of the English school generally regard these strata as an essential result of the process of marine denudation during slow depression; if such strata are absent from a dissected plateau, their absence is explained by denudation after uplift. The American school does not give the cover of unconformable strata an essential place in the problem; if present, it is generally ascribed to deposition following the submergence of a region already for the most part baseleveled by subaerial agencies.

Review of the *a priori* Argument.

It may be noted that the value of marine agencies gained a high reputation for effective work before subaerial agencies were recognized as significantly affecting the form of the land, and that from that time to the present the importance of the latter agencies has been steadily increasing in the minds of geologists. The manifest work of waves on a bold coast was perceived at a time when the production of valleys by rain and rivers was scouted. Today it is not so much that the absolute strength of marine erosion is given a smaller value than heretofore, but

that the relative importance of subaerial erosion is rated much higher than at the beginning of the century. While the sea works energetically along a line, subaerial forces work gently over a broad surface. Chiefly for this reason Geikie concludes that "before the sea, advancing at a rate of ten feet a century, could pare off more than a mere marginal strip of land between 70 and 80 miles in breadth, the whole land might be washed into the ocean by atmospheric denudation."*

A slight movement of elevation usually sets the sea back to begin its work anew on the seaward side of its previous shoreline, but such an elevation only accelerates the work of subaerial denudation all over the elevated region. The waves on the seashore shift their line of attack with every slight vertical movement of the coastal region; but the subaerial forces over large continental areas gain no notice of slight movements until a considerable time after they have been accomplished, and hence they perform their task only with reference to the average attitude of the land. Observers near a shoreline naturally have their attention directed to the unsteadiness of the land, as indicated by marks of many recent changes of land level; hence they are perhaps indisposed to admit that any land has ever stood still—or oscillated slightly above and below an average attitude—long enough to be nearly or quite baseleveled by subaerial agencies. They prefer to think that the sea is, in spite of its many stops and starts, the great leveler of the lands.

Some have intimated that the insular position of English observers has led them to exaggerate the relative power of the sea. Thus W. T. Blanford, after much experience in India and elsewhere, as well as at home in England, writes:

"It is not surprising that the power of rain and rivers should be recognized with difficulty in regions where their effects are comparatively so dwarfed as in the British isles, while the power of marine denudation is at its maximum from the enormous coastline exposed and the small amount of detritus furnished for its protection by rivers of small length and in which floods are of exceptional occurrence."†

But even this well practised observer contended only for the subaerial origin of valleys, not of plains also. On the other hand, those whose studies have been directed chiefly to large interior areas seldom have occasion to observe the action of energetic shore waves, and hence are apt to attribute relatively little importance to their work. The small share of attention recently given by Powell to shore waves and coastal forms in a general discussion of physiographic processes and features is perhaps thus explained.‡ The citation from Dawson, given above, is

* Text-book, 1885, p. 432.
† Geol. and Zoöl. Abyssinia, 1870, p. 158, note.
‡ Nat. Geog. Monographs, vol. i, 1895, nos. 1 and 2.

an especially good illustration of the manner in which large continental surroundings may affect the opinions of an observer who, from certain associations, might be expected to follow the insular school.

Although mature deliberation and good judgment may lead through *a priori* argument to a safe conclusion in many problems, the method is of difficult application here on account of the great number of variable factors whose appropriate values can be hardly determined. It is probably by reason of assigning different values to variable factors that the opposite conclusions summarized above have been reached.

STATEMENT OF THE *A POSTERIORI* ARGUMENT.

In attempting to decide by arguing from effect to cause whether evenly denuded regions have been worn down by subaerial or marine agencies, let us try to stand on a provisional Atlantis, hoping that it may give steady support long enough for us to gain an unprejudiced view of the opinions that are so generally accepted on the lands to the east and west. From this neutral ground let us attempt to deduce from the essential conditions of each explanation of the problem as many as possible of its essential consequences, and then confront these consequences with the facts. The measure of accordance between consequences of theory and facts of observation will then serve as a measure of the verity of the theory from which the consequences are derived. No final decision can be reached in many cases; for, however clearly the consequences may be deduced, the facts with which they should be compared are often beyond the reach of observation. In such cases it is advisable to announce indecision as clearly as decision is announced in the others.

As far as I have been able to carry the analysis of the problems, it is more difficult to find positive criteria characteristic of plains of marine denudation than of plains of subaerial denudation; hence I will take up the latter class first. It should be remembered, however, that in each class of plains both classes of agencies may have some share, one preponderating over the other.

CONSEQUENCES OF SUBAERIAL DENUDATION.

Imagine a region of deformed harder and softer strata raised to a considerable elevation. Then let the land stand essentially still, or oscillate slightly above and below a mean position. The rivers deepen their valleys, the valleys widen by the wasting of their slopes, and the hills are slowly consumed. During this long process a most patient and thorough examination of the structure is made by the destructive forces,* and whatever is the drainage arrangement when the rivers begin to cut their

*See Bearing of physiography on uniformitarianism. Bull. Geol. Soc. Am., vol. 7, 1895, pp. 8–11.

valleys a significant rearrangement of many drainage lines will result from the processes of spontaneous adjustment of streams to structures. This involves the adjustment of many subsequent streams to the weaker structures and the shifting of many divides to the stronger structures. Adjustment begins in the early stages of dissection, advances greatly in the mature stages, and continues very slowly toward old age, while the relief is fading away. Indeed, when the region is well worn down some of the adjustments of maturity may be lost in the wanderings of decrepitude, but this will seldom cause significant loss of adjustment except in the larger rivers. Now, if a region thus baseleveled or nearly baseleveled is raised by broad and even elevation into a new cycle of geographical life, the rivers will carry the adjustments acquired in the first cycle over to the second cycle. Still further adjustment may then be accomplished. The master streams will increase their drainage area in such a way that the minor streams will seldom head behind a hard stratum. In a word, the drainage will become more and more longitudinal and fewer and fewer small streams will persist in transverse courses. All this is so systematic that I believe it safe to assert that the advanced adjustments of a second cycle may in many cases be distinguished from the partial adjustments of a first cycle. It should be noted further that in the early stages of the second cycle the residual reliefs of the first will still be preserved on the uplands, and that they will be systematically related to the streams by which the dissection of the upland is in progress, as noted in the examples described by Darton and Hershey.

It is manifestly impossible to apply what may be called the river test to plains of denudation upon which a cover of unconformable sediments is spread; but, before assuming that such buried plains are of marine origin, their uppermost portion next beneath the cover should be examined to see if it presents indications of secular decay before burial; and, if so, a subaerial origin for the plain may be argued. Certain aspects of this division of the subject have been discussd by Pumpelly.* Another matter of importance is the character of the undermost layers of the cover. If these are fresh-water beds a subaerial origin for the plain on which they rest may be inferred. The Potomac formation offers an example of this kind.†

Consequences of marine Denudation.

Now suppose that a region of disordered structure is partly worn down by rain and rivers and is smoothly planed across by the sea during a time of still-stand or of gradual depression. The land waste gained in the

* Bull. Geol. Soc. Am., vol. 2, 1891, p. 211.

† McGee: Am. Jour. Sci., vol. xxxv, 1888, p. 137; Fontaine: Monogr. xv, U. S. Geol. Survey, 1889, p. 61.

later attack will be spread off-shore on the platform abraded in the earlier attack. The basal strata of the unconformable cover thus formed must indicate their marine origin and must be appropriately related in composition and texture to their sources of supply. The drainage systems of the land will be essentially extinguished by the encroaching sea. When the region rises, with the cover of new sediments lying evenly on its smoothed back, a new system of original consequent streams will take their way across it. If the elevation be sufficient, the streams will incise their valleys through the cover of new sediments and in time find themselves superposed on the "oldland" beneath. As time passes, more and more of the cover will be stripped off; at last it may disappear far and wide, although the stripped surface of the oldland may still retain a generally even sky-line as a memorial of its once even denudation. Now, in this case, the rivers by which the dissected plateau is drained will have at most only a very slight adjustment to its structure. Their courses will have been inherited from the slope of the lost cover; they will at first run at random across hard and soft structures; a little later some adjustment to the discovered structures will be made, but as long as the even sky-line of the upland is recognizable, only the incomplete adjustments appropriate to the adolescent stage of denudation can be gained.

Examples of dissected Uplands with adjusted Drainage.

This essay has already reached so much more than its expected length that it will not be possible to give extended space to the consideration of specific examples. This is, however, no great disadvantage, inasmuch as the number of examples in which the problem has been considered in relation to drainage arrangement and other discriminating features is very small. The various articles already referred to concerning the geographical development of the Appalachian region treat this aspect of the subject with some care; to these may be added my paper on "Certain English rivers," in which it seems to me that there is shown some ground for the consideration of the alternative to the usual English view. Of the Ardennes it may be briefly said that systematic longitudinal and transverse streams are well developed in certain areas, and in those parts, at least, there does not appear direct evidence of marine transgression. Sheets 48 and 54 of the Belgian topographical map (scale, 1 : 40,000) exhibit these features very clearly. On the other hand, the branches of the Rhine and the Moselle in the Schiefergebirge suggest superposition from a lost cover, as mapped on the sheets of the Karte des Deutschen Reichs (scale, 1 : 100,000).

It is manifest that many plains of denudation, now uplifted and more

or less dissected, may be found in which no simple test based on the presence of superposed streams will serve to settle the question of marine origin. Indeed, it appears to me a difficult matter to adduce any examples of extensive plains of denudation whose origin is demonstrably marine and to whose planation subaerial agencies have not contributed the greater work. A region may be almost reduced to baselevel by subaerial denudation when the transgressing sea completes the work, extinguishing the adjusted valleys and introducing superposed streams in the next cycle of denudation. A region well baseleveled under the air may by quick depression suffer rapid ingression of the sea, whose shore waves will during depression nowhere reside long enough to perform a significant amount of abrasion. When the region is thus submerged and stands again relatively quiet, the waste from a non-submerged area, gained both by marine and subaerial denudation, may be spread over the denuded and depressed plain, and when afterwards elevated with an unconformable cover that will induce superposed drainage, all trace of former adjustments will be lost; yet here the planation was not marine. A district of superposed drainage in central New Jersey, where the Amboy clays once spread over the red shales and sandstones of the Trias, may probably be taken as an example of this kind. Superposed rivers cannot, therefore, always be taken to prove that the uplands which they dissect are uplifted plains whose denudation was chiefly performed by the sea.

Regions of essentially horizontal structure normally have wandering streams; no systematic arrangement of drainage is here to be expected. Discrimination in such regions has seldom been attempted between examples of one cycle of subaerial denudation, now adolescent or mature, and examples of two cycles, the first having reached old age and the second now being in its adolescence or maturity. The sky-line would be smooth and even in examples of either class: in the first, because its original constructional form was a plain; in the second, because it was planed down essentially smooth at the close of the cycle preceding the current cycle. It is, however, sometimes possible in regions of horizontal structure to recognize the records of old age reached in a former cycle by a slight discordance between the general upland surface and the attitude of the strata; or by the association of the region with an adjacent region of tilted structure where indications of an earlier cycle of subaerial denudation are manifest, both these tests being applicable in the Allegheny plateau; or by the arrangement of the faint residual relief of the uplands, where not trenched by young or adolescent streams, this test having been applied in the Piedmont district of Virginia, in the Ozark plateau of Missouri, and in the Great plains of eastern Montana. Further study of many other examples is desirable.