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STUDIES FOR STUDENTS

RELATIVE GEOLOGICAL IMPORTANCE OF CONTINENTAL, LITTORAL, AND MARINE SEDIMENTATION

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JOSEPH BARRELL

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ADVANCE SUMMARY

The purpose of the following articles is to give a proportionate view as to the relative geological importance of continental, littoral, and marine deposits, and to discuss the use of some criteria for separating them. This is in accordance with the movement which is now taking place from the preliminary qualitative state of geological science to a more balanced quantitative state. To this end, use has been made of the facts of observation concerning present

[1] ~~The contents of the three parts are outlined here~~. Parts II and III will appear in later numbers.

sedimentation already recorded in the geological literature of the past fifty years, rather than to new observations; and it is thought that a certain value will be attained by bringing together this widely scattered body of information. The references are frequently given to the most accessible source, rather than necessarily to the original statement of facts, frequently difficult of access and sometimes in foreign languages; but the effort has been, not to found arguments upon commonly quoted generalizations, but to go back to their sources, often largely lost sight of, and to examine from this starting-point the quantitative value of those generalizations. The ultimate conclusions will be found to be sometimes in accordance with, sometimes at variance with, views which have frequently been expressed in geological literature. The outline of the work is as follows:

The littoral zone is strictly limited to those portions of the shore lying between the average highest flood-tide and the average lowest ebb-tide of the month. Above this all deposits belong to the land surface, even though they may be in the form of low-lying deltas which perhaps once a year are flooded by the sea. Below the littoral zone all deposits belong to the general class of marine sediments, which may in turn be subdivided into estuarine, shallow open sea, and true deep sea.

It is pointed out that the sediments of the continental, littoral, and marine zones are accumulated under distinctive conditions which should frequently allow them, upon sufficient study, to be sharply separated. It is, moreover, concluded that, in comparison with continental and marine deposits, those of the littoral zone should form but a small fraction of the stratigraphic series, and that therefore, in the case of certain formations bearing marks of shallow-water origin and occasional exposure to the air, their frequent reference to an origin between tidal limits over the mud-flats of a shallow sea is inherently improbable, and should only be accepted where indubitably proven.

On the other hand, it is argued on inductive and deductive lines that an appreciable portion of the mechanical sediments incorporated into the geological record should have been made as subaërial delta deposits and therefore continental in nature, laid down in close association with the sea, and more or less interbedded with marine formations.

Besides these delta deposits, it appears that, taking the world as a whole, interior basin deposits, both of desert and pluvial climates, are now widely forming, frequently under favorable chances for preservation, and that such deposits should also occur to an appreciable extent in the geological record.[1]

Finally, it is concluded that the ratio of continental to marine sediments should have fluctuated widely through geological time. Following an epoch of continental uplift with mountain-making, the deposits formed in interior basins should attain a maximum, especially the deposits made under desert conditions. Accompanying this stage, piedmont alluvial deposits would be formed, largely temporary in character, since, upon the topography passing into the stages of maturity, they tend to be removed by the rivers which laid them down.

As the erosion verges toward maturity, subaërial delta-building, encroaching upon the shallow seas, would attain greater importance, since the amount of stream-dissection over the region of the headwaters increases; the streams, now being graded, carry the sediment through to the shores, and submerged continental platforms have had time to form. The greatest proportion of subaërial alluvial deposition should take place after epochs of mountain-making which have taken place without notable uplift of the continental platforms, as seems to have occurred several times during the Paleozoic. Since in that case a large portion of the river sediment is poured into more or less protected epicontinental seas, none of this portion reaches the deep ocean, and much of it forms a subaërial delta, since the seas are shallow and the wave-action weak.

Eventually, as the continent becomes topographically old, the mountain slopes become subdued, the burden of the rivers lessens and becomes more largely rock matter in solution. The rivers can no longer build out extensive deltas against the seas, and marine planation, aided by a slight elevation of the ocean surface, may cause

[1] While this article was being written, in December, 1905, a paper on "Torrential Deposits and the Origin of Sandstones and Conglomerates" was read by title to the Geological Society of America by Professor W. H. Hobbs, in which he argues for a much larger proportion of subaërial arenaceous deposits in ancient strata than has been recognized. This article the writer has not yet had the pleasure of reading. The recent volumes of Chamberlin and Salisbury, 1906, also place emphasis upon the importance of subaërial river deposits, especially in Cenozoic times.

the latter to widely transgress the base-leveled land. Therefore, in the topographic old age of a continent shallow-water marine deposits should attain a maximum.

This cycle of relations between continental and marine sedimentation is then applied to geological history, especially to the late Proterozoic and Paleozoic, and it is concluded from the general geographic relations of certain epochs, as understood at the present time, that notable subaërial deposits of river waste might be expected to occur within those particular epochs.

The preceding discussion prepares the ground for a second portion, concerned with the detailed consideration of the significance of mud-cracks in association with other features, as indicating the continental and alluvial nature of certain deposits. Since mud-cracks also occur in littoral deposits, the necessity for the preceding quantitative study is seen. It is concluded that, next to coal-beds formed *in situ* or an abundance of land fossils belonging to the animal kingdom; in association with certain other easily recognized features mud-cracks form one of the surest indications of the continental origin of argillaceous deposits. The structure is also seen to most commonly originate under climatic conditions where the other tests are apt to fail. It is not contended that mud-cracked littoral deposits may not also form, but it would appear that they should be relatively rare.

This conclusion stands in opposition to the interpretation given to mud-cracks in the standard textbooks, where they are ascribed to the drying of tidal flats and regarded as evidences of shallow seas; the flood-plain origin, if noticed at all, being given second place.

On account of this divergence from the prevailing interpretation, attention is called to the desirability of confirming or modifying the present conclusion.

Finally, the criteria developed as to the significance of mud-cracks are applied in detail to the Belt terrane of Montana and the Unkar and Chuar terranes of the Grand Canyon, both of late Proterozoic age. This furnishes an example of the use of the criteria, and at the same time draws conclusions in regard to the origin of these formations, which in general are barren of both animal and plant fossils, and therefore lack the usual guides for arriving at their origin.

It is concluded that the Belt gives an illustration of two sedimentary cycles, each of which contains a strongly marked formation of mud-cracked red shales, the shales alternating with sandy strata, and both judged to have been deposited on the flood-plains of rivers whose deltas had gained over the subsidence, finally filling up and displacing the shallow epicontinental sea. The cycle is thus seen, not only to pass from arenaceous and argillaceous to calcareous formations and back again, but to pass from land to sea, and back again to land, the latter transition being marked, not by a plane of unconformity, but by subaërial river aggradation. Ancient land surfaces are not to be recognized alone by the work of erosion, but may be surfaces of sedimentation, and resemble in this respect the work more usually done within the domain of the sea.

In the Grand Canyon region it is concluded that at least a large part of the Unkar terrane, with its 6,830 feet of strata, was built up by subaërial aggradation as the delta plain of a large river exposed to a climate characterized by frequent seasons of desiccation alternating with seasons of flood. Thus the detailed examination of these late Proterozoic terranes confirms by largely independent reasoning the general expectation arrived at in the earlier part: notable amounts of continental deposits being here found collected in geosynclinal basins formed within the continental platforms during this area of wide land extension. The agreement of conclusions from the geographic and stratigraphic lines of approach is felt to strengthen the degree of probability that in these instances the indications as to origin have been correctly interpreted.

INTRODUCTION

As pointed out by Walther in 1893,[1] although all geologists are familiar with the occasional extensive deposition of land-waste upon the land as among the results of geological activities at the present time, yet the prevalence of erosion on the land and of sedimentation beneath the sea has governed the interpretation of nearly all ancient sedimentary deposits. It has ordinarily been accepted as a geological principle that ancient continental surfaces are only determined by unconformities, while, on the other hand, all sediments, unless obviously deposited by fresh waters as proved by their organic contents, are

[1] *Einleitung in die Geologie*, pp. 719, 720.

taken as indications of the presence of ancient seas. Numerous instances illustrating this tendency could be cited from the writings of the leaders of the science, but a single illustration will suffice. In 1893 Bailey Willis contributed a most valuable article to the *Journal of Geology*, entitled "Studies for Students: Conditions of Sedimentary Deposition." It is because of the originality and value of this writer's numerous geological articles in general, and of this one in particular, that it is chosen for illustration. In this article sedimentation is defined as follows: "Sedimentation consists of three sub-processes—sorting, distribution, and deposition. These are effected by waves and undertow, tides, winds, and oceanic currents."[2]

While lacustrine deposits could be included under this definition, it leaves no place for fluviatile sedimentation, and of course does not pretend to include sorting, distribution, and deposition by the wind. While it would hardly have been within the limits of this one article to have treated fully of these land deposits, yet it is noticeable that in the introductory pages no mention is made of them, and sedimentation is repeatedly referred to as pertaining to the sea, rock disintegration and decomposition to the land, while the streams are mentioned as the carrying agents which sweep the sediment to the sea.[3]

In the above-mentioned article the subject of marine sedimentation is ably treated, especially noteworthy being the dependence indicated between the relation of the sediments upon both the activities of the ocean and the topographic character of the land. The present article aims to treat of some of the general relations of marine and continental sedimentation, and to partially indicate how these relations may be expected to fluctuate with the extent, topography, and climate of the continental masses. It may be considered, therefore, as supplementary to the above-mentioned article on the conditions of marine sedimentary deposition.

As showing exceptions to this tendency to neglect the deposits formed upon the land must be noted the work of the geologists of the Indian survey for the past thirty years, and that of other geologists who have been most familiar with the Tertiary and Recent deposits within the interiors of Asia and America.

While the importance of land deposits has, during the past decade,

[1] Vol. I, pp. 476–520. [2] *Loc. cit.*, p. 480. [3] *Ibid.*, p. 480.

become more fully appreciated, it is nevertheless true that the greater part of the sediments comes to rest beneath the sea. Yet the fact that in the past the possibility of other modes of origin has not been sufficiently held in mind, throws doubt, in the opinion of some geologists, upon the interpretation of certain ancient formations consisting of unfossiliferous sandstones and shales.

Further, in regard to those deposits which are universally conceded to be of fresh-water origin, it has formerly been unconsciously assumed, without adequate proof, that the deposits were laid down in permanent bodies of standing water, and hence were lacustrine rather than fluviatile or æolian. To illustrate the important consequences flowing from such an interpretation, it may be mentioned that in all of the older American literature it was always confidently stated, without discussion of other possibilities, that the Tertiary was characterized in the Rocky Mountain region and over the Great Plains by enormous fresh-water lakes, larger than any in existence in the world today. Within a few years this view has been vigorously combated, and Matthew, W. D. Johnson, Haworth, Davis, and Hatcher have shown that the greater number of the Tertiary formations are better interpreted as the deposits of aggrading rivers wandering over broad flood-plains.

In view of the several modes of origin which are possible for shales, sandstones, and conglomerates, and the variable interpretations which have been sometimes given for a single formation, the writer, in that part of a lecture course upon advanced structural and dynamical geology which deals with sedimentary structures and their origins, has been accustomed for the past two years *first, to discuss the conditions of formation of sedimentary deposits*, as they are observed to occur at the present day in various continents and under various climatic conditions; *second, to compare the relative areal and volumetric importance* of the several kinds of deposits forming at the present time; *third, to discuss the probable changes in the relative importance* which may be expected to have occurred in the earlier ages, owing to such general movements of continental uplift and subsidence, mountain making, climatic change, etc., as are generally recognized to have characterized and individualized the preceding ages; *fourth, to give the detailed distinctions in composition, texture, and structure* by which the several kinds of deposits may be distinguished according to their mode of origin; and, *lastly, to apply the foregoing principles to a few examples*, in order to illustrate their use, and to interpret the geography and climate of preceding ages.

In order to bring together the facts for such a discussion, it is only necessary to search the abundant literature of the past fifty years; but the writer has found no single article which presents the subject in quite this way, or arrives by this method at the conclusions to which he has come in regard to the relative importance of certain classes of deposits and their distinctive features. It has seemed worth while, therefore, to arrange portions of this in form for publication, omitting much which is necessary for class work, but which can be found ably developed in various books and articles, and enlarging on other portions which are not so fully discussed elsewhere.

For this presentation it seems best to give, first, an inductive discussion of the relative importance of continental, littoral, and marine deposits, as observed under process of present or recent formation, and to follow this by an abstract and deductive discussion as to the chances for the preserval in general of these several classes of deposits; and, finally, to close with another deductive argument as to the varying relative importance through geological time. This latter discussion should, however, be kept free from positive statements of opinion upon individual formations, in regard to which there may be doubt or difference of opinion; the purpose of the article being accomplished in merely opening the question as to what kinds of deposits should be expected to predominate, from the premises of our present ideas in regard to the geography and climate of past geological times. It would be suitable for a later article, however, to discuss in detail certain distinctive chemical, textural, and structural features characteristic of the several kinds of deposits, and to apply these to individual formations, thus confirming or disproving by an inductive process the preceding general conclusions arrived at by deductive reasoning. Only by a combination and confirmation of these two methods can safe conclusions be arrived at in interpreting the fragmentary remains of the results of unseen and now vanished processes.

Either inductive or deductive methods used by themselves are always liable to error, since we can seldom be sure that man has apprehended all of the essential factors which lead to a result. This is especially true of geological science, where the field of the unknown is so great, and where, for example, the past few years have brought forth facts in regard to Cambrian and Permian glaciation which have overthrown previous confident deductions in regard to the nature of Paleozoic climates. Deductive conclusions, especially, therefore, until confirmed by detailed study, should be offered as suggestive, rather than conclusive; to be tested by investigation before being finally accepted; but on that account they are none the less valuable.

The following article must therefore, as previously stated, be divided into two portions: first, an inductive study from observed facts as to the general relations of land, seashore, and marine sedimentation; and, second, the deductive application of the relation of these to the topographic cycle and to previous time. The last is to be taken as true only in a broad way, and with many possible exceptions; as suggestive rather than final.

THE IMPORTANCE OF CORRECT INTERPRETATION

Stratified deposits may be laid down either upon the land, beneath the sea, or in that transition zone known as the littoral, which by the ebb and flow of tides belongs alternately to the sea and the land. It is of fundamental importance in stratigraphic geology that land and sea deposits should be sharply distinguished from each other, as may be seen from the consequences which follow in attempting to outline the ancient geographies. On the one hand, if the formation is considered marine, it implies a submerged attitude to the land, a spread of ocean waters, a home suitable for the development of marine faunas, a barrier between lands—separating into distinct provinces the neighboring terrestrial faunas. On the other hand, if the formation is considered to be of terrestrial origin, precisely the opposite conditions are implied, the region now excluding the life of the ocean and serving for the support of land-dwelling types, and possibly offering means of communication between otherwise separated lands. The third alternative is to consider the deposits as transitional and belonging to the littoral zone, in which case the life is predominantly related to the sea, though invaded between tides by life from the land.

As oceanic, transitional, or continental, the region must be represented upon maps of the period; and thus in any restoration of the relation of land and sea of past times the paleogeographer is called upon to commit himself as to the origin of the deposit, with all of its far-reaching implications.

Even if the formation is considered as originating upon a continental surface, the problem of interpretation is not ended; for several alternatives remain to be considered: whether the deposit has accumulated within the confines of lakes, or has been laid down under humid climates upon aggrading river plains, or washed upon arid plains by intermittent floods, or, finally, accumulated by the action of the desert wind as loess or dune sand. To extend the illustration previously mentioned: Under the view that the Tertiary accumulations of the Great Plains and Rocky Mountain region in general were made in enormous fresh-water lakes, the Great Plains must have acquired later their tilted character, implying a more recent westward uplift of some thousands of feet. The mountainous plateau has consequently often been regarded as at that time low-lying and the climate moist. Under the contrary view, that the deposits are largely fluviatile or Æolian, the region may, however, be regarded as having been as greatly elevated and tilted then as now, and the climate on the whole as always semi-arid.

THE CLASSIFICATION OF CONTINENTAL, LITTORAL, AND MARINE DEPOSITS

The term "continental," as used by Penck and Walther, applies to all deposits upon the land, whether made by talus, creepage, by rivers, by lakes, or by the wind. The fact that they are made upon the visible surface of the continents and can show no relation to the sea is the only bond of union among these otherwise unrelated deposits. Each is marked by a certain assemblage of characteristics, which cannot be given in detail here, the most certain being the presence of fossils of an abundant fresh-water or land life, and an absence of marine. Where the deposit is unfossiliferous, there may frequently be doubt as to its continental or marine origin.

To marine or estuarine deposits belong all formations deposited in the ocean, or its outlying portions, below the level of the average of the lowest tides. Within this area, covering about three-fourths of the earth's surface are laid down a great variety of deposits, varying from the oozes of the oceanic depths to the muds of protected bays or of epicontinental seas, and the sands and gravels which front the beaches facing the more or less open seas. It is only in regard to the detrital shallow-water deposits that serious doubt as to their origin is liable to arise, and it is only these, therefore, which need to be considered in the present connection.

Where salt or brackish water fossils occur in abundance, a possible continental origin is eliminated, and there will be expected also species which do not live within the zone of the littoral, thus proving the absence of a littoral origin. Where fossils are absent, the more uniform and widespread character of the deposit, the color, and other features, summed up by Walther,[1] may settle definitely the marine origin of an ancient deposit. The marine deposits are, however, as thoroughly characterized by the absence of most of those features which mark continental and littoral deposits, as by their own distinguishing features. Chief among these may be mentioned the absolute absence of mud-cracks, rain-prints, and the foot-prints of terrestrial animals.

To the littoral division belong, strictly speaking, only those deposits which are laid down between the limits of high and low tide. The term is frequently, however, rather broadly used as relating to the neighborhood of the shore. Thus one may encounter expressions in regard to dune sands of the littoral belt or conglomerate deposits as indicative of the littoral; yet dunes are entirely beyond the limits of the tides, and gravels may be laid down at some distance from the actual beach. The littoral zone, with its deposits, is regarded by Walther as related most closely to the land; but this is a view upon which a difference of opinion may be justly held, and the majority of geologists would doubtless decide that its affinities were rather with the sea.

For present purposes it will be necessary to define the littoral zone more exactly, and to sharply restrict its limits. It may, consequently, be considered as the zone embraced between the *average* of the *highest* flood and the *average* of the *lowest* ebb tides of the month. This means that, on the average, the highest portions of the littoral

[1] *Einleitung in die Geologie*, III. Theil, "Lithogenesis der Gegenwart."

zone will normally be flooded by sea water once every two weeks, while storms and extra high tides may flood still higher portions at longer intervals. The mechanical deposits of the littoral zone are apt to be extremely variable in nature, and the individual beds more limited in area than is the case either upon the land or under the sea. Muds rich in organic matter, and of irregular distribution and thickness, are the common deposits of lagoons; sands and gravels will be deposited in tidal channels and as off-shore bars, the strata showing current marks and cross-bedding. Cleanly sorted sands, gravel, shingle, and sometimes bowlders will mark the face of the outer beach.

The littoral zone is characterized, in common with land deposits, by ripple-marks, mud-cracks, rain-prints, foot-prints, and fossils of land animals and plants; in common with neighboring marine or estuarine deposits, by ripple-marks and brackish or salt-water fossils. As distinctive shore marks held in common by the littoral zone and the margins of lakes are wave-marks, rill-marks, and the shelving nature of the beach.

ORIGIN OF TENDENCY TO CLASSIFY LITTORAL AND FLOOD-PLAIN DEPOSITS AS MARINE

Although the littoral zone is seen to have a number of distinctive marks which separate at least the upper half of its limits from the marine area, it is regarded in the great bulk of geological literature as merely a border portion of the sea, and its deposits, except where beach structure is shown, are commonly thought of as marine deposits made in shallow water, and ordinarily at no great distance from the land. Mud-cracks, rain-prints, and foot-prints are frequently cited as evidence of mud-flats exposed at low tide and bordering the sea.

This close alliance of the littoral zone with the marine might be unimportant, were it not that the majority of the criteria which are relied upon as determining the presence of the littoral zone apply equally well to flood-plain deposits made upon the land at any distance from the sea. Furthermore, in periods of vigorous erosion river deltas may completely fill up shallow seas and receive large amounts of river sediments upon their upper surfaces; then by a slackening of erosion or an increase in subsidence, may frequently become submerged. In such a way river deposits bearing these features common to the littoral zone may occur between truly marine formations. Thus, *first*, the perception of the principle that erosion dominates the land and sedimentation is largely restricted to the sea; *second*, the fact that in Europe and eastern America river aggradation is much less important that in many other regions; *third*, the confusion of littoral and flood-plain deposits ; and, *fourth*, the grouping of littoral with marine formations, render it probable that in the past certain unfossiliferous river deposits have been misinterpreted as marine or estuarine.

It is intended to show that the area of the zone of true littoral deposits is always a small fraction of the area of shallow-water marine deposits, and usually but a small fraction of the area of various forms of land deposition; that, furthermore, the chances for the preserval of littoral deposits is slight in comparison with those of either marine or continental origin, and consequently that, unless an ancient formation is clearly of littoral origin, it is more likely to be either marine or continental. For that reason it will be necessary to discuss the relative areas of deposition of the three classes of deposits, the characteristics which they hold in common, some of their distinctive features, and especially their relative chances for preserval.

THE REGIONS OF CONTINENTAL SEDIMENTATION

Formations made upon the land may be classified under several divisions, as follows:

Desert deposits.—Typically where the evaporation exceeds the precipitation and no outflowing drainage results.

Piedmont river deposits.—Built up by rivers or shallow lakes upon the foreland plains or piedmont belt fronting high mountain ranges.

Basin deposits of pluvial climates.—The deposits laid down by rivers or in lakes in down-warped basins, such as those of the Great Lakes, situated in continental interiors, but not necessarily associated with mountains. If a large river, laden with sediment, flows across such a region, a lake condition can hardly arise, but, on the contrary, a broad river plain is more likely to be found, constantly built up as subsidence takes place.

Subaërial delta deposits.—Where powerful and sediment-laden rivers meet the sea, especially if the latter is shallow and protected from tides and storms, a delta is rapidly developed, a considerable portion of which is a land surface reclaimed by the river from the sea.

GEOLOGICAL IMPORTANCE OF DESERT DEPOSITS

To consider the areas occupied by each of the above divisions, it is to be noted that the arid regions at present cover about 11,500,000 square miles; that is to say, at the present time over one-fifth of the land of the world has no outlet for drainage to the sea.[1] Within these regions extensive sedimentation goes forward, the waste of the mountains filling interior basins, either by wash from the mountain slopes, by streams which sink within their subaërial deltas, or which may flow into shallow interior seas. By far the greater portion of the waste is laid down by rivers, owing to the vanishing of the water into the dry air and the porous soil. At such places the streams flow in channels, but not in valleys, and in time of flood spread in a thin sheet of water for miles over the desert plains. Instances of this nature has been noted by Davis in Turkestan,[2] and by McGee in the Sonoran desert.[3] In Australia large temporary lakes are formed during the wet season, which during the seasons of drought become arid and burning deserts.[4] At irregular intervals, sometimes extending over several years, the most arid portions of the interior will for a few days assume the appearance of a boundless, though shallow, inland sea.[5] The conditions are thus of rather widespread occurrence in desert regions for the formation of stream deposits, current-marks, and mud-cracks associated with river flood-plains and broad, level, sandy tracts and playas—features possessed in common with deltas of arid climates and the mud-flats of the littoral.

In topographic youth torrential deposits near the mountains, and finer alluvium in the central portions, may accumulate to great depths in the interior basins. In maturity the waste is more widespread, though over much of the region more shallow in depth, while in old

[1] Dr. John Murray, "Origin and Character of the Sahara," *Science*, Vol. XVI (1890), p. 106.

[2] *Explorations in Turkestan*, p. 54 (Monograph, Carnegie Institution, 1905).

[3] "Sheet Flood Erosion," *Bulletin of the Geological Society of America*, Vol. VIII (1897), p. 87.

[4] E. A. Petherick, Mill's *International Geography*, p. 615.

[5] C. H. Barton, Mill's *International Geography*, p. 580.

age, as Passarge has shown, a thin layer of sandy or gravelly waste[1] is almost universal.

Besides these features, chiefly made or modified by the work of water, it is well known that wind transportation plays an important part in desert erosion and deposition. Immense stony wastes, as the belt of the Sierran Hamada, may in this way have all soil removed, the finer dust being carried to great distances and ultimately out of the desert region, the sand being swept in the form of dunes over great areas of country; the dunes themselves, frequently hundreds of feet in height, being but the upper, wind-tossed portion of a deep deposit of sand. From the study of the surface of arid regions it would seem that a conservative estimate would arrive at the conclusion that at least one-half of the desert areas, and consequently one-tenth of the land surface of the world, is covered with more or less important deposits of recent desert accumulations, only a small portion of which are characterized by salt and gypsum. In interpreting desert conditions from the sedimentary record of previous ages, redness of formations, indicating subaërial oxidation, and roundness of sand grains, as indicating æolian action, and other features, are sometimes used; the presence of salt and gypsum is, however, the only characteristic which is determined at a glance and considered as a positive indication of an arid climate, and the only feature which is commonly used. But from the small proportion of present desert areas which are characterized by these deposits, and the great amount of land surface which is now desert, it would seem that the problem of ancient desert deposits should enter much more largely into geological history than is usually appreciated.

PIEDMONT RIVER DEPOSITS

Piedmont river deposits are built up in front of young and lofty mountain regions removed from the sea, by torrential rivers, which on escaping from the mountains are loaded with waste which they are unable to carry across the gentler slopes of the plains. As a region where such work is actively in progress at the present time may be cited the Pampas of northern Argentina. An early and excellent account of this region is given by John Miers, writing in 1825, who,

[1] Review by W. M. Davis in *Science*, N. S., Vol. XXI (1905), pp. 825–28.

although not a professional geologist or geographer, made many acute observations. His most significant statements in regard to the present topic may be quoted as follows:

The rivers which flow from the Cordillera proceed only from the melting of the winter's snow, and bring down with them an amazing quantity of fine alluvial mud. In their long passage through the mountains, and for some distance after leaving them, the descent is so rapid that the great quantity of matter held in suspension cannot subside. The Tunuyan, for instance, even as far as Coro Corto, has as much mud in it as can be suspended in agitated water. This is the case with the water supplying Mendoza, which none of the people can drink without either filtering, or placing it for a long time in a state of quiescence; so surcharged is it that they are obliged every day or two to clean out their irrigating channels, which would otherwise be filled with fine sand. If we take into consideration the nature of the country to the southward, its long and almost imperceptible descent towards the ocean, the immense bulk of alluvial matter that must yearly be brought from the Cordillera, and which must somewhere deposit itself,—we cannot but conclude that the rivers which may once have flowed in deep and uninterrupted channels to the ocean, must, from such causes, have had their beds raised in progress of time to the level of the surrounding country: the continual shifting of their courses over level plains; the constant accumulation of muddy detritus, must have effected the gradual disappearance of navigable or continuous streams, and produced that series of swamps, and the kind of country, which, according to the most credible accounts, exists throughout the vast Pampa territory.[1]

In the case of rivers which run through to the sea this process of deposition comes to an end when they have built up this portion of their courses to the necessary grade, unless a geosynclinal warping takes place in front of, and in line with, the neighboring geanticline; in which case the rivers may still continue to build up an extensive plain with a slope of from 1 to 10, or even 30, feet per mile. This process will be favored when the area of the plain is deficient in rainfall, as is the case with the high plains of the United States and Argentina; since under such climatic conditions there is no added volume of river water to assist in carrying through to the sea the detritus obtained from the mountains. The same effect may take place, however, where the climate of the plains is humid, provided that the lessening of the grade is not fully compensated for by the added volume of waters.

[1] *Travels in Chile and La Plata*, by John Miers, in two volumes (London, 1826; C. Baldwin, printer), Vol. I, p. 113.

This is illustrated by the recent or subrecent alluvial deposits of the Ganges, fronting the Himalayas for nearly 1,000 miles, and maintaining a breadth of from 100 to 200 miles. The most western portion of this plain, as well as the confluent plain of the Indus, receives near the Himalayas between 10 and 30 inches of rain per year, and is relatively dry; but the greater portion of the piedmont Gangetic plain receives between 30 and 50 inches per year. In some ways, however, this plain is not a good illustration, since it graduates insensibly into the delta and is restrained by the plateau area to the south. In no place does it reach 1,000 feet above the sea, the highest elevation recorded being 924 feet above the sea on the low alluvial divide between the Ganges and the Indus.[1]

The Ganges system at the present time is probably eroding more than depositing, but must have built up the river-plain in the past. Nearly the whole area, however, of the Brahmaputra valley, in Assam, a region of heavy rainfall, is occupied by the newer alluvial deposits, and hence must be in the process of piedmont valley-building.[2] Similar important deposits of river conglomerates, sands, and clays of Oligocene, Miocene, and Pliocene age are found on the northern slopes of the Pyrenees and Alps, where the climate was presumably as humid as at present, but the intercalation of marine strata among these indicate a low-lying condition and a proximity to the sea, so that the sediments are probably as much of the nature of delta deposits as of piedmont slopes of waste.

In estimating the areal extent and importance of such piedmont waste slopes of continental interiors, it is to be noted that their extent in the western United States, in Argentina, and in India may be taken as roughly equal in area to that portion of the lofty mountain region from which they come. Such deposits would, of course, be ultimately eroded in a later stage of the same topographic cycle which witnessed their production, were it not that downward warping in front of a mountain axis is a not uncommon incident, allowing a progressive accumulation of waste, and protecting the lower portions from ultimate erosion until some reversal of the geological activities occurs. Owing to such downward warping before the later upturn-

[1] Medlicott and Blanford, *Geology of India* (1897), p. 391.

[2] *Ibid.*, p. 396; Mill's *International Geography*, p. 475.

ing, some 14,000 feet of river deposits were laid down in the Siwalik formation of the Upper Tertiary in the northwest Punjab.[1] In searching the past for similar deposits, from the nature of their origin they need be looked for only upon the ancient mountain forelands, and only after periods of orogenic revolution.

BASIN DEPOSITS OF PLUVIAL CLIMATES

The basins of the Great Lakes may be taken as good examples of down-warping in continental interiors. Formerly regarded by many as largely owing their origin to ice-erosion, they are rather looked upon at the present time as chiefly due to crustal warping, somewhat accentuated and scoured clean by the Pleistocene glaciation. Their recency, and the fact that no rivers laden with detritus from mountain regions flow into them, cause them to be still unfilled and their basin nature to be clearly apparent. It would seem that such basins are not unique, but are rather constant features of the continental platforms. In times of diminished land surfaces and lessened erosion these may be connected with the oceans and exist as epicontinental seas. In times of wider continental extension and increased erosion they are likely, if shallow, to soon become completely filled with sediment, after which rivers will flow through them on their way to the sea. In this event only a geological study of the region may demonstrate the basin-like structure of the underlying basement.

Perhaps the most conspicious examples of interior continental basins receiving large quantities of river sediments at the present time are to be found in South America. The Brazilian plateau, like an island, is surrounded on all sides by a wide lowland, at no place more than 650 feet above the level of the sea. The headwaters of the Paraguay and the Guapore, the latter one of the southernmost tributaries of the Amazon, with hardly 4 miles between them, are often covered by the same floods.[2] The greater portions of the great river valleys of South America are underlaid by Tertiary deposits, and the superficial formations are of recent origin.[3] This is indicated by any good map, where it is seen that the central basin of the Amazon possesses braided rivers, lagoons, and unexplored distributaries connecting

[1] Geikie, *Text Book of Geology*, 4th Ed., p. 1297.

[2] J. Batalha-Reis, Mill's *International Geography*, pp. 865, 866.

[3] *Ibid.*, p. 867.

them, the whole, from the geographic descriptions, constituting a more or less perpetually flooded and impenetrable tropical forest jungle. This great basin is largely shut in on the east by the uplands of Guiana and Brazil.

A similar physiographic condition is graphically described by Mr. H. H. Smith as characterizing the headwaters of both the Madeira and the Paraguay.[1] These streams in their upper portions flow through more or less separate and inclosed basins. The upper Paraguay rises 30 feet annually. All the flat lands above the Fecho dos Morros to Villa Maria—over 400 miles in a direct line—are subject to river floods, and these are deepest toward the north. The width of the flood-plain at the mouth of the Sao Lourenço can hardly be less than 150 miles from the rocky lands on the east to the base of the Serra dos Dourados. The whole region is a labyrinth of lakes, ponds, swamps, channels, and islands in a grassy plain, the only forest being near the river. Even at low water one-fourth of it is flooded; when the river is at its highest, the whole plain is a vast lake, covered with floating grass and weeds.

The South American instances illustrate most fully the manner in which large interior basins may be filled with river sediments. Usually the process of aggradation is not so striking and rapid. Where the down-warping is of minor importance, as in the central plain of Hungary, fertile and habitable plains may occur. Where the down-sinking of the crust has been deep and far more rapid than the infilling by the rivers, large interior seas may result.

Europe is largely surrounded, and separated from the other continents, by a series of such interior basins, but the dividing bridges are so low that they let in the ocean waters, and on the southern side all but the Caspian and Black Seas are united into the Mediterranean. Of these basins the upper Adriatic, the Ægean, and the Black Seas have witnessed great changes since the Tertiary, and Suess[2] regards the formation of the Ægean and Black Seas as even post-glacial. Previously to this recent down-sinking, fresh-water deposits were formed over the site of the Ægean, and still remain on certain islands in the

[1] J. B. Hatcher, "Origin of the Oligocene and Miocene Deposits of the Great Plains," *Proceedings of the American Philosophical Society*, Vol. XLI (1902), No. 169.

[2] *Das Antlitz der Erde*, Eng. trans., Vol. I, pp. 344, 345; also Plate V, opp. p. 463.

sea. The ability of large rivers to maintain land surfaces over sinking areas may be illustrated by taking a hypothetical case. Choosing Lake Superior, since it is the largest body of fresh water in the world, and the Mississippi-Missouri river system as a type of the greater rivers of the globe flowing from regions of rapid erosion, it may be computed how long it would take the Mississippi to fill the Lake Superior basin with sediment. Taking the annual discharge of the Mississippi, according to Humphrey and Abbot, as a mass of sediment sufficient to cover one square mile 268 feet deep, and again taking the area of Lake Superior as 32,000 square miles, and the average depth, derived from the contours of the bottom, as 550 feet, it may be readily computed that the Mississippi would fill up the basin in approximately 66,000 years. Therefore, if such a basin should originate in the path of a great river bearing a quantity of sediment equal to that of the Mississippi, it would only show at the surface during its subsidence as a somewhat swampy alluvial plain, without a distinct lacustrine stage, unless the movement of subsidence was irregular or the entire depression originated in less than 66,000 years. It is not probable that the majority of epicontinental basins originate as rapidly as this, indicating the conclusion that in periods of high land relief and rapid erosion river deposits, rather than those of lacustrine or marine origin, may be expected to fill the down-warpings within continental areas, and to a lesser extent those which are marginal. On the other hand, Forshey has computed that it would take the Mississippi 11,000,000 years to fill the Gulf of Mexico with sediment, providing that the bottom did not sink under the load; and this points the contrast between the relatively small and shallow epicontinental basins and the true oceanic gulfs or mediterranean seas.

In conclusion, it is seen, then, that interior basins may be divided into two classes, the shallow and the deep. The former, if within the reach of important rivers, may be maintained as a continual land surface, the basin nature being not conspicuous; the latter will more usually form true mediterranean seas. Basins of these two classes occupy appreciable portions of the present continental surfaces, and doubtless have frequently been as important in the past. The shallow warpings still belong to the continental platforms, and their deposits, either fluviatile, lacustrine, or marine, are frequently exposed by erosion; but it is doubtful to what extent such deep downbreakings as those of the mediterranean basins are ever restored to the surface of the land, and their deeper deposits consequently opened to observation, the most favorable chance being where the region becomes involved in a later mountain revolution. Whether or not the deposits of the shallow basins are continental or marine will depend upon the vigor of stream-erosion, the rapidity of subsidence, the breadth and height of the surrounding lands, and nearness or distance from the sea. As epeirogenic and orogenic movements have been intermittent and variable in nature, the continental or marine infillings of such basins will thus have varied largely through geological time.

DELTA DEPOSITS

A delta may be divided into two chief portions, one of which, above the water, forms a low land surface, usually fertile and densely inhabited; another portion being deposited beneath the sea, and building forward the front of the delta. As is well known, borings in the Mississippi, Ganges, and Po deltas have revealed fresh-water fossils and beds of vegetable matter at some hundreds of feet beneath the present level of the sea. Such facts have led to the view that large delta surfaces are frequently regions of subsidence, and that they may be maintained above the sea-level by the continual deposit of river material. Thus it is seen that delta formations are divided into portions which are continental, littoral, and marine.

The possibly subaërial delta origin of certain ancient formations has been long since suggested; to cite a single instance, as far back as 1886, Bonney, in his presidential address before the British Association, concludes that the English Bunter is probably a subaërial delta formation, analogous to the Siwalik deposits of India.[1] Notwithstanding such instances, however, it will probably be admitted by most that, in interpreting the mechanical deposits of previous ages, especially where these are thick, barren, and suggestive of discharge at the mouths of large rivers, usually no adequate discussion has been given as to the possible intermingling of subaërial and submarine portions. The section at one place may represent wholly the land-surface deposits; at another, the wholly off-shore zone; and at still

[1] *Report of the British Association for the Advancement of Science*, 1886, p. 618.

another, an intercalation of subaërial and submarine strata. As an illustration may be cited discussions regarding the Neopaleozoic deposits of the eastern United States. The interpretation has usually been that of river sediments distributed over the bottom of a shallow interior sea, in which subsidence took place *pari passu* with sedimentation, so that occasionally mud-flats or marshes became exposed; but subaërial delta surfaces are hardly considered, and the region is held to have been essentially a permanent sea, so long as sediments of the time were formed.

Of course, where marine fossils occur, there is no question of the presence of ocean waters, and, on the other hand, at times of coal-formation there is no question as to the presence of a delta swamp; but in regard to the great volume of more or less completely unfossiliferous detrital deposits the interpretation has usually been one of marine origin, without an adequate consideration of a possibly subaërial delta nature; and this sometimes in spite of the fact that mollusca are found whose habitat seems indicative of non-marine waters, as, for instance, Amnigenia of the Upper Devonian.

The deposits of the present, as Walther has noted, are studied in horizontal plan; the deposits of the past are studied in section. It is to indicate from present delta-building the vertical relations which are to be expected in ancient deposits between the continental, littoral, and marine portions of the delta, that a considerable discussion seems necessary.

RELATION OF DELTAS TO REGIONS OF SUBSIDENCE

The ratio of these three portions to be anticipated in the stratigraphic record will depend largely upon the conception of the part which subsidence of delta regions plays, as a usual, or merely an occasional, accompaniment of the process of delta-building. As facts bearing upon the question, may be cited the presence of fresh-water deposits within a number of the present larger delta regions at levels beneath the surface of the sea. Again, periodical flooding of the delta surface is evidence of land deposition going forward at the present time, while rivers intrenched, and never overflowing the plains formerly built up by their agency, are evidence that aggradation has ceased, or even that degradation has begun. Taking a general view of river characteristics, it is seen that at least in North America piedmont slopes of alluvial waste are now frequently undergoing dissection, but that the great delta regions, such as those of the Mississippi and the Colorado, are receiving annual accessions of fresh-water deposits. In many cases, especially on the eastern coast, subsidence has been so recent that the rivers have only begun the work of filling their embayed valleys, and notable deltas have not yet been constructed. On the whole, however, the work at the river mouths stands in contrast to that of their middle and upper courses. Extending the view to the greater rivers of the world, it would seem to be a safe conclusion that, as a rule, they are building up their flood-plains, even if not encroaching upon the sea.

The problem next following is whether this is due to a local stationary attitude, or even subsidence of the delta regions, or to an average general stationary attitude or subsidence of the lands as a whole. In answer to this general problem there appears to be no unanimity of opinion. The continental margins frequently show drowned coastal shelves cut across by river gorges, but this is no indication as to the character of present movements. In Andrée's *Hand-Atlas*, p. 4 (Leipzig, 1904), movements of elevation are indicated as taking place at the present time at many places along the shores of all continents, while movements of depression are indicated only along the eastern coast of North America, the coasts of France and the Netherlands, the eastern shore of the Adriatic, the delta regions of the Nile and Amazon, and more than half of the oceanic islands. While there are undoubted errors of detail in this map, it may be assumed as a first hypothesis that the general result is true, and that the continents at the present time are in a general stage of upward movement; or, perhaps speaking more correctly, the oceans, by the subsidence of their basins, are receding from the lands.

If this conclusion be true, the subsidence of regions of sedimentation at the present time is probably less conspicuous than in the average of past time, since it is only where the local downward movement is more pronounced than the general regional upward movement of the lands that actual subsidence would result.

Turning from induction to deduction, subsidence of deltas as distinct from the surrounding regions is to be anticipated only where the load of sediment is sufficient to lead to isostatic readjustment, or where the river debouches into a natural geosyncline. That such subsidence was common in ancient geosynclines is accepted on the evidence of shallow-water formations accumulated to a thickness of many thousand feet, and whether the formation was made slightly below or above the water surface would apparently have but little influence upon the movement of subsidence. Again, in periods of quiet the erosion of the lands, as Chamberlin has shown, would tend to lift the level of the sea and lead to an apparent subsidence of all delta regions to the extent of some hundreds of feet from this cause alone. Further, the drainage of the continents is, in general, away from the geanticlinal regions and toward the geosynclinal areas. The land-waste is carried in both directions from the geanticline across the stationary tracts, with the exception of those receiving piedmont deposits, and is thrown down by the river in crossing some region of subsidence, or upon meeting the ocean upon the continental shelf or at the margin of the continental platforms. Usually the waste from at least one side of the geanticline must be carried a considerable distance before passing beyond the limits of the continental platform, and the chances are frequently good for deposition before reaching that limit.

Where a geosyncline or epicontinental sea is encountered, the sediment will accordingly be concentrated; and even if the load of waste should not have any influence in leading to isostatic down-sinking, these areas would still be characterized as the great catchment basins of sediment deposited upon the continental platforms; the most favorable situation being that illustrated by the Great Valley of California, where a trough exists between mountain ranges, and the waste naturally gravitates into it; the least favorable being found in such isolated basins as those of the Great Lakes, far removed from any considerable mountain range. There is therefore frequently, but not necessarily a sympathetic relation between regions of subsidence and the discharge of great rivers, with their load of sediment.

From these lines of reasoning it may be accepted that the portions of the continental platforms occupied by the mouths of the larger rivers have frequently been through past time regions of subsidence, with consequent river aggradation; but the strongest evidence for this conclusion is not obtained so much from the nature of present movements as from the evidence of the upturned and eroded strata themselves, deposited as the geosynclinal axes sank.

Where there is no subsidence, as is to be expected in the case of the smaller deltas, the subaërial character is readily maintained and extended as a result of delta-building, but the subaërial deposits cannot extend below the water level. Where subsidence accompanies sedimentation, however, the subaërial character of the delta tends to be destroyed; but if the river is able to build its plain upward as fast as the downward movement takes place, the subaërial deposits may reach to any depth. In the larger deltas which have been tapped by boreholes this appears to be the case.

FACTORS GOVERNING DELTA LAND SURFACES

The strata of a delta have been classified into the bottom-set, foreset, and topset beds;[1] the first consisting of fine material deposited from suspension on the bottom of the sea beyond the main portion of the delta, the foreset beds comprising the steeply inclined portion consisting of slightly coarser detritus, and the flat topset beds being the result of the aggradation work of the river, building up its stream to grade as the front of the delta advances farther outward, or as the whole slowly subsides. The topset beds are largely of subaërial origin, though the delta is fronted for a short distance by a shallow submerged platform, across which the detritus is carried to deeper water. Of these three portions, the foreset beds usually comprise the greater *volume* of the deposits, but the thinner bottomset and topset spread over the greater area.

The ratio of the submerged to the emerged portions of the topset beds depends upon a number of factors. A rapid subsidence may carry the whole beneath the sea, but *where subsidence is slower than upbuilding*, the proportion of the topset surface which is submerged will depend upon the balance of power between the waves, tides, and currents on the one hand, and the constructive work of the river on the other.

The depth of water over the submerged portion of the delta also depends upon the strength of the waves. Thus, an inspection of maps

[1] Chamberlin and Salisbury, *Geology*, Vol. I, p. 191.

possessing bathymetric contours shows that the Amazon, facing the open ocean, and subject both to wave-erosion and tidal scour, has a submerged delta which for 200 kilometers is less than 20 meters beneath the surface of the sea, while the aërial portions belong rather to the flood-plain, since they do not extend eastward beyond the adjacent margins of the continent. On the contrary, in the case of the Nile, the Danube, the Po, and the Mississippi, flowing into relatively quiet and tideless seas, practically all the foreset beds are above water, and thus the greater part of the *area* of the river delta, neglecting the attenuated bottomset beds, is a region of subaërial—that is, of continental—sedimentation.

According to Forshey

more than two-thirds of the Mississippi delta in the ordinary state of the river are above water. . . . . But if the river were unrestrained by levees, the highest floods would fill the alluvial basin and make a sea 600 miles long, 60 miles in mean width, and 12½ feet in mean depth.[1]

As another illustration,

the delta of the Hoang Ho (Yellow River) extends along the coast from near Peking, on the north beyond the Pei Ho, to Hung-tse Lake on the south, where it joins the plains of the Yang-tse-Kiang. The distance is 400 miles, but the mountainous province of Shan-Tung is to be excluded. From the coast the delta extends westward for 300 miles. The river is here useless for navigation. The whole delta region would be under water during flood seasons except for drainage by artificial canals and dikes of great length.[2]

Under natural conditions every flood would, by the settling of mud or sand from the broad flood-waters, contribute to the upbuilding of the delta plain; as, for example, the statue of Rameses II at Memphis has been buried in about 9 feet of river deposit in somewhat over 3,000 years. The interference of man has, however, doubtless here changed the natural rate.

The geological importance of this aggradational work of rivers over their deltas is obvious. During periods of rapid subaërial denudation an appreciable volume of the sediments removed from the interior of the land should be laid down, not beneath the sea, but as a land surface facing and encroaching upon the salt waters. Such a character of river deposition would be at a maximum in a shallow

[1] J. D. Dana, *Manual of Geology*, p. 197; quoted from C. G. Forshey, 1873.

[2] *Ibid.*, p. 198.

epicontinental sea, protected more or less effectually from ocean currents and possibly from tides; a sea which for that reason would be unable to cut away the rapidly forming deposits of the encroaching delta. Such a sea existed over much of the northeastern portion of the United States during much of the Neopaleozoic times. Within this basin of sedimentation former shallow-water conditions are indicated in certain formations by mud-cracks and supplemented by ripple-marks, cross-bedding, and inconstancy of arenaceous strata. This must signify that the upbuilding power of the ancient rivers was, on the whole, equal to or in excess of the progressive subsidence of the basin. There is not likely to be long maintained an exact balance between the two, and hence in general it may be said that such structural feeatures indicate a capacity in river-building to more than compensate for the progressive subsidence of the geosyncline. But, having granted this excess of sedimentary power, it is seen that, especially in the protected bays, the surface of deposition should be very largely a land surface; occasionally flooded, as a result of the rainy seasons, by the fresh waters from the land; occasionally flooded over the seaward portions during combinations of storms and high tides by the waters of the sea.

Diagrams illustrating the relations of foreset and topset beds under ideal conditions are given in Figs. 1 and 2. In Fig. 1 a delta is supposed to be built out into a quiet lake with constant water-level. The thicknesses perpendicular to the planes of stratification of the foreset and topset beds will vary approximately with the angle of dip of each. The ratio of volumes will depend upon the area multiplied by the thickness, and although the topset beds under these conditions may not be more than one-tenth as thick as the foreset beds, their area in a large delta, especially in a shallow sea, may be ten times that of the latter, so that the volumes of sediments deposited above and below the sea may be of the same order of magnitude. In Fig. 2 a *subsiding* delta is supposed to be built upward and outward, with just such speed that the front of the delta is maintained at a constant line. In this hypothetical case the gradient of the delta would be less than in the first case, the currents more sluggish, the delta more frequently flooded, and a greater proportion of the waste would be dropped upon the topset surface. Under such conditions the topset beds might equal or exceed in thickness the foreset beds. Where the area of the delta becomes as great as was the case of the Carboniferous coal swamps of the eastern United States, the resulting volume of land deposits may far outweigh the volume of the foreset beds building the delta front.

At first thought it might be supposed that over a subsiding delta region the only effect would be an encroachment of the sea, without

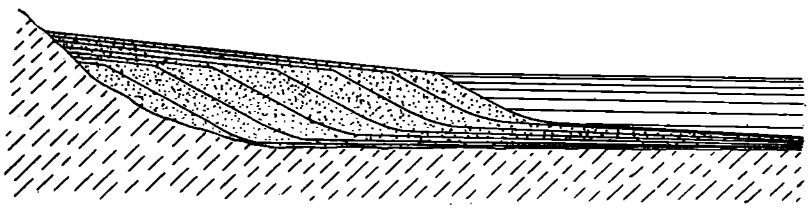

FIG. 1.—Ideal section of delta built out into quiet water of constant level.

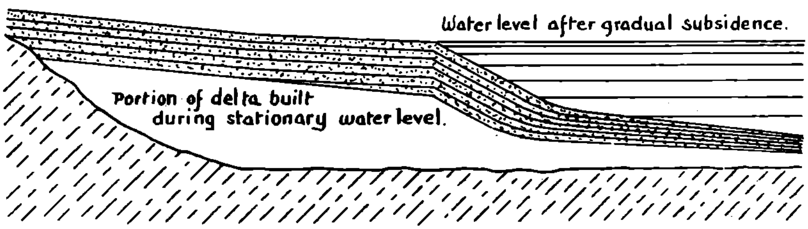

FIG. 2.—Ideal section of delta built out into quiet water when subsidence just balances deposition, resulting in a stationary shore-line.

changing the slope of the delta surface, diminishing the subaërial portion without increasing the rate of river deposition upon it. When a dam is thrown across a stream, however, and the water-level artificially raised, the gradient is flattened, and the stream made more sluggish for some distance upstream at levels higher than the upper edge of the dam. Where similar elevations of the water-level occur through natural causes, it is presumed, therefore, that the effect would result in an enlargement of the zone of fresh-water morass and increased river deposit, as well as a tendency to restrict the margin of the delta.

It is probable that many deltas reach a point beyond which they advance but slowly. This occurs in those fronting large bodies of water, and exposed to heavy tides and storms. For example, Tremenheere has shown that detritus from the Indus is swept northwestward along the coast beyond the limits of the delta by the winds of the southwest monsoon.[1] The monsoon winds of the Arabian Sea are reversed during the year, with a resulting reversal of ocean currents; and this exposure of the delta front to the alternating and powerful waves, tides, and currents is doubtless the cause of the fact, made known by Murray, that terrigenous deposits extend 800 miles from the mouth of of the Indus and cover an area of more than 700,000 square miles.[2]

Under such circumstances the materials which in a quiet sea would contribute to make the foreset beds and advance the delta must be largely swept along shore and out to sea, contributing to widespread bottomset beds.

Excluding these widespread portions from the delta proper, it is seen that under these conditions the topset beds of subaërial origin, while not contributing a larger volume than before, may form a larger ratio of the entire delta deposit. On the other hand, as the delta advances into deeper and open water, a larger amount of material is deposited beneath the surface on the delta front, in order to build it out; and this also would cause the delta to advance more slowly, but diminish the ratio of the land-formed deposits. When a delta has reached a stationary limit, it is only possible for superficial deposits to be deposited through subsidence; but as this appears to be not unusual to such areas at the present time, it is also to be expected in the past.

The diagrams, furthermore, indicate that the ratio of subaërial to marine deposits in an advancing, but not subsiding, delta depends for one factor upon the relative gradient of the topset to the foreset beds. The gradient depends upon a number of factors which cannot be fully discussed here, but it may be mentioned that a river carries the greater amount of its burden in times of flood, and that those are the times when it also overspreads its flood-plain. From the broad and shallow flood waters much material is thrown down, more being

[1] "On the Lower Portion of the River Indus," *Journal of the Geographical Society*, Vol. XXXVII (1867), p. 77.

[2] "Marine Deposits in the Indian, Southern, and Antarctic Oceans," *Scottish Geographical Magazine*, Vol. V, No. 8 (August, 1889), p. 420.

deposited the shallower the waters, since the bottom velocity becomes less for the same surface gradient.[1] A broad delta, unrestrained by valley walls, unless these valley walls themselves furnish sediment, is therefore advantageous for surface deposition. The same may be said of deltas covered with vegetation, since Lyell long since pointed out from observations on the Mississippi delta the effectiveness with which vegetation entangles the sediment of flood waters. Coarseness and abundance of material, signifying rapid erosion at the headwaters of a river, are likewise favorable for subaërial deposition on a steeper gradient.

Summing up the foregoing discussion, it may be said that moderate subsidence, originally shallow and quiet seas, broad and long delta areas, and the presence of not far-distant mountain uplifts are all favorable to a large proportion of subaërial delta deposition. In addition, periodical floods over an arid delta region, and dense vegetation over a humid one, work to the same end.

While there is probably not sufficient data at hand to give quantitative expression to these statements, and indeed they must vary for every example, it may still give definiteness to thought to attempt to express in figures the ratios for the several classes of delta deposits. James Ferguson, quoting F. Prestage, states that in 1861 careful simultaneous experiments were made as to the quantity of solid particles held in suspension in the waters of the Matabangah (one of the distributaries of the Ganges): first on leaving the Ganges, where it was found to be 1 in 294 parts; while nearly at its junction with the Hoogly the quantity was 1 in 884, proving that two-thirds had been deposited *en route* in that short distance of not much over 50 miles in a straight line, though much longer by the meandering river.

In answer to the question as to how much of the entire Ganges alluvium is deposited upon the delta, and how much is carried to sea, Ferguson points out that during the cold weather, when the rivers are low, almost all of their silt will be carried to sea; but then the quantity of water is small, and that little comparatively clear. At the height of the inundation, when the river is overflowing its banks, at least one-half is deposited inland.[2] It is also pointed out that up to

[1] J. J. Rèvy, *Hydraulics of Great Rivers* (London, 1874), p. 147.

[2] "On Recent Changes on the Delta of the Ganges," *Quarterly Journal of the Geological Society*, Vol. XIX (1863), pp. 350, 351.

early in the eighteenth century the Brahmapootra joined the Ganges some 60 miles above the present junction, and that for a century later the Brahmapootra probably deposited nearly all its load of sediment in filling up the shallow back-water lakes across which its new course was taken. These lakes and swamps, having been bridged over by the date of writing, Ferguson was of the opinion that the delta face would be built outward with comparative rapidity in the place where it was then deficient.[1]

Thus the ratio of land and marine deposition is variable even on the same delta, with the season and in longer cycles. From various descriptions, however, the present writer would, as his impression, estimate that possibly in the case of large rivers from 30 to 50 per cent. of the material reaching the sea is sufficiently fine to be borne beyond the steep delta front, deposited as widespread blue muds, and forming the bottomset beds. These are largely spread at the present time beyond the limits of the continental platforms, and, where deposited at equal depths during preceding periods, have not entered to that proportion into the structure of the present continental surfaces, but still largely lie beneath the sea. Of the remaining 70 to 50 per cent., possibly from two-thirds to three-fourths has been deposited beneath the water, and from one-third to one-fourth as topset beds laid down upon the land. It is unnecessary to repeat that no value must be attached to these estimates. At any one time, however, the *area* of the land-formed portion is a much greater ratio the discrepancy between area and volume being due to the fact that the subaërial beds are thinner, and a given thickness requires a longer time to form.

In closing the topic, the problem of the unfossiliferous nature of many ancient deposits apparently well suited for the preservation of fossils may be mentioned.

It may be questioned as to why, if certain formations were deposited largely upon land surfaces, those surfaces were not overgrown by vegetation, preserved as carbonaceous deposits. To this it may be answered that other factors, such as climate, enter into such a problem, and that it may equally well be asked: How is it, if these strata belong to the littoral or the shallow sea, that fossils common to those zones

[1] *Loc. cit.*, pp. 332, 333.

of life are not present throughout? Here again various factors enter external to the present subject, which cannot be discussed without too much digression. It may be said in closing, that the absence of fossils leaves the origin of the formation in doubt, and that an unfossiliferous formation may have originated either on the land or beneath the sea. Certain structural criteria which may frequently throw light upon this question will be discussed in a following part.

SUBMARINE TOPSET DELTA DEPOSITS

In connection with the discussion upon the subaërial part of the delta, some mention has necessarily been made of the submerged part of the same, but more especially the steeply inclined foreset beds. Under the present head it is intended to discuss particularly the shallow, submerged portion of the delta in some detail, in order to show what relations it holds under various conditions throughout the world to the emerged portions of the same.

Relation of Waves and Nature of Deposit.—The proportion of the topset delta surface above and below water will depend upon several factors. Two of the more prominent are the rapidity of the

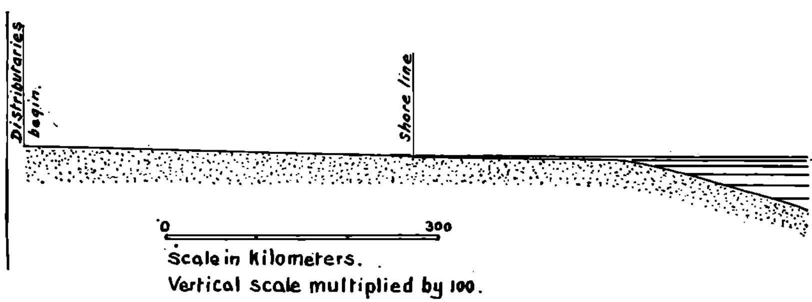

FIG. 4.—Profile. Delta of the Volga in the Caspian Sea.

deposit and its coarseness on the one hand, and the power of the waves on the other. The maximum of land topset beds may therefore be seen in such instances as Lakes Geneva and Constance, but especially the former, where the gritty sediment of rapid and loaded streams is confined closely between valley walls and discharged into the relatively quiet waters of a lake. The fact that practically all the upper surface of the delta is a land surface in the case of Lake Geneva is shown by the section (Fig. 3) plotted from the bathymetric contours shown in Andrée's *Hand atlas.*

Turning to deltas which show a greater or less frontal submergence, the submerged portions are observed to lie either within or without the outer limit of the general coast-line, as determined by the off-shore reefs. Such important shallow submarine delta platforms lie in front of and completely beyond the limits of the land in the case of the great Chinese rivers and the Amazon. In these instances the development of the submerged delta surface may be due in part to the fineness of the river deposit, allowing the sediment to be largely flooded out to sea in the fresh river water, as it spreads over the salt water below. On the other hand, the waves, tides, and currents are important and aid in cutting back the land surface by marine planation, the land material being swept by the undertow to seaward into the gradually deepening water. Thus in any particular case a certain equilibrium tends to be maintained between the continental and marine portions of the delta surface—an equilibrium which is especially liable, however, to be temporarily destroyed by irregular movements of subsidence or upheaval, since a small vertical movement will transfer the beach-line a long horizontal distance across the almost level surface.

Effect of Variable Point of Discharge.—In the above instances the delta surface is sharply divided into a land and water portion, and the littoral zone is at a minimum.

In another class of cases, illustrated by the Mississippi delta and the combined deltas forming the Netherlands, the deltas inclose within their outer land limits considerable bodies of shallow water or brackish lagoons, as the Mississippi and Chandeleur Sounds, and the Zuider Zee. In these cases it is observed that a large amount of sediment is discharged at one or two separated points over an extended delta coast-line, building out the delta at those places. The waves, drifting the material laterally, throw up barrier beaches, and shut off more or less completely large bodies of water, which thus lie within the front limits of the land delta. Usually it is only a matter of a few centuries at the most until the river abandons its built-out mouths and turns into the intermediate lagoons, as the Mississippi has been known to do near New Orleans, breaking through its levees in times of flood and pouring into Lake Pontchartrain. Such a course would possibly before this have become permanent, had the river not been restrained by artificial means. Even in these cases, however, of land-protected sounds and lagoons, it is to be noted that the area of mud-flats exposed between tides is much less than the areas permanently covered by lagoon waters.

A river possessing a broad land delta, and shifting across it periodically, will thus build up a delta formation whose seaward portions will embrace an alternation of marine or lacustrine and fluviatile deposits. Farther inland the deposits will be entirely fluviatile.

Effect of Variable Water-Level.—Another condition which must normally modify the relations of land and sea in delta-building is that of changing level, resulting either from those variations in the water-level to which inland seas are peculiarly liable, or from irregular vertical movements, usually of subsidence, such as are known to be characteristic of regions undergoing sedimentation.

Interior seas.—The case of inland seas is illustrated by the delta of the Volga, shown in cross-section in Fig. 4, and which may be

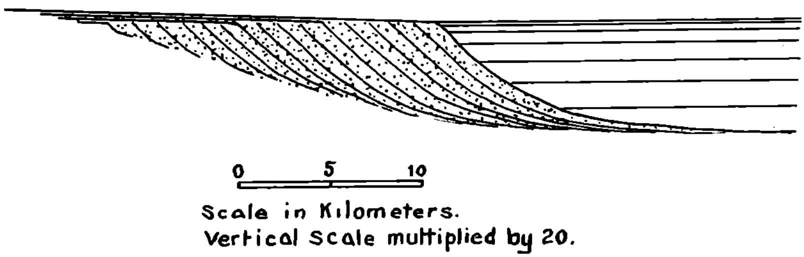

FIG. 3—Profile. Delta of the Rhone in Lake Geneva.

contrasted with Fig. 3. A good map shows that the entire northern portion of the Caspian Sea, lying chiefly east of the line of the section, is but from 1 to 11 meters deep. Such an extended shelf to an inland sea facing two large rivers cannot reasonably be ascribed to wave planation of the river deltas, nor, on comparing this shelf with other deltas, can it be supposed that waves in the absence of tides and currents could have transported the land-waste to such a distance from the river mouths.

It seems certain, then, that the present submerged shelf was developed as a land surface, and presumably by river-building rather than by river erosion. In confirmation of a former lower level of the Caspian Sea, Walther quotes the record of a boring on the shore of the Caspian southeast of Krasnovodsk, in which dune sands were found to a depth of 35 meters;[1] and more recently Davis has noted the evidence of a low-water epoch between the Tertiary and Quaternary periods of Caspian expansion, as indicated by the stream-eroded character of the present shores at Baku, which must have endured for a much longer measure of time than that of the Quaternary high-water stage and the present mid-water stage taken together.[2] Davis does not correlate the low-water stage with the development of the present submerged shelf, but unless crustal warping has materially disturbed the relations, it would seem a not unnatural correlation.

Not only are interior seas thus liable to long periods of expansion and diminution, resulting in an alternation of fluvial and lacustrine deposits, but cycles of shorter period, though enduring for centuries, may be superimposed. Thus Huntington has recently presented the evidence for a working hypothesis that the Lake of Sistan has passed through at least ten fluvial epochs during the Quarternary era;[3] the fluvial epochs being marked by widespreading floods over temporary playas, leaving pink beds of clays and very fine silts, often passing into layers of fine brown sand. The lake stages are marked, on the contrary, by white or, more exactly, greenish clays, and form but a small portion of the thickness in the exposed sections. In this alternation of fluvial and lacustrine deposits the former comprise the bulk of the mechanical sediments, the latter the bulk of the fossils.

By seasonal changes in the water-level of interior seas there is an especial liability to the development of a broad intermediate zone, corresponding to that of the littoral bordering the open sea, and characterized by variegated shales showing mud-cracks, rain-prints, and ripple-marks. Thus in ancient interior basin deposits there may be shore relations indicated by the nature of the strata which might

[1] "Das Oxusproblem in historischer und geologischer Beleuchtung," *Petrographische Mitteilungen*, Vol. XLIV (1898), p. 211.

[2] *Explorations in Turkestan*, Carnegie Institution (1905), p. 25.

[3] *The Basin of Eastern Persia and Sistan*, Carnegie Institution (1905), Plate X. and p. 291.

readily be mistaken for those of an epicontinental sea in tidal connection with the ocean. As distinguishing features it may be noted that in the former case the subaqueous shore deposits take place continuously for months. The periods of exposure likewise endure for months, and the prolonged desiccation gives a maximum opportunity for the formation of mud-cracks and the hardening of rain-prints or foot-prints. This hardening is favorable to their preservation, as Lyell has shown, since the record is not readily washed out by the returning waters, which bring with them another layer of sediment, by which the record is buried and indefinitely preserved.[1]

The shores of the epicontinental sea, on the contrary, if open to the tides, are subject to two daily inundations, and the chances for the formation and preserval of mud-cracks is at a minimum, except at the highest limits of tidal flooding.

Variable water-level—marine deltas.—To consider the effects of irregular vertical movements upon deltas facing the ocean waters, it is to be noted that the change is due to movements of the land rather than of the sea. Of land movements the nature of subsidences is more difficult to observe than that of elevations. In the latter, successive beach-lines carved along coasts, successive development of partial peneplains, and the actual observations of uplifts, as those noted during the nineteenth century along the coast of Chili, all give testimony to the largely intermittent character of upheaval. But in regard to subsidences also, observations have been made. These are sometimes slow, and for a time at least equable, as that affecting the present eastern coast of the United States, at other times subsiding at unequal rates, as indicated by the halt during the past century of the subsidence of the deltas of the Rhine and the Meuse, compared with the occasionally disastrous inroads made during the previous millennium.[2] Again at times districts suddenly subside during earthquakes. Such movements must tend to occasionally flood considerable portions of the delta surfaces of large rivers with sea water, which will stand over the regions perhaps for centuries or millenniums before it is again reclaimed by delta-rebuilding.

Perhaps the most striking instance is to be found in the Runn of

[1] *Quarterly Journal of the Geological Society of London,* Vol. VII (1851), p. 239.

[2] A. de Lapparant, *Traité de géologie,* 4th ed., pp. 570, 572.

Cutch on the southern portion of the delta of the Indus, a brief account of which is given by Suess[1] after Cunningham, Wynne, and Burnes.

The Indus, at least since 680 A.D., has delivered the most of its water along the western side of its delta. On the extreme eastern side walled off from the sea by the hilly island of Cutch, is found the Runn of Cutch, a salt desert, estimated to comprise about 10,000 square miles in area. The great Chinese traveler Hwen Tsang, who visited it in the year 641 A. D., describes the district even at that time as low-lying and damp, and the ground as filled with salt. This immense plain of the Runn is covered, during a southwest monsoon from Lakhpat, with salt water; during the floods of the Indus with fresh water, conveyed by the channels of the Banas or the Luni; at other times it is dry, and is then strewn with great patches of salt of dazzling whiteness.

This region was visited in 1819 by a violent earthquake and a low mound called the Allah Bund, or "mound of God," was raised across the northern side. Wynne and Suess, however, in contradistinction to Burnes and Lyell, consider that the real movement was one of subsidence of the Runn, as indicated by the fact that eight years after the earthquake the Indus burst its banks in upper Sind, flowed across the Allah Bund, which thus offered no obstacle to its progress, and spread over the Runn of Cutch.

Without attempting to sharply discriminate between variable delta-building and variable subsidence in this disputed case, it remains as the most striking instance of how, for more than a thousand years, portions of a delta surface the major part of which is land may be covered by the sea. Here the alternation of fresh- and salt-water floods with seasons of aridity is not representative of pluvial climates, but depends upon, *first*, the small rainfall of the region; *second*, the southwest monsoon which raises the sea-level slightly during one season; and, *third*, the river floods produced by a period of rains in distant mountains.

Under more usual circumstances the reach of the ocean waters, which now spread periodically over the Runn, would doubtless be greatly diminished, since in the course of the six hours between high

[1] *Das Antlitz der Erde*, Eng. trans., Vol. I, pp 40–47.

and low tide the water could flow but a limited distance over tidal flats, and in a more pluvial climate much of the region would doubtless be covered with fresh-water lakes and lagoons. Both salt and fresh water, by wave - and current-action, would tend to differentiate the water from the land. This conclusion is in conformity with what is observed upon deltas facing the sea, the delta being normally divided into a land surface occasionally covered by river floods and a subaqueous portion perennially covered by the sea water, the two being separated by a relatively subordinate littoral zone.

CONCLUSIONS ON GENERAL NATURE OF DELTA DEPOSITS

A review of the deltas of the world at the present time shows that, as a rule, the shallow basins marginal to the continents are filled with alluvial deposits, except in regions where the submergence or warping is very recent, as in the case of the Baltic Sea and Hudson's Bay, or where tidal scour tends to maintain an open estuary.

The deltas of the larger rivers, where they have had a reasonable geological time to form, customarily end in deep water beyond the general limits of the coast-line.

But the present is a time of continental extension and mountain-building, though the late Tertiary was still more striking in this respect. Therefore it may be reasonably concluded that at times of similar topographic character in past geological history such epicontinental seas as remained became, as a rule, largely filled, and usually rather rapidly, by delta deposits, and shallow seas would thus give way to alluvial plains. Even in times of partial continental submergence, however, as in the upper Devonian and the Carboniferous, the mountain-building then present would be expected by the accompanying erosion to have given rise to extensive subaërial delta deposits, which could, however, have only occupied the landward portions of the broad epicontinental seas. Under such circumstances the preceding discussion has indicated that the beach might be a shifting line, usually fluctuating about a certain limit, but sometimes transgressing the alluvial delta plain, or again moving a shorter distance seaward. The strata, as seen in vertical section, would be, under these assumed conditions, to a considerable extent land deposits in the region of thick sedimentation, largely marine where they thinned out on the seaward side. The two kinds of formation would be intimately interfingered at the contact—an interfingering which might extend for tens, or occasionally for hundreds, of miles.

The distinction, however, which it is wished to emphasize here is that these deposits would be chiefly either land or marine, and only subordinately littoral. The broad exposure of the land surface is not a matter of between tides. Limited districts, as the Runn of Cutch, might be regularly inundated by sea water during a certain portion of the year, and other districts might be occasionally covered by great storms; but more usually changes over considerable border districts from land to sea would be a matter of centuries at least. In interpreting such deposits, mud-cracks, rain-prints, foot-prints need not necessarily, nor even usually, indicate exposures of tidal mud-flats, as is usually assumed,[1] but may equally well be interpreted as records of a subaërial delta surface, regularly flooded by river inundations or occasionally by the sea. Again, an occasional intercalation of strata holding marine or estuarine fossils in a great series of mechanical sediments is not evidence in itself that the entire formation is marine or estuarine. On the other hand, an occasional occurrence of fresh-water strata in an unfossiliferous formation is not evidence in itself that the entire series is of continental origin.

In times when the lands are topographically old, it is to be anticipated that land surfaces upon delta deposits will be at a minimum since marine planation will not have been lessened in power; while, on the other hand, the ability of the rivers to build out against the seas, or to build up whenever subsidences occur, will have greatly diminished.

CONCLUSION ON PRESENT CONTINENTAL SEDIMENTATION

It has been shown in the preceding pages that important continental deposits either now in process of formation, or so recently made as still to exist as superficial formations, cover an appreciable portion of the continents.

Of these the interior formations of arid climates have been roughly estimated to cover a tenth of the land surface of the globe, the pied-

[1] The question of the origin and preserval of mud-cracks made on tidal flats is considered later.

mont waste slopes of several continents to cover an area of the same order of magnitude as that of the great mountains from which they come. Interior basins of pluvial climates are seen to be largely filled by fluviatile deposits; again, where the land meets the sea sediment is deposited as deltas, forming fluviatile deposits with bottoms far below the level of the sea. These have been observed to be of varying importance in different continents, and no estimate of their aggregate areal extent has been given. Still, it would seem to be in the neighborhood of the truth to place the subaërial deposits of piedmont waste, of continental basins, and of deltas as covering a tenth of the emerged continental surfaces. Adding this to the estimate of the deposits of arid climates would give a fifth of the land surface as mantled by continental formations. From the generalized profile showing the relative areas of the earth's crust at different heights given by Penck,[1] and also by Gilbert,[2] from Murray's figures it is seen that one-fifth of the land surface is elevated more than 1,200 meters above the sea. The more elevated portions of the crust suffer, *on the whole*, the most severe and rapid erosion. Consequently, a general idea of the localization and rapidity of erosion upon the land may be gained by stating that at present one-fifth is subject to extremely rapid erosion, one-fifth to rapid erosion, one-fifth to moderate erosion, one-fifth to slight erosion, and one-fifth, either now or in recent geological times, to sedimentation. Not all of the latter would be permanently preserved by the continued action of the forces which have led to their accumulation. Such superficial formations as those deposited upon slightly warped slopes previously graded, as the Lafayette formation of the eastern United States is presumed to be, or the thin deposits of ancient deserts, are especially liable to be destroyed, so that the geological record of former ages should show a far less proportion of thin and superficial land deposits. Basin deposits of either desert or pluvial climates and delta deposits possess, however, indefinite thickness, and the chances of indefinitely long preservation of at least the lower portions is nearly as good as in the case of the deposits upon the floors of epicontinental seas. As, however, changes in geological activities

[1] *Morphologie der Erdoberfläche*, Vol. I (1894), p. 136.

[2] "Continental Problems," *Bulletin of the Geological Society of America*, Vol. IV (1892), p. 180.

frequently take place by subsidence of land areas, even the highest of such land deposits stand a chance of preserval. Therefore others of a similar nature should be expected to occur buried in older portions of the geological record, but not so abundantly as those originally formed at lower levels. Continental deposits depend, however, so largely upon the climate and geography that their areal extent and importance must have varied largely through geological time.

STUDIES FOR STUDENTS[1]

RELATIVE GEOLOGICAL IMPORTANCE OF CONTINENTAL, LITTORAL, AND MARINE SEDIMENTATION

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PART II

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THE REGIONS OF MARINE SEDIMENTATION

For the present purpose it is unnecessary to consider the deep ocean deposits, or even the massive limestone formations, since the discussion centers on the comparison of the areal extent and importance of the detrital deposits upon the land and beneath the sea.

The investigations of the Challenger expedition[2] showed that the rubble, sand, and silt were practically limited to the upper 100 fathoms of the ocean bed, and that this corresponded rather closely with the limits of the continental shelves. At about this depth the bottom is in general rarely disturbed by the action of currents or waves. Except in bays, fjords, and inclosed seas where mud is met with in shallow water, it may be said that in general, fronting all

[1] Continued from p. 356.

[2] Murray, *Deep Sea Deposits*, p. 184.

open coasts, 100 fathoms is the average depth at which fine mud or ooze commences to form; but local exceptions may be noted. In general, the cleaner sands are restricted to a belt within 30 miles of shore, and the average limit of the blue muds is about 200 miles, though this varies greatly in different regions. The relation of these terrigenous to the true pelagic deposits is well brought out in Chart I, *Deep Sea Deposits*, Challenger Expedition. This area of marine deposits of land-waste is etimated to cover about one-seventh of the globe and to be equal to half the area of the continents, while the area within the 100-fathom line, which more immediately concerns the present subject, is estimated at 10,000,000 square miles, or about one-fifth of the continental areas.

The deposits of former ages corresponding to the shallower and deeper portions of the terrigenous zone may be distinguished by a number of textural and structural features. For instance, considering the conditions of present deposition, it is seen that the ancient equivalents of the present blue muds will be rather widely extended, uniform, massive, argillaceous deposits, usually slightly carbonaceous and grading into calcareous formations. They will be without cross-bedding and ripple-marks, since movements sufficient to form these would prevent the settling of muds. They may be distinguished from ancient estuarine muds by all these features, and especially the absence of frequent alternations of sand. It is doubtful, however, if the deeper portions of these blue muds have ever been elevated into land surfaces. On the other hand, the shallower belt of marine deposition will be marked by a sandy character of deposits, provided that the rocks of the land can furnish sand, by evidences of shifting current-action and by ripple-marks. A. R. Hunt has shown that the waves of storms may stir the sands of the bottom to a depth of 40 fathoms sufficiently to move gravel and injure living molluscs.[1]

The charts of the United States Coast and Geodetic Survey also show sand and comminuted shells to similar depths, from which it may be inferred that widespread arenaceous and unfossiliferous formations may be formed on the bottoms of shallow seas, and not necessarily in close proximity to the littoral zone.

[1] "On the Formation of Ripple Marks," *Proceedings of the Royal Society of London*, Vol. XXXIV (1882), p. 1.

Approaching the shore, the material of the shallow bottom becomes coarser and ends in the undertow slope of the beach. This is sometimes coarser than the material of the beach itself,[1] stones of a certain size being swept here by the undertow and only carried back to the beach by the heavier storms. It is to be concluded, therefore, that one of the most striking characteristics of ancient beach-action, a basal conglomerate, is hardly so much a mark of littoral deposition as of marginal marine deposition *bordering* the true littoral zone.

As river deposits of delta surfaces, on the one hand, tend to extend themselves both by building forward into the sea and by building backward over the land, so, on the other hand, marine deposits, as Chamberlin has pointed out, tend to extend themselves in both directions.[2] Toward the deep ocean basins the clays are swept and deposited near their brink, doubtless building out submarine deltas, as is suggested by the submarine platforms of the Caribbean Sea.[3] and by the hypsographic curve of the earth crust given by Penck.[4] In the opposite direction the waves are always at work upon the coast, and tend to cut the sea-cliff landward, except where the supply of material from the land is equal to that removed by the sea. As the wave-beaten material is rolled backward and forward, it is gradually reduced to a fineness where the undertow can sweep it away from the beach-action and allow it to finally settle at some little distance from the land. The result of these activities within the upper portions of the ocean is to cut back all headlands, to fill up recessions in the coast line, and to cut away all islands except where these have been thrown up as barrier beaches by the sea.

The rapidity with which the waves may cut into unconsolidated material has been frequently illustrated by the destruction of recent ash-cones, which in a few months or years have completely disappeared. Barrier beaches, the only form of islands tolerated by the sea, are thrown up where the waves drag and break in shallow

[1] Dana, *Manual of Geology*, p. 223.

[2] T. C. Chamberlin, "The Ulterior Basis of Time Divisions," *Journal of Geology*, Vol. VI (1898), p. 454.

[3] Bailey Willis, "Conditions of Sedimentary Deposition," *Journal of Geology*, Vol, I (1893), pp. 496, 497.

[4] *Morphologie der Erdoberfläche*, Vol. I (1894), p. 136.

water, and can attain any degree of permanence only where they face a gently shelving land mass.

The waves not only tend to unify and extend the shallow submarine platform, but tend to cut away its highest portions to a certain depth, dependent upon the power of the waves. Thus, by taking nautical charts it is observed that over any district where there is open water the bottom maintains a certain depth close up to the off-shore beach. Facing the open oceans this is usually from 30 to 40 feet, but in more protected places, such as Long Island Sound, it may be but 6 to 12 feet. Thus, up to the line of surf the submarine platform extends without any confusion with the littoral zone.

EXTENT AND CHARACTER OF THE LITTORAL ZONE

The littoral region, as has been shown, is rather sharply delimited from the marine by the trimming action of the sea, marked along a shelving shore by the line of barrier beaches. Where a bold land meets the sea, it is merely the lowest exposed portion of the sea-cliff. On the landward side, however, the littoral is not so regularly defined, but consists of irregular tidal lagoons consisting of three portions; the mud-flats, exposed at low tide, the salt marshes flooded only at high tide, and a rather abrupt transitional mud-slope between them. Both the mud-flats and tidal marshes are cut through by tidal channels, those on the marsh being characterized by meanders.

The littoral finds its greatest development in estuaries or where the land meets the sea in the form of a plain, either a base-plain of erosion, or a river plain of aggradation. The littoral does not show a tendency, like the two previous regions, to extend its limits, since the flood-tide tends to leave sediment upon the tidal marshes, building them up to the extreme tidal limit; and, on the other hand, the tidal scour of ebb-tide tends to remove sediment to the open sea. On the contrary, the forces of both land and sea tend to fill up and obliterate the littoral. On the one hand, the river deposits and the wash from the land creep out over the tidal flats, and, on the other, the sea, by wearing the beach deposits smaller and by removing the finer shore material outward to a greater depth, tends to push its beaches farther inland.

The littoral zone is partly maintained by the contest of the two forces—the rivers building out by irregular delta mouths, inclosing lagoons and providing new tidal marshes; the sea cutting off headlands and sweeping the material along the coast, forming spits which shut off new lagoon spaces.

The chief maintenance of the littoral belt is, however, due to vertical land movements, especially subsidence of a flat land surface, but one still showing slight relief. This may produce extensive estuaries, and the waves, by throwing up barrier beaches in shallow water at some distance from the land, may form a continuous series of lagoons and salt marshes, as is illustrated by the present condition of the seaward margin of the coastal plain of the eastern United States from Long Island southward. The questions of immediate importance in the present connection are those of the width and areal extent of the littoral zone and possible fluctuations in importance in past times, owing to the prevalence of conditions not now operative, such as absence of tides in ancient protected seas, or hypothetically greater oceanic tides due to a possibly greater nearness of the moon. It is first necessary to collect the facts for the argument, by observing the various shore conditions as they exist today. Arranging these with respect to the tidal range, a representative set is as follows, the information being taken largely from the charts of the United States Coast and Geodetic Survey:

OBSERVED RELATION OF TIDES TO THE LITTORAL ZONE

TIDE 1 TO 1.5 FEET (EXAM. MOBILE BAY AND MISSISSIPPI DELTA, GULF OF MEXICO; STORM TIDES THE ONLY IMPORTANT ONES)

Mud-flats at mean low tide, 0.1 to 0.25 mile wide in protected places.

Salt marshes.—Frequently absent. Around Mobile Bay a few up to 2 miles wide. On the delta of the Mississippi (General Chart No. 19) they average 27 miles in width, cut through by the fresh-water channels and showing a poorly developed system of channels for tidal drainage.

TIDE 2.5 FEET (EXAM. GARDINER'S ISLAND AND OYSTER PONDS)

Mud-flats few in number. At mean low tide 0.33 to 0.66 mile wide in protected places.

Salt marshes average 0.25 mile wide.

TIDE 4 TO 6 FEET (VICINITY OF NEW YORK AND NEW HAVEN)

Mud-flats from 0.16 to 0.33 mile wide, of limited development.

Salt marshes in protected inlets behind barrier beaches 0.5 to 1.0 mile wide.

Along river valleys, as north of Newark Bay, they extend some 3 miles from the open water, passing into the fresh-water marshes. Tidal channels fairly well developed upon marshes.

TIDE 7 FEET (SAVANNAH, GA., ENTRANCE TO SAVANNAH RIVER)

Mud-flats 0.33 to 0.66 mile wide. More commonly present than in previous examples.

Salt marshes filling up a former estuary, 4 to 5 miles wide, with a well-developed network of tidal channels ramifying through them.

TIDE 10 FEET (BOSTON HARBOR AND DELTA OF THE INDUS RIVER)

Mud-flats extensive. At Boston they average from 0.5 to 1.0 mile wide, but are cut up by tidal scour into smaller separated areas.

Salt marshes.—At Boston, filling up protected depressions, they average 0.25 to 0.75 mile wide. On the Indus delta a well-developed network of tidal channels, 2 to 4 fathoms deep, and distinct from the distributaries of the river, extends 17 miles from the coast, and this may be taken as the limit at which the salt-water tidal marsh gives place to the fresh-water swamp. Tide reaches 11 feet in spring tides.

TIDE 16 FEET (DELTA OF THE GANGES AND BRAHMAPOOTRA)

Mud-flats.—Extent not mentioned.

Salt marshes.—Extent indicated on the map by means of the tidal channels (see reference later). The fresh-water swamps of the delta are protected from the sea by a chain of sandy islands, separated from each other by tidal channels and known as the *Sunderbuns*, the name evidently signifying severed mounds. This chain of islands averages 58 miles wide, but only the outer half is markedly cut up by tidal channels. Therefore it seems probable that the present tidal flooding extends some 30 miles inland, and the inner portion may have been built at an earlier date. Tidal effects on rivers are of course felt much farther but do not flood wide stretches of their banks.

TIDE 40 TO 70 FEET (BAY OF FUNDY, BASIN OF MINAS)

Mud-flats.—Widest in protected heads of bays. In the basin of Minas, estimated by J. A. Bancroft to average 0.75 mile wide. Along sides of the bay the current of from 6 to 8 miles per hour keeps the channel deep and open, and the sides scoured clean.

Salt marshes.—Shaler speaks of the dominance of the mud-flats over the upper marshes, and the rapidity with which the latter are built up by sediment thrown down at flood-tide when obstructions are built across the tidal marshes. Lyell speaks of thousands of acres having been reclaimed in this way.

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Basin of Minas:

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N. S. Shaler, "Sea Coast Swamps of Eastern United States," *Sixth Annual Report* (1885), United States Geological Survey, p. 368.

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From the preceding facts a number of principles governing the development of the littoral zone may be drawn.

With lunar tides of less than 2.5 feet storm tides become of greater importance. The development of extensive mud-flats and salt marshes takes place in protected places. In exposed places the cutting action of the waves prevents either from forming. Mud-flats exposed at low tide become conspicuous with tides of about 6 feet range. When the tide is 10 feet, these may form belts a mile wide, but broken up by tidal channels. With higher tides there is but little tendency to increase the width of exposed flats, but the material constituting them may become coarser, the Gallegos River in Patagonia, where the tides reach 46 feet, showing lower flats composed of gravels and even of coarse bowlders.[1] With the larger tides the tidal channels for draining the tidal marshes are wide and deep, forming convenient protected passages for the larger vessels through silted-up estuaries or behind the barrier beaches.

The salt marshes are built up to near the upper limit of tidal flooding. Where storm tides are the most important the system of drainage of these marshes is very imperfect. With tidal range of from 4 to 6 feet this becomes developed, and with a range of from 10 to 16 feet they become rivers in size, capable of quickly leading an immense volume of water into the limits of the tidal area, but more important for quickly draining the tidal grounds during the ebb. The width of the salt marshes appears to be less dependent

[1] J. B. Hatcher, *Princeton Patagonian Expeditions*, Vol. I, Fig. 33, and p. 239.

upon the tidal rise than upon the greatness of the river and its delta which faces the tidal wave. This may be due to the great quantity of sediment furnished to the sea by the rivers, swept back by the tide and dropped at its flood, or to the subsidence which frequently characterizes such areas and which tends to drown the seaward end of the delta. Probably both causes contribute. This is illustrated by noting that on the Mississippi delta this width of marsh is 27 miles, while in Mobile Bay near by it is from nothing up to 2 miles. At Boston the marshes average less than a mile in width, while the Indus delta, with the same tidal range, shows them at least 17 miles wide. The delta of the Ganges in the presence of a tide of 16 feet is flooded by the tides for a distance of 30 miles, while in the Bay of Fundy and the Basin of the Minas the salt marshes average less than a mile in width.

The conclusion is geologically of some importance. The broad development of a littoral zone is largely independent of tidal influence, since, where the tides are small, oscillations of level through storms may develop it to practically the same width. The topographic character of the littoral zone, as indicated by dominance of mud-flats, size of tidal channels, etc., is, however, dependent upon the tidal range as one factor. Where the land is shelving, as along the eastern and southern coasts of the United States, the shore may be much broken with estuaries, but the land and the water are separated by a littoral, which, including both its upper and lower portions, does not average more than a mile in width. The littoral is therefore of insignificant area compared to the breadth of the coast plains on the one hand, and of the shallow sea on the other.

The littoral becomes broadest where a great quantity of sediment is poured into the sea by a great river and a contest ensues between the sea and the land. But in such places the river, if sufficiently powerful, builds out a land surface delta in the face of the storms and tides, while the undertow of the latter builds out another extensive platform, submerged in gradually deepening water, and ending where a depth is attained of from 50 to 100 fathoms. Even beyond this limit important quantities of the finer sediment are swept, forming occasionally bottom deposits from 200 to 800 miles from land.

It is seen, therefore, that in places where the littoral attains a maximum width of 30 miles there are at the same time far greater areas receiving land and ocean sediments, so that the proportion of the littoral zone is hardly greater than before.

These few places where the littoral attains a maximum width are offset by the thousands of miles of coast-line where the sea is cutting into the land, and the tide rises and falls against a narrow beach at the foot of a sea-cliff; so that the previous conclusion may be further extended to include all continental coast-lines; and it may be stated that, taking the world as a whole, the width of the littoral zone does not average a mile, and therefore comprises but a small fraction of the earth's surface compared with the great extent of marginal marine and even of continental deposits.[1]

With respect to the shallow-water marine formations this remains true under all geological conditions, and therefore remains true for all geological time. But occasionally, in periods when the continental surfaces were physiographically old, of greatly diminished area and supplying but little sediment, continental deposits may well have sunk to less importance than the littoral. During such periods, however, there is a corresponding expansion of epicontinental marine sediments, though at such times of a calcareous character, so that the insignificant proportion of the littoral to the sum-total of other sediments deposited upon the continental platforms would not be greatly changed, and has been a constant feature of the earth's surface.

CAUSES RESTRICTING THE WIDTH OF THE LITTORAL ZONE

The previous examination of open sea and estuarine coasts shows that the width of the littoral is not dependent merely upon the flatness of the shores, nor upon the magnitude of the tidal range. These, while contributory factors, can operate only within certain limits. In order to see why this is so, it may be well to state briefly some of the causes which influence the result.

1. The influence of varying slope of shore may be seen in Fig. 5.

[1] Chamberlin and Salisbury, *Geology*, Vol. I, p. 352, give the width of the littoral zone as half a mile, the length of the coast-lines of the world as 125,000 miles, and consequently the area of the littoral zone as 62,500 square miles, as against 10,000,000 square miles for the area of the shallow-water zone within the 100-fathom line.

Suppose that the shore, to begin with, is a smooth, gently inclined plane, represented in cross-section by *OB* or *OC*. The level of low tide being *OD*, the volume of water passing *O*, the lowest part of the littoral, will be represented in the one case by the triangle *OAB*, in the other by the triangle *OAC*. But the areas of these triangles are to each other as their bases *AB* and *AC*. Hence in this ideal

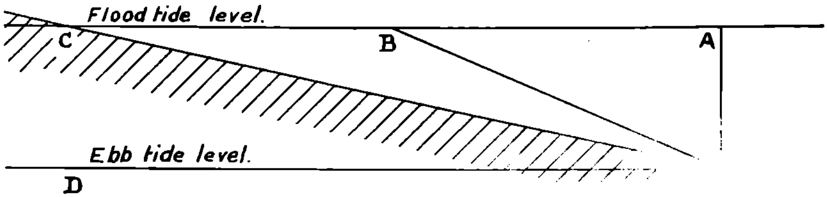

FIG. 5.—Diagrammatic relation of the width of the littoral zone to unadjusted slope of land surface.

case the volume, and consequently the mean velocity, of water flowing past *OA* will vary directly with the width of the littoral zone. But Révy has shown that the average velocity is an arithmetical mean between the bottom and surface velocities, and that the swifter the current, the more nearly the bottom velocity approaches the mean.[1]

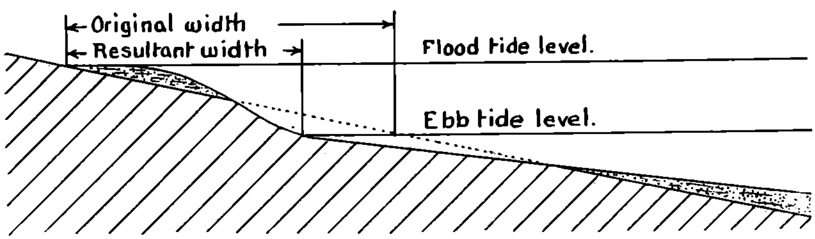

FIG. 6.—Diagram of littoral zone adjusted to slope, wave work neglected.

Therefore the bottom velocity increases somewhat faster than the width of the littoral in the ideal case. But the eroding ability of water varies as the square of the bottom velocity and the transporting ability as the sixth power. On an originally flat shore the mid-tide would consequently possess such scouring power for some distance on each side of the original low-tide limit that, as shown in Fig. 6,

[1] *Hydraulics of Great Rivers* (London, 1874), p. 147.

the bottom would be cleaned out, part of the detritus swept to the upper tidal limit and deposited, while a larger and coarser part aided by the downward grade would be swept seaward by the ebb-tide.

In nature the land slope is never smooth, and the discharge of the ebb-tide is concentrated along those lines which give the quickest egress and the greatest depth of water, the result being the building up of tidal marshes in protected places, the scouring of tidal channels, and the formation of extensive flats chiefly below the level of low tide. In these ways an originally widely extended littoral zone would be narrowed to a certain stable width for a given height of tide. The above discussion neglects the action of waves, chiefly operative at the upper and lower tidal limits, in exposed situations.

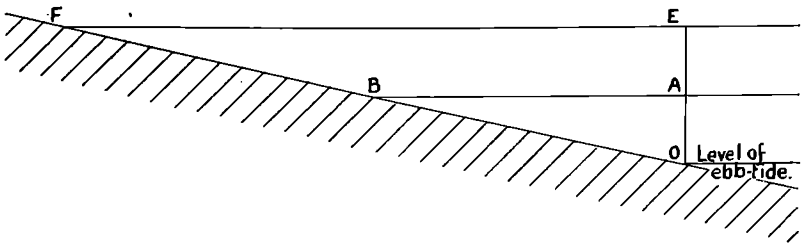

FIG. 7.—Diagram to illustrate relation of littoral zone and tidal scour to height of tide.

2. The influence of varying height of tide may be seen in Fig. 7. Letting *AB* and *EF* be the respective upper limits of tides on a recently invaded shelving shore: the volumes of water flowing past the low-tide limit will be as the areas of the two triangles *OAB* and *OEF*. But these being similar, the ratio of the areas will be given by the ratio of the squares of similar sides. Consequently, the volume, and with it the mean velocity, of the water invading the shore varies at the line *OE* as the square of the height of the tide, *OA* or *OE*. But Révy has shown that as the depth of a current increases the bottom velocity approaches more nearly the mean velocity, until in great depths and in strong surface currents they are substantially alike.[1] *Therefore on an ideal newly formed shore the bottom velocity past the point of low tide will increase somewhat faster than the square of the height of the variable tidal rise.*

[1] *Op. cit.*, p. 148.

The result as observed in nature is an added scour in regions of high tides by which the bottom is cut away, tidal marshes at the heads of bays or other suitable places are built with great rapidity, and these are dissevered from each other by tidal channels draining the marshes, which in the more striking cases may be sufficiently deep and wide even at low tide for the purposes of commerce. In time, if subsidence does not take place, the tidal marshes become raised by accretion through æolean and organic action until reclaimed from the sea, and the littoral zone is diminished as before to a certain stable width.

CONDITIONS FOR PRESERVAL OF THE SEDIMENTARY RECORD

It has been seen that in the making of the sedimentary record but an insignificant portion would be contributed by the littoral zone. There are still, however, two factors to be considered—that of the preserval of the record, and that of its ultimate exposure to observation through partial erosion.

In order to become part of a permanent geological record, the sedimentary structures must be preserved without obliteration, first, until buried and lithified, and, secondly, indefinitely protected from erosion until some new cycle of activities proceeds to destroy it and while so doing transitorially exposes it to observation.

PRESERVAL OF THE CONTINENTAL AND MARINE RECORDS

In regard to the river sediments, slow subsidence of the region or elevation of an adjoining region is necessary for their continual formation. Each layer of sediment from the flood waters is laid down upon the previously dried and hardened layer, and there is therefore not much tendency to erase the record made on the previous surface except in the lines of the channels. Soil beds, swamp deposits, mud-cracks, and ripple-marks are consequently abundantly recorded in fluviatile formations. Unless, however, subsidence carries at least the basal portions of the deposits below the ultimate base-level of erosion, the formation will be finally destroyed, as is illustrated by the present erosion of the Tertiary river deposits of the Great Plains facing the Rocky Mountains. In river deltas, however, the proper conditions are observed to occur. Here the upper limits are but slightly above the level of the sea, and subsidence in such regions is observed ordinarily to go forward with accumulation. This will indefinitely protect the formation until some new and adventitious geological activity reverses the processes which resulted in the accumulation.

To sum up, then, it is seen that the geological processes which result in the accumulation of desert deposits, if carried to their limit, will ultimately destroy those same deposits, as Passarge has recently shown.[1] The same is apt to be largely true of Piedmont plains of river deposits; but in the case of interior basins, and more especially in deltas, the conditions are most favorable both for temporary and ultimate preserval of the land-surface record.

The same is, of course, true of the record made on the ocean bottom, since this is normally the region of deposit and not of erosion.

CONDITIONS FOR PRESERVAL OF THE LITTORAL RECORD

In regard to littoral deposits it will be seen, however, that the chances are frequently unfavorable for the preserval of its deposits until burial.

1. On an emerging land, such deposits would form a surface veneer and be the first layer to suffer erosion, before even a chance for lithification had occurred.

2. On a stationary or slightly subsiding coast, where delta deposits are encroaching upon the sea, the fresh-water material will fill up the estuaries and lagoons, covering and preserving their records, and crowding the beaches farther out to sea. The littoral deposits in that case would be preserved as old beach, lagoon, and estuarine deposits transitional, in a vertical section, between the off-shore marine deposits below and the fresh-water land-surface record above.

3. Where an old land surface is slowly subsiding, the weak erosive power of the upper portions of the rivers is no longer able to supply sediment for building out deltas against the sea, and there is, on the contrary, a transgression of the sea across the land. Assuming that the land surface slopes gently seaward, the depth of the littoral deposits behind the barrier beach where such exists cannot in general

[1] "Rumpfflächen und Inselberg," *Zeitschrift der deutschen geologischen Gesellschaft*, Vol. LVI (1904), Protokol., 193–209; review by W. M. Davis, *Science*, Vol. XXI (1905), p. 825.

be as great as the depth of the sea in front. The advancing sea will therefore tend to cut away and destroy whatever littoral deposits may be made in advance of it, as illustrated in Fig. 8*A*. Observations confirming this statement may be occasionally made along a subsiding coast, as that of New England. To illustrate, Boston is found to be sinking at the rate of a foot a century and New York City, according to the most recent estimates, at the rate of 1.5 feet per century.[1]

That the coast between the two cities participates in this movement is indicated by the sharp boundaries of the salt-water marshes.

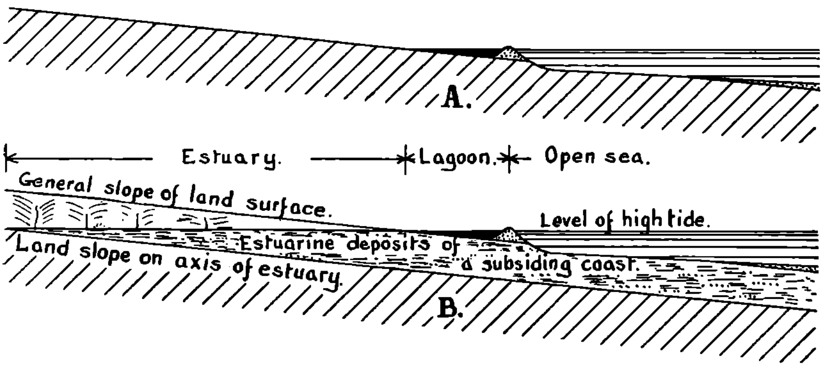

FIG. 8.—*A*, diagram illustrating progressive destruction of littoral deposits by marine planation over a subsiding land. *B*, cross-section on line of an estuary, illustrating part preserval of estuarine deposits during the transgression of the sea over a subsiding land.

These extend sharply to old alluvial slopes which rise at gentle angles from beneath them without any belt of fresh-water meadow being found between. If the land had been stationary for many centuries, the wash from the land, aided by the sediment from the highest tides, would have raised the border somewhat above the salt-marsh level. The opposite condition of affairs indicates therefore continual subsidence, but at a rate so slow that the organic and inorganic detritus, held by the roots of the marsh grass, is able to accumulate with sufficient rapidity to keep the surface at about the level of mean high tide.

A particular instance where the beach may be observed cutting

[1] G. W. Tuttle, *American Journal of Science*, Vol. XVII (1904), pp. 333–46.

away the older lagoon and marsh deposits may be cited from unpublished observations of Mr. I. Bowman. This is 2.5 miles south of Scituate Harbor, Mass., between the third and fourth cliffs, where the beach has retreated inland from 225 to 300 feet since 1898. The beach ridge is of pebbles, from 100 to 125 feet wide at mid-tide and from 8 to 10 feet above the level of the salt marsh behind it. In consequence of the rapid retreat, the marsh material at present shows at mean and low tide on the *seaward* side of the beach, illustrating the tendency of the sea to cut away the littoral as it advances upon the land.

There are a couple of ways, however, by which littoral deposits may be preserved upon a subsiding flat land. The first is illustrated by the unequal beach-cutting observed along the New Jersey coast.

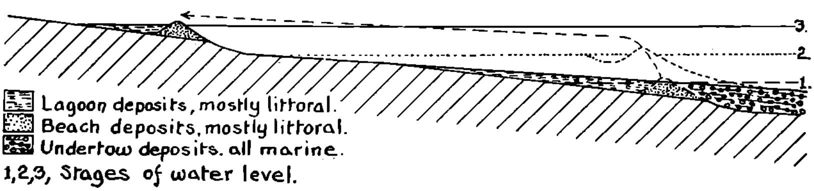

FIG. 9.—Cross-section illustrating occasional preserval of littoral deposits by building up of a beach, stages 1 and 2, without landward movement during land subsidence.

At Long Beach the sea has cut the lagoon space entirely away and is fronted by bluffs. Farther southward the barrier beaches begin and shut off Barnegat Bay. There is known to be a lateral transfer of beach material southwestward along the Atlantic coast. By this means it is possible for an offshore beach to be built up vertically as the coast subsides, the lagoon space behind broadening and deepening, as shown in Fig. 9. Finally, when the lateral supply of material ceases through recession of the bluffs, the beach will be rapidly transferred inland, but the depth of wave-planation may not reach to the bottom of the marsh deposits.

Again, the shore will be more or less indented with shallow river valleys turned into embayments or estuaries, and in these a greater depth of littoral and estuarine deposits may accumulate, and partly escape the marine transgression and planation which ensue with further subsidence. The protective effect will be slightly diminished, however, by the incurving of the spit-bars thrown partly across the mouth of the estuary. Illustrations of this nature are well exhibited along the Atlantic coast of the United States. As seen in cross-section, the bottom line of Fig. 8*B* represents the center line of the estuary bottom, while the depth of the marine planation is determined by the average slope of the land.

In the sedimentary record made, therefore, upon a subsiding land, only a fragmentary littoral record should be preserved at the base, and upon tracing the formation laterally there should be frequent places where the marine off-shore sands, gravels, or conglomerates should rest directly upon the old land surface. This contact of true

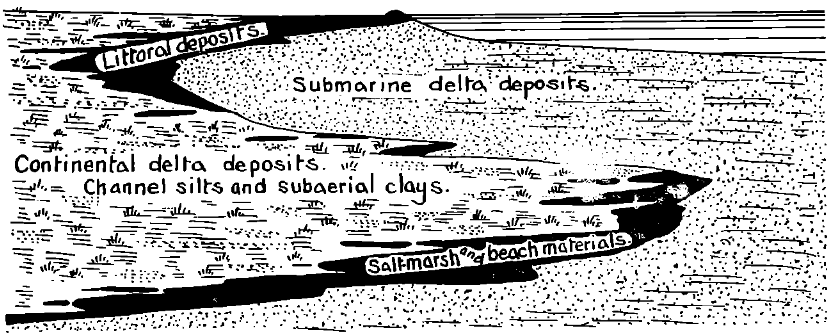

FIG. 10.—Ideal cross-section of a delta, showing geological relations of fluvial, littoral, and off-shore deposits. Vertical scale much exaggerated.

off-shore marine deposits with the old land surface seems to be the common rule observed upon that most striking of American transgressions, that of the middle and upper Cambrian, across the greater portions of the North American continent, though Dana[1] states that the beds "are in part beach made and wind made sandstones, ... and the layers often bear ripple-marks, shrinkage cracks, worm burrows, and, in some places, tracks of animals." The shrinkage cracks may doubtless be taken as good evidence in this instance of a littoral origin.

To sum up, it is to be expected that littoral deposits should be found dividing former land surfaces from sea bottoms, commonly present where the land surface is represented by subaërial delta

[1] *Manual of Geology*, p. 464.

deposits and comprises the *overlying* formation; frequently absent where the old land surface, ordinarily a land erosion surface, *underlies* the marine deposits. The littoral zone is small in local area compared with the occasional delta deposits which border it on the one hand, and the universal marine deposits which border it on the other. As seen in vertical section, therefore, the littoral deposits should have but limited lateral development on any one horizon. If the movement has been the subsidence of an old land, they should not be again encountered in the superior strata, but in the case of the contact of a delta with an epicontinental sea the littoral zone, as shown by the diagram, Fig. 10, might move backwards and forwards as a zigzag line through the vertical section, representing the advance and retreat of the sea as the subsidence on the one hand, or delta-building on the other, dominated at the moment, the littoral deposits dividing the marine from those made upon the surface of the land.

RELATIONS OF CONTINENTAL AND MARINE SEDIMENTATION THROUGH GEOLOGICAL TIME

In the preceding discussion the relative importance in area and volume of modern land, seashore, and shallow-water marine deposits has been discussed. It has been seen that the littoral zone occupies the least area and stands the smallest chance of preserval, while land deposits of various sorts hold second place; most important among these, on account of their favorable chances for preserval, being river sediments, made in interior basins, or as deltas encroaching upon the sea. The marine detrital deposits of the continental margins are, however, the most widespread and important of the three classes.

In discussing these relations they were seen to be dependent upon many broad features, such as the degree of continental uplift and areal extension, recency and magnitude of mountain movements, climatic zones, and other such factors. These have varied widely, however, through past time, and while the geographic details of former ages are largely wanting, still the general character of the terrestrial surface is in a manner known; as, for example, it is known that the Triassic over every continent was in general characterized by broad continental uplift, orogenic movements, and variegated climates, while the Jurassic was, on the contrary, characterized by a spread of epicontinental seas, less rugged and elevated land-masses, and warm, equable climates extending into the polar regions. This conception of world-wide conditions characterizing the several ages, and distinguishing them from each other must, according to Chamberlin, form the ulterior basis of time-divisions and the classification of geologic history. But if the several ages have been characterized by certain relations of mountains, plains, and seas, then they should also be characterized by the kinds of deposits made under these conditions. The most natural method of testing this question would be to study all of the formations of the world belonging to a certain age, and group them according to area and origin. This has been done, and it is the method by which the conclusions in regard to the broader features have been arrived at. But as the very subject under discussion involves the possible confusion of certain unfossiliferous littoral and shallow-water marine deposits with those made upon the land, this method must be reversed, and by basing the arguments upon the known continental relations, as determined by formations in regard to which there is no doubt, conclusions may be reached in regard to the relative importance of deposits of those three classes which should characterize the different ages. This may be of value in suggesting discriminations not otherwise thought of, but it is not the purpose to offer here criteria for finally and definitely testing the origin of any particular formation. The latter question must, of course, be finally settled by a detailed study of the formation in the field and in all its aspects.

As introductory to this discussion it may be well to restate briefly certain of the principles which are found to govern the development of several classes of deposits at the present time.

Where young and lofty mountain ranges stand sharply above the surrounding country there will be much local waste on the Piedmont plains at their feet. If at least one slope faces the interior of a continent, this will result in extensive continental deposits, perhaps accentuated by conditions of aridity. Down-warped interior basins may also receive deposits. For effective delta building, however, there must be a submerged continental platform, or epicontinental seas, and Chamberlin has pointed out[1] that the effect of the greater earth-movements has been to temporarily reduce to a minimum these shallow submerged portions of the continent. Such movements of continental uplift, or rather down-sinkings of the ocean basins, seem, however, to carry up portions of the crust to heights notably above the plane of isostatic equilibrium, from which they gradually settle back toward equilibrium by virtue of the slow fluency or quasi-fluency of the rocks.[2] At the same time, base-leveling is proceeding from the margins of the continents, reconstructing new coastal shelves, whose edges tend to become submerged both by the slight filling of the sea with sediment and by the settling back of the continental platforms. Assuming the truth of these general laws of major earth-movements, subaërial delta-building encroaching upon the shallow seas would attain greater importance as the erosion verged toward maturity, since the amount of landwaste increases; the streams, now being graded, carry it through to the shores, and submerged continental platforms have had time to form. At the same time, the deposits of arid interior basins and of Piedmont slopes will diminish in importance, and finally become more or less eroded.

Finally, as the continent becomes topographically old, the mountain slopes become subdued, the burden of the rivers lessens, they can no longer build out extensive deltas against the seas, noteworthy land deposits no longer form, and slight elevation of the ocean sursurface will cause it to widely transgress the base-leveled land.

Turning to the marine deposition of mechanical sediments, they should be observed to immediately increase in volume following continental uplift, several chief types being noted according to the nature of the land and the movement of uplift. If from a near-by mountain range, the sediments will be coarse in nature and formed through rock disintegration more largely than through decomposition. If from an older coastal plain, the marine deposits will comprise siliceous residues from a previous period of erosion. If from a decomposed regolith of a former near-by low-lying land, the sediments will be

[1] The Ulterior Basis of Time Divisions and the Classification of Geologic History, *Journal of Geology*, Vol. VI (1898), pp. 449–62.

[2] *Ibid.*, p. 455.

marked by an abundance of leached argillaceous and ferruginous silts discharged at numerous points along the coast. If from a distant mountain system, the material will be similarly fine-grained, but will show less decomposition and leaching, and be discharged in great quantity by great rivers at a few widely distant points. Thus there are a variety of types of marine sedimentation, the material becoming more uniform in character and more widely spread over the growing circum-continental shelves as the erosion passes into the stages of maturity. Finally, with old age the amount of mechanical detritus greatly lessens, the conditions for limestone formation approach near to the shores, but greensands and the limy shales are still indicative of the presence of land-waste long after all *subaerial* detrital deposits have ceased to form.

Even in old age, however, it is still possible that slight regional uplifts and warpings may result in a temporary renewal of rapid erosion, since under such circumstances the regolith will have formed a deep and voluminous mantle to the continent, readily removed and swept to sea upon the least rejuvenation of the rivers. If the movement is accompanied by an adjacent down-warping in a continental interior, the deeply decayed rock mantle may be swept into it and be built up by river aggradation as a continental deposit, which further warping may carry beneath the sea.

GENERAL APPLICATIONS TO GEOLOGICAL HISTORY

Having sketched these outlines of the relations of continental and marine sedimentation to the broad earth-movements which have separated and individualized the geological ages, it will be in order to apply them, by way of illustration, to certain typical periods. It will be seen that they suggest, though they do not prove, rather different interpretations for certain formations from those which have been ordinarily held.

Pre-Cambrian æon of continental extension.—It is a matter of familiar knowledge that nearly everywhere the marine deposits of the Cambrian lie upon a far older and unconformable basement. Occasionally the Cambrian appears to have a downward unfossiliferous extension, as in the southern Appalachians, or sometimes rests unconformably upon older, usually barren sediments, but little or no more metamorphosed than itself, as in Montana and in Arizona. More frequently, however, over all the continents it rests directly upon steeply dipping gneisses and schists. These structures, characteristic of the zone of rock-flowage, indicate widespread and profound erosion previous to the Cambrian transgression, and therefore a period of wide and long-enduring continental extension.

The usual concept of the development of the North American continent embodied in the textbooks of the past begins with the widespread submergence of the late Cambrian and early Ordovician. From that stage Dana has long since shown how the continent through the Paleozoic gradually, and with many regressions, gained in dry land.

Walcott considers, however, that the prevailing view of the geographic distribution and extent of the continental area at the beginning of Paleozoic time is too restricted, and that the continent was larger at the beginning of the Cambrian period than during any subsequent epoch of Paleozoic time.[1] At this date (1891) Walcott had not yet separated the underlying belt formation of Montana from the Cambrian, and consequently considers this portion of the Northwest to have been beneath the sea during Lower Cambrian time. With the discovery of an uncomformity separating the Belt from the Middle Cambrian,[2] this statement in regard to the extent of the early Cambrian land is further justified, and will probably be considered by those familiar with the subject as very conservative.

LeConte also emphasizes the significance of the Pre-Cambrian record of erosion, the subject being briefly stated in his *Elements of Geology*.

A truer appreciation of the facts of the world-wide Pre-Cambrian unconformity may finally lead to the erection of this Pre-Cambrian period into an æon of continental extension as widespread and as long-enduring as that of the Mesozoic and Cenozoic.

Yet it is only the end of this period, as marked by the Lower Cambrian unconformity, which is known with any accuracy. On going backward in time, evidences of repeated orogenic movements

[1] "The North American Continent during Cambrian Time," *Twelfth Annual Report* (1891), U. S. Geological Survey, Part I, p. 562.

[2] C. D. Walcott, "Pre-Cambrian Fossiliferous Formations," *Bulletin of the Geoogical Society of America*, Vol. X (1898), p. 210.

are encountered widely separated in time, deforming older basins of sediments, and resulting in erosions and unconformities. It is not to be implied, therefore, that such formations as the Belt of Montana and the Grand Canyon terranes, because they lie immediately below the Middle Cambrian, were necessarily deposited in an *immediately* Pre-Cambrian period.

From the thickness of their detrital accumulations situated in the interior of the continent, they probably belong to interior basins of subsidence within rather wide land masses. That these basins were, at least during a part of the time, connected with the open sea is shown by limestone formations, thousands of feet in thickness, which they contain.

In the Lewis and Livingston Ranges Willis has measured a thickness of the Algonkian of about 10,000 feet, without either the upper or lower limits being visible. Of this from 4,500 to 5,300 feet are argillites and quartzites, while 5,400 feet are limestones, divided into two great formations.[1]

Near Helena, in west-central Montana, Walcott has estimated the total thickness of the Belt terrane at 12,000 feet, of which 7,600 feet consist of argillites and quartzites, the remainder, as before, being divided into two great limestone formations.[2] This region is possibly not far from the limits of the original basin during much of the time of deposition, since the Belt formations disappear from between the older gneisses and the younger Cambrian some 60 miles to the south.

In the Pre-Cambrian Grand Canyon series, exposed in northwest Arizona, Walcott gives the Unkar and Chuar terranes a combined thickness of 11,950 feet, of which about 400 to 500 feet are limestones, and about 1,000 feet lavas. The remainder are sandstones and argillites.[3]

In view of these great thicknesses of sandstones and argillites accumulated in interior basins of Montana and Arizona at a time of at least considerable continental extension, the hypothesis of a subaërial origin by river aggradation may well be held in mind as a possibility for certain formations, as well as the more common

[1] *Bulletin of the Geological Society of America*, Vol. XIII (1902), pp. 316, 317.

[2] *Ibid.*, Vol. X (1898), p. 204.

[3] *Fourteenth Annual Report*, U. S. Geological Survey, Part II, pp. 508–12.

hypothesis of the accumulation of such materials at the bottoms, or within the margins, of shallow seas.

Again, in the Lower Cambrian, according to Walcott, the eastern side of the narrow Appalachian trough appears to have been a bold and precipitous mountainous area. In the trough itself beneath the Olenellus sandstone occurs a great series of variegated shales.[1] These are of course no proof of land accumulation, but the geographic relations of land and water were such as to suggest the possibility that delta deposits may have been built out into a trough which later, by a slackening of erosion or a greater subsidence, allowed the region to pass from largely subaërial to marine conditions, the marine transgression being marked by the deposit of the Olenellus quartzites.

In conclusion it is suggested that the Pre-Cambrian and Lower Cambrian ages of wide continental extension offered conditions favorable for the accumulation of the several types of subaërial deposits, and that in the interpretation of the mechanical sediments of those times this possibility should be always held in mind. The presumed absence of a fossilizable land fauna and flora in the life of those periods would remove the possibility of proving a continental origin through such secure means.

Paleozoic epicontinental basins.—During the Eopaleozoic the continents became largely submerged, but in the Neopaleozoic partial emergence was the rule, varying from fairly extensive land conditions at times (in late Silurian and Lower Devonian), as has been shown by Ulrich and Schuchert,[2] to submergence possibly nearly as complete as that of the Ordovician. At times mountain-making forces and regional uplift operated on an extensive scale, as is witnessed, for example, by the enormous mass of Upper Devonian sediments along the northeastern portion of the Appalachian trough from which Willis computes that the uplift supplying these sediments corresponded in volume to a mountain range similar to the Sierra Nevada,[3] and the sediments deposited in the Old Red Sandstone

[1] "The North American Continent during Cambrian Time," *Twelfth Annual Report*, U. S. Geological Survey, Part I (1891), pp. 536, 551.

[2] "Paleozoic Seas and Barriers in Eastern North America." *N. Y. State Mus., Bull. No. 52*, pp. 633–663, 1902.

[3] *Paleozoic Appalachia*, Maryland Geological Survey, Vol. IV (1902), p. 62.

basins of the British Isles, Norway, and the Arctic islands to the north.

This mountain-building, taken into consideration with the restricted nature of the interior sea of eastern North America between the Cincinnati axis and the eastern border, forms geographic conditions which should favor the development of extensive deltas filling up shallow seas and giving rise to the formation of subaërial deposits. Turning to the strata themselves to find an answer to this suggestion, one notes the sparingly fossiliferous character of the Catskill group of the Upper Devonian and the fact that the few fossils found are those of fishes, Eurypterids (Stylonurus), and some fresh-water lamellibranches (Amnigenia), suggesting that, occasionally at least, subaërial deltas may have covered considerable regions, and should be looked for by a critical study of textures and structures. Many geologists would grant this possibility, though it has found but little recognition in geological literature.

That differences of view among able living geologists may be held upon the subject of the Paleozoic formations is indicated by the fact that Willis, as a result of his prolonged and detailed studies of the Appalachians, interprets the Tuscarora (Medina) sandstones of Maryland as submarine coastal plain deposits,[1] while more recently Grabau, in a preliminary paper, advances the hypothesis that the Siluric conglomerates and sandstones are part of a huge subaërial fan, whose apex was in southeastern Pennsylvania.[2]

This is not mentioned with the intention of urging the continental point of view, since the cleanly sorted character of much of the formation would seem to indicate to the present writer that prolonged sorting by waves, rather than the limited sorting and variable character of river work, had been concerned. It might well be, however, that an alternation of conditions has occurred, marine deposition dominating in one district, river work in another.

Of the Paleozoic formations it is in the coal-measures, however, that the relations between continental and marine deposits are most distinctly shown and most fully appreciated; largely because the climatic conditions were such as to lead to the formation of swamp

[1] *Op. cit.* (1902), pp. 55, 56.

[2] "Physical Characters and History of Some New York Formations," *Science*, New Series, Vol. XXII (1905), p. 533.

jungles whenever delta surfaces were exposed to the air without either uplift sufficient to produce erosion or subsidence sufficient to result in burial. With occasional exceptions, which may be due to river driftage, it is conceded that the coal was formed *in situ*, and thus each coal-bed becomes a determined land surface, although once in a swamp condition.

The analogy of the carboniferous swamps with those existing at present upon delta surfaces or buried beneath the later river deposits has been perceived and pointed out since the time of Lyell. This analogy, together with the usual absence of marine fossils and the occasional presence of land or fresh-water forms in the associated strata, has led to the well-founded belief in the chiefly fresh-water or brackish-water origin of the coal-measure shales and sandstones of Nova Scotia, the Pennsylvania anthracite basins, and other regions. But over the western portion of Pennsylvania and much of the continental interior, beds of limestone with marine fossils occur at intervals through the coal-measures, indicating in those regions periodic invasions of the sea.

From these facts it is inferred that periodic subsidences took place, allowing transgressions of the widespreading epicontinental sea across the submerged delta surfaces. But the absence of the limestones nearer the shore and in basins like that of Nova Scotia, where the great thickness of shales, sandstones, and conglomerates testifies to rapid erosion and sedimentation, indicates that subsidences did not allow the sea to reach this far inland, but that it was kept out by the rapidity of river aggradation, which, as the basin subsided, distributed mud, sand, and gravel *pari passu* over the old forest swamp. Thus, the same conclusion is derived inductively as that previously arrived at by deduction concerning the phenomena of a subsiding delta region, where it was concluded that the marine and continental portions should be broadly interfingered, the sea cutting in from one side, the rivers building out from the other, and the littoral being a relatively unimportant transition zone resulting from the contest between the two.

Statements might be quoted from able writers in which it is assumed that the subsidences were of an oscillatory nature, and that the reclamation of the land surface from the sea was due largely to uplifts which would cause the sea bottom to just emerge above the sea-level when coal-swamps would form, while subsidences would carry it downward, maintaining depths of 100 feet or more during which sediments were being deposited.

Upward oscillations are, of course, not to be excluded, but in regard to the major cause of land-surface reclamation the following may be quoted from Geikie:

> It has been assumed that, besides depression, movements in an upward direction were needful to bring the submerged surface once more up within the limits of plant growth. But this would involve a prolonged and almost inconceivable see-saw oscillation; and the assumption is really unnecessary if we suppose that the downward movement, though prolonged, was not continuous, but was marked by pauses, long enough for the silting-up of lagoons and the spread of coal jungles.[1]

LeConte emphasizes the same conclusion as to the cause of the alternation of strata; it being due not to crustal oscillation, but to the operation of two opposing forces, one depressing (subsidence), the other upbuilding (river deposit), with varying success.[2]

Dana also states that, when

> under verdure, the surface must have lain for a long period almost without motion; for only a very small change of level would have let in salt water to extinguish the life of the forests and jungles, or have so raised the land as to dry up its lakes and marshes. Hence the grand feature of the period was its prolonged eras of quiet, with the land a little above the sea-limit.[3]

It is inconceivable that uplifts should have terminated and the land rested quietly almost indefinitely when it was brought exactly to the sea-surface, and it has been shown in the earlier part of this article that the sea and land always tend to be differentiated.

It is seen then that, supposing a small subsidence of, for example, 100 feet to take place, the river building would on the landward side keep pace with it. The coal-jungles would first be quietly flooded with fresh-water lagoons, as over portions of the Ganges delta. In these clays would be laid down, quietly burying and protecting the extinguished forest, and preserving within itself numerous fossils of ferns and leaves. Following this, the shifting river distributaries would deposit sand, or possibly even gravel, the whole

[1] *Text-Book of Geology*, 4th ed. (1903), p. 1018.

[2] *Elements of Geology*, revised ed., p. 390.

[3] *Manual of Geology* (1895), p. 708.

covered continually with sufficient vegetation to leach out by its decay the iron from the deposited sediments, but not standing in water, and therefore finally destroyed by oxidation.

On the seaward side the subsidence brings about a transgression of the sea with considerable erosion of the forerunning transitional littoral zone, or even of the underlying fluviatile and swamp formations, such as is sometimes observed to have occurred in the coal-measures of Illinois, Kentucky, and Missouri. In order to observe the process of land-reclamation by the river deltas from the sea, suppose, to continue the example, that the subsidence has been sufficiently rapid for the sea to gain 10,000 square miles from the land with an average depth of 50 feet, at which time the subsidence ceases.

The Ganges annually carries across its delta to the sea sufficient sediment to cover one square mile 221 feet deep; the Mississippi annually discharges into the Gulf of Mexico sufficient to cover one square mile 268 feet deep. Applying these figures to the hypothetical case, and assuming that one-half of the discharged sediment goes to make the fore-set beds by which the delta is built outward, it is seen that the Ganges would completely reclaim this area in 4,524 years, the Mississippi in 3,730 years. These, however, are two of the greatest rivers. But even if the carboniferous rivers discharging across the region of the Appalachian coal-fields delivered but a tenth part of the detritus borne to the sea by the Ganges and the Mississippi, it is seen that the transgressive effect of the supposed subsidence would be completely nullified in periods of 45,240 and 37,300 years. During this period of quiet and of land extension, conditions for the formation of coal would exist over much of the delta surface not actually traversed by the rivers, the swamps by the deposit of organic débris keeping pace to some extent with the distributaries raising their beds as the delta advances, and thus tending to prevent the wandering of the rivers across them.

In the present connection it is desired to emphasize not only the upbuilding but the outbuilding capacity of rivers, by which, if their sources are in highlands, their deltas may rapidly push into and fill up shallow epicontinental seas. Under such circumstances it is largely a question of the rate of river deposition and the volume of the sea to be filled.

In conclusion, then, it may be said that during the Paleozoic the eastern margin of the United States witnessed repeated uplifts and occasional mountain-making movements, which poured down great quantities of sediments into a shallow and at times restricted interior sea. These conditions should lead during times of rapid erosion to extensive subaërial deltas; sometimes temporary fresh-water marshes or periodically inundated desert flood-plains; sometimes verdure-covered swamps and plains: deltas showing great thicknesses of subaërial beds advancing to a considerable distance into the sea, alternating with periods of relatively more rapid subsidence or slackened erosion when the sea would transgress across the subsiding delta. At present the coal-beds, and the occasional presence of shells of fresh-water facies in the associated dark shales, are considered the only decisive evidence of such conditions, but the absence of coal-beds does not prove the contrary side of the question.

Mesozoic and cenozoic continental deposits.—The possibility of the occurrence of Mesozoic continental deposits has been widely recognized in both the New and Old World, especially for the closing stages of the Paleozoic and the opening of the Mesozoic, when the continents appear to have been broadly uplifted concomitantly with orogenic movements, and conditions of coldness and aridity occurred in many parts of the world, coldness and humidity in others. The conditions seem to have been of a somewhat similar nature to those recurring at the end of the Tertiary and enduring in a measure to the present time. It does not seem necessary, therefore, in the present connection to enter into a detailed discussion of the possibly or probably subaërial Mesozoic deposits of Europe, Asia, and America. Neither is it necessary under the present heading to discuss the deposits of the Tertiary and Quaternary still enduring at the surface, since it is the accumulated knowledge of these which has been used as the key and the test of this discussion, and it is by a further study of them that added light will be shed upon the past.

STUDIES FOR STUDENTS

RELATIVE GEOLOGICAL IMPORTANCE OF CONTINENTAL LITTORAL, AND MARINE SEDIMENTATION

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INTRODUCTION

The previous parts on the relative geological importance of continental, littoral, and marine sedimentation have shown that the bulk of present sedimentary deposits are formed either upon the land or beneath the sea, and that the littoral, restricted to its distinctive limits as that belt of shore exposed between the highest and lowest monthly tides, forms but a relatively narrow transitional zone. Furthermore, it was shown that the chances for preserval of the true littoral deposits are but slight, for if the land is upraised, they are the most superficial deposits and the first to suffer erosion. If the land is slowly sinking, the margin of the sea moving across the land planes away the deposits made in advance of it to the limits of wave action, and this is ordinarily greater than the depth of the littoral deposits. Under these conditions the unlithified deposits formed in advance of the transgressing sea will only be preserved where protected in some manner from the work of the waves which follow.

The most favorable places for the development and also for the preserval of a broad littoral zone were found to be the frontal portions of the larger river deltas. In such places it has been seen that a slow subsidence frequently takes place *pari passu* with the accumulation of river-borne sediment, but the sea does not advance inland, and the littoral deposits are therefore not destroyed, but finally become buried to depths where they are beyond the reach of surface agencies and hence indefinitely preserved. But even in this case the littoral deposits form but a transitional zone between much more extensive and equally well-preserved marine deposits on the one hand and continental flood-plain deposits on the other.

It was furthermore shown that a considerable portion of the sediment of rivers was deposited not beneath the sea, but upon deltas facing and encroaching upon waters of the oceans or their outlying seas. This subaërial deposit of river waste upon deltas not only stands an excellent chance of preserval and incorporation into the geological record, but is ordinarily more important in area and volume than that of the littoral zone which borders it on the seaward side, and becomes most important where the deltas are broadly developed in shallow seas, since the deposits upon the delta surface hold under such conditions, a greater ratio to those deposited in advance of the delta. Even disregarding other important forms of continental deposits, the magnitude of subaërial deltas and the relatively small quantity of the littoral deposits which will be preserved indicate that a much larger place should be given to fluviatile deposits in the geological record and much less to littoral than has been customary in the past.

In that article the distinctive features of the marine, littoral, and continental deposits were incidentally mentioned, as well as the features which they held in common, but the purpose was not to give criteria for their distinction so much as to discuss the relative areal and volumetric importance which they should assume in ancient sedimentary formations deposited under various geographic and climatic conditions. It was urged, furthermore, that formations belonging to these three zones should be sharply discriminated and separated, not only because of the strikingly different conditions under which they were accumulated, but also because of the fundamental importance of such distinction in many problems of paleogeographic and paleobiologic geology.

The present article is supplementary, and it is proposed to take up the subject of mud-cracks as a distinguishing feature and to note to what extent and in what associations they should be expected to occur in various kinds of deposits. Such a discussion seems the more pertinent since in the absence of fossils there are many detrital formations in regard to which there is at present no unanimity of opinion as to whether they were formed by means of either one, two, or three of the following agencies, viz., aeolian, fluviatile, lacustrine, estuarine, or those pertaining to the open shallow sea. It is possible that there are still other formations which have been unhesitatingly ascribed to an origin in shallow seas which may have originated upon the continental surfaces, since on account of the dominance of marine deposition there has always existed a tendency in the absence of fossils of land-dwelling organic forms to ascribe to sedimentary formations an origin beneath the surface of the sea.

METHODS OF ORIGIN OF MUD-CRACKS

The closeness of resemblance between the mud-cracks which are of such frequent occurrence in ancient sedimentary formations of an argillaceous nature and the mud-cracks formed in modern drying mud flats is such that no other origin for these ancient structures has ever been, or seems likely to be, suggested, than that of exposure to the air. They may be formed in any fine-grained argillaceous or limy deposits which upon drying shrink notably in volume. Deposits whose grains are predominantly of sand size cannot give rise to mud-cracks, since when wet the water stands in the pores, and the deposit does not lose markedly in volume upon drying, but only in weight. This limitation in regard to the necessary size of particles requires that the deposit should originate under very quiet waters, which are either removed by evaporation or slowly drained away with bottom velocities of less than a third of a mile per hour, since such a current will lift fine sand.

Mud-cracked surfaces are observed to vary much among themselves. Sometimes they inclose polygons a few inches across, sometimes a foot or more in diameter. In depth they may terminate within a few inches or they may pass downward as many feet. As factors governing the nature of the mud cracks may be mentioned the shrinkage ratio of the deposit; the porosity by means of which water may be conveyed upward by capillarity, tending to prevent shrinkage; the varying nature of the stratified deposit, the cracks not being able to pass through thick strata of sand; the thoroughness of saturation; the length of the period of desiccation; the temperature and dryness of the air. It seems that a thorough observational and experimental study should throw important light upon some of these relations by means of which certain of the conditions attending the formation of mud-cracks in ancient strata could be recognized.

It is possible that a definitive solution is not usually to be obtained on account of the number of the governing factors. But the solution should be narrowed to one of two or three alternatives. For instance, providing that an argillaceous formation is homogeneous throughout, the depth of the crack will probably vary roughly as the square of the time of desiccation. It will also vary with some power of the temperature measured on a centigrade scale, and with some power of the degree of dryness of the air. A knowledge of these values would enable one to say if certain mud-cracks could have been formed in the fortnightly interval between spring tides, or if a season or more of desert heat and dryness were necessary.

As a striking example may be cited the mud-cracks described by Gilbert which penetrate ten feet downward into the variegated shales of the Upper Shinarump of the Jura Trias where exposed on the northern flank of Mount Ellsworth.[1] The formation of these mud-cracks was followed by a complete change of sedimentation at this point into the homogeneous sandstones of the Vermilion cliff group, so that it is quite certain here that the mud-cracks were not formed in the brief interval between two similar tidal invasions. So little is known, however, of the relations between the governing conditions and the characteristics of the mud-cracks that, in the absence of more data, this detailed subject cannot be profitably discussed, and the attention will therefore be turned to the various conditions under which they originate and the associated chemical, textural, and structural features which accompany them in each case.

Such conditions are observed to obtain first, over playas and temporary lakes of arid regions; second, upon the margins of interior lakes; since the latter are peculiarly liable to seasonal fluctuation in level; third, over many river plains as a result of the periodical floods in places where the surfaces are not covered with an arboreal vegetation; fourth, over the higher portions of the littoral zone, where mud-flats or tidal marshes are exposed to the air sufficiently long for the mud-cracks to originate. The littoral in the previous article has been limited to the level which is flooded on the average twice per month by the tides of the new and full moon, since above this limit the tidal flooding is in a manner accidental and occasional and only occurs during abnormally high tides or storms. Mud-cracks will therefore be formed also over an adjacent portion of the continental zone due to unusual elevations of the level of the sea.

CONDITIONS FOR TEMPORARY PRESERVAL OF MUD-CRACKS

Before taking up the detailed discussion of the conditions of origin, relation to other features, and final preserval of mud-cracks, it is desirable to state some conclusions which the writer has reached from observation and experiment upon the conditions necessary for the temporary preserval of the cracks until the stratum shall become buried and form no longer the surface layer.

Experiments were conducted first upon interstratified light brown silty clay and dark brown clay of Champlain age; the former smooth to the fingers, but giving a fine grit to the teeth; the latter

[1] *Geology of the Henry Mountains* (1877), p. 9.

perfectly smooth to the teeth. Second, upon a modeling clay giving a fine grit and third, upon clay from New Haven harbor, gray-black when wet, light gray when dry, giving a very small amount of fine grit to the teeth. Lack of time did not permit accurate soil analyses to be made of these types.

The Champlain silty clay, firm and strong when removed from the clay pit, was dried and then covered with water. Within from five to ten minutes a stratum half an inch in thickness would soften, swell, and begin to disintegrate, losing all coherency, turning to a creamy mud and the margins sliding down to the angle of repose. The clay and silty clay were then ground up, mixed in nearly equal proportions, allowed to settle in pans from water and dried in the sun. After becoming thoroughly dry and cracked, two out of three pans were baked over gas, one at a temperature up to 70° C., the other above 100° C. This was done in order to test the effects of drying at and beyond the most extreme temperatures of torrid deserts. Upon being covered with water, the swelling and disintegration took place as before, indicating that a mixture of equal parts of pure clay with silty clay would not preserve the stratum from disintegration, and that the highest ranges of temperature found in nature were equally ineffective. Upon drying, cracking, and then rewetting, the lines of the cracks are partly closed by swelling. The remainder becomes filled and veiled with a more fluid mixture, and upon redrying the cracks are established chiefly upon the same lines, indicating a weaker cohesion along the lines of previous cracks. The same feature was observed in the field after a rainstorm, the deeper parts of the cracks having been closed by swelling, but still forming lines of weakness; the upper parts blurred by the slaking of the mud. Upon wetting in the laboratory, adding a new layer, and redrying, the two layers adhered as a unit, and the cracks were twice as widely spaced. Those which formed, however, followed in general previous lines of cracking, and those cracks which did not reopen were still to a slight extent lines of weakness. Finally, the pure clay in strata half an inch in thickness was dried for a couple of weeks at ordinary temperatures, broken, and placed in water. They gradually softened in the course of an hour, but for days retained their sharp edges and showed no tendency to disintegrate, though swelling 5 per cent.

linearly upon the plane of stratification. When rubbed to a batter in water and allowed to dry and crack, the edges disintegrated and the cake softened more rapidly, indicating that the original closer-knit texture had given it superior resistance. Drying and baking up to the boiling-point did not affect the result.

The modeling clay was not baked, but, in all respects tested, behaved like the mixtures of Champlain clay and silty clay.

Finally in August, 1906, excellent opportunities were offered for observing the behavior of the unctious and sticky gray mud of New Haven harbor; a reclamation company building turf walls around many acres of salt marsh land, and pumping water, mud, and sand from the center of the harbor into these artificial reservoirs, the sediment settling and the water draining away. In this way from 6 to 20 feet of sediment were laid down under most favorable conditions for observation. It was found that from mid July to mid August beds of gray mud up to a foot in thickness, resting upon sand, had dried and cracked into irregular polygons 1, 2, and even 3 feet in diameter, the cracks opening from 3 to 4 inches.

Where the mud was thicker, the bottom was still soft, but the top was cracked. Where the water was still standing no cracks had formed, but upon the disappearance of the water they began to appear as wedge-shaped cracks, while the top clay was still soft to the hand and the bottom so fluid as to make walking impossible.

These cracks had formed and the clay underlain by sand had dried and hardened to the depth of a foot during an interval, as stated, from mid July to mid August, during which time the mean temperature was 71° F., the average humidity 0.83, the precipitation, in thirty-one days, 3.0 inches, ten days partly cloudy, and twelve days cloudy.

Rain had failed to efface these cracks, though washing more or less mud into them, especially when the cracks were still young and narrow and the clay not yet hardened. Reflooding by pumping was observed to soften the clay to the consistency of a stiff gelatine and expand it somewhat, but did not obliterate the sharpness of the cracks even in the course of days; and where mud or sand was washed over the surface, the cracks were permanently buried and preserved. Where filled with similar mud and redried, the filling may be detected, even where the crack fails to reopen, by the interruption of the faint lines of stratification at the margins and a slightly marked weakness along this line. When this mud was beaten up with the water, dried quickly over gas and then recovered with water, the air rapidly escaping from the many minute bubbles produced an audible simmering, and the mud, originally so retentive of its form, soon fell into a mush. It was also observed that the dry natural clay was subject to a slight exfoliation upon rapid wetting. These facts point out the importance of close texture, obtained by slow subsidence and long standing under water before drying. This requires the moisture to be transmitted slowly, by capillary action, and allows the mass to expand as a whole.

The conclusions from these observations and experiments will doubtless be somewhat modified by more extensive observations in suitable regions, but may be preliminarily stated as follows:

A mud-cracked loam or silty clay, even when the sand particles are imperceptible to the fingers, is an unfavorable material for the preservation of its detailed surface structures, except possibly when remaining moist, so that but little swelling and exfoliation take place. Upon being wet by rain, the rapid swelling and disintegration of the surface stratum would turn the surface of such a deposit into a creamy mud, which, if remaining *in situ*, might preserve upon redrying blurred impressions of the previous cracks and other larger surface features, but which would be peculiarly liable to be swept away and intermingled with the detritus of the following flood similar to the one which left the material. Even if the flood sweeps down from the mountains upon previously unwet desert plains, the few minutes of wetting necessary would suffice to destroy the detail of surface features before a sufficient new layer of sediment could be laid down. This would seem to explain the mud-lakes into which many playas are transformed during the rainy season. Upon such a formation becoming lithified, the record of mud-cracks might be greatly masked, if not entirely obliterated. The development of joint planes, and even a faint cleavage, would add to the difficulty of detection. Where the finer details of the original surface are preserved, however, or the sharp surfaces of stratification between unlike laminæ, it would seem impossible that the mud-cracks could become completely obliterated. This, therefore, may be a test as to their former presence or absence.

A pure clay, slowly subsiding from quiet waters, and wet sufficiently long to become compact upon drying, would retain its mud-cracks upon rewetting, either by rain previous to flooding or by the flood waters themselves. Such a clay, on account of its tenacity, resists erosion even by quite rapid currents, as is seen from the presence of occasional areas of sticky blue mud on relatively shallow and open parts of the coastal shelf. In case such a sun-baked clay is covered and its cracks filled by a similar layer, it should retain a clear record of the cracks, provided it possesses a well-defined bedding cleavage, since such a cleavage will be interrupted at the margins of the cracks. Such pure and massive clay deposits form, however, the rocks most susceptible to dynamic metamorphism, and a pressure cleavage, even if developed upon the bedding planes, would tend to mask any previous interruptions. Frequently, however, such clay deposits from standing water will be interstratified with more or less arenaceous deposits swept along the bottom by the rising floods. Such sandy wash filling the cracks of the previous clay layer would give a persistent record to the buried mud-cracks. If the sand be sufficiently coarse not to shrink markedly upon drying or swell upon rewetting, the combination of the two kinds of laminæ should give a maximum opportunity for the complete preserval of mud-cracks, footprints, raindrops, and other surface markings. It is noteworthy that this is the typical nature of those beds in the Triassic formations of the Connecticut valley which have preserved such a magnificent record of mud-cracks and footprints. Large portions of these formations, however, consist of rather massive sandy shales or arkoses, and in these the writer has not noted the occurrence of mud-cracks.

On the larger river flood-plains, such as that of the Mississippi, the soil survey of the Department of Agriculture has established three principal types, grouped under the Yazoo series and seven miscellaneous types. Of these ten types only two are clays. The Yazoo clay—a heavy, drab clay loam—occupies low areas back from the low, flat ridges which form the front lands near the stream courses. It is a frequent type of soil. The Sharkey clay is a stiff, impervious clay occupying the lowest portions of river bottoms and subject to annual overflow. Both are characterized by sun-cracks—a characteristic not ascribed to the other types of soil. It is noteworthy that the purer clay, and therefore that more favorable for the preservation of mud-cracks, is deposited, not from flowing, but rather from stagnant back waters, the one at high-water stage, the other when the water-level is lower. Only a portion of the deposits of the larger flood-plains are, therefore, well fitted to retain surface impressions until buried, and this principle must be carried into the past.

It is seen that mud-cracks may originate in pluvial climates, but the thick mat of vegetation apt to form under such conditions would tend, wherever it existed by the binding action of the roots, to prevent cracks from forming. An arid valley climate, therefore, and abundant sediment would be more favorable conditions for the broad development of mud-cracks. Rock decomposition, rather than disintegration at the sources of supply, the mark of a pluvial climate, should, on the other hand, be favorable as furnishing a larger proportion of pure clay mixed with the coarser material.

In conclusion, it is seen that special conditions are necessary for a complete temporary preserval of mud-cracked surfaces even where continued sedimentation without intervening erosion occurs. In formations which show traces of mud-cracks it is to be anticipated that other, more or less argillaceous layers may also have been exposed to the air. Sediments swept along by broad, slow-moving waters will ordinarily possess too much loam for the good preserval of mud-cracks. But where the flood waters stand quietly before being drained away, or where the loam is strained out or settles at another place, the fine clay will settle, forming a deposit free from sand, and capable of retaining even the faintest markings made upon its drying sufrace.

Classification of Mud-cracks-

MUD-CRACKS OF PLAYAS

Description.—The characteristics of these may be best appreciated by quoting from Russell's descriptions of the present and extinct lakes of Nevada.[1] Speaking of the ephemeral lakes forming either after the rainy season or even after a single storm he says:

[1] *The Physiography of the United States* (American Book Co.), Monograph 4, pp. 105–10.

Should the storm continue, the sheets of water in the valleys will expand, and possibly become many square miles in area. Such lakes are always shallow, and always yellow with mud in suspension. When the sun breaks through the storm clouds, evaporation becomes active, and the lakes gradually contract their boundaries, and perhaps in a few hours or in a few days are entirely dissipated. When the water has disappeared, absolutely barren mud plains remain, which harden under the sun's heat, and become cracked in all directions as their surface contracts in drying. The lake beds then have a striking resemblance to tesselated pavements of cream-colored marble, and soon become so hard that they ring beneath the hoof beats of a galloping horse, but retain scarcely a trace of his foot-prints.

Such bare, level mud plains are characteristic features of the greater part of the valleys of Nevada, and are known in Mexico and adjacent portions of the United States as playas. The lakes to which they owe their origin are termed playa lakes. . . . . The largest ephemeral lake of Nevada is formed during winter months on what is known as Black Rock Desert in the northwestern part of the State. This desert valley is irregular in shape, and has lateral valleys opening from it. Its length from northeast to southwest is over one hundred miles, and its average breadth twelve or fifteen miles. In summer it is almost entirely without tributary streams, except such as are fed by hot springs. In winter many brooks descend the mountains to the east and west; and the channel of Quinn River, which enters the basin from the northeast, is transformed into a veritable river. The course of this stream in summer is marked only by a dry channel, with an occasional water hole; but in winter it is flooded so as frequently to be impassable to a man on horseback, and has a length of upward of a hundred miles. Its waters then spread out on Black Rock Desert, and at times form a long narrow lake from 450 to 500 square miles in area. Although seldom over a few inches deep, it is impassable on account of the softness of the mud forming its bottom. Many times the "lake" is a vast sheet of liquid mud, and for this reason is known as "Mud Lake" by the settlers of the region. This name is not distinctive, however, as many other playas have the same name attached to them. . . . .

The winter lakes on Black Rock and Smoke Creek deserts, as in many other similar instances, do not occupy the entire valley bottom, but are surrounded by a broad fringe of what to the eye appears level land. This broadening tract is covered with sagebrush and other desert shrubs. In early spring many flowers beautify the ground, and fill the air with a faint perfume. The playas left by the desiccation of the lake, however, are always barren. Not a plant takes root in their baked and hardened surfaces. Where these mud-plains meet the surrounding areas clothed with desert shrubs, there is often a belt of ground that is soft and marshy in winter, and frequently retains something of this character after the lakes have disappeared. In summer it becomes white with salts brought from below by ascending water, and left on the surface when evaporation takes place. These efflorescent deposits become unusually abundant about some of the hot springs, and are then apt to contain borax in addition to the sulphate and carbonate of soda, common salt, etc., which make up the bulk of such incrustations. . . . .

North Carson and South Carson lakes are of the playa type, but are more persistent than the lakes of Black Rock and Smoke Creek deserts. They sometimes hold their integrity for a succession of years, but evaporate to dryness during seasons of more than usual aridity. North Carson Lake is rudely elliptical in outline, and is from 20 to 25 miles across from east to west, and about 14 miles broad from north to south. That its depth is never over a few feet, has been shown by examining its bed when dry. . . . .

Hundreds of other inclosed basins, particularly in southern Nevada, are partially flooded in winter in a similar manner to those already enumerated, and become desert plains of hardened mud in summer. Various portions of the region surrounding Nevada, and especially those embraced within the boundaries of Utah, Arizona, and California, experience changes similar to those just described, and illustrate some of the most striking peculiarities of a region where the topographic and climatic conditions favor the existence of temporary lakes.

Numerous playa lakes are also found in Australia and in Africa, especially in the Kalahari, and may be looked upon as common features of desert regions where the regolith is not sufficiently deep and sandy to absorb all of the occasionally precipitated water. Playa formations are not necessarily accompanied by conspicuous saline deposits since the clay washed in, and subsiding each year prevents re-solution of the buried salts and may largely exceed them in quantity. The amount of salt will also depend upon the area of the playa to the catchment area and the extent to which ground water contributes. In old desert regions such as the Kalihari there may be thus wide playa surfaces where water stands for a longer or shorter period. Speaking of the Kalihari, Brewer states that "Lake Ngami is fresh in the rainy season, but covers much less surface in the dry season, and is then brackish; and the other lakes of this desert are described as brackish rather than salt."[1]

Nature of the geological records.—The preceding is a description of playa surfaces. In the absence of descriptions of partially eroded playa deposits seen in cross-section the following statement of the characteristics which they would presumably show when incorporated into the geological record must be to some extent deductive and open to corroboration by observation.

[1] Wm. H. Brewer, *Warren's New Physical Geography.*

Playas will be flooded with water partly by means of stream channels, partly by a general wash from the outside over the slopes, partly by a gradual rise of the water level flooding the surface from the inside. In places of inflowing currents, the cracks should fill up with sand and thereby permanently preserve the structure; in places where clay settles in from quiet water, the infiltration may be almost identically the character of the wall materials and the former presence of the crack therefore escape record. The water stands over the flat bottom in periods varying from a few days to a few years, according as to whether it is an evanescent playa or one dry only during an occasional year. The periods of desiccation will vary in inverse order. In general, however, it may be said that the playa bottoms become thoroughly wet for a depth of several feet and undergo some months of desiccation with the formation of deep mud-cracks. Where the deposits are perfectly homogeneous and result in massive saline clays there may be no permanent record of the cracks. As playas are characteristic of typically desert regions there is but little likelihood of the incorporation of an organic record, either of leaves, bones, or tracks. As embodied in the geological record playas should occupy the centers of flat basins in mature desert regions, and in that case their deposits may conceivably attain a thickness of several thousand feet as the mountains are gradually leveled off and their waste accumulated in the tectonic intermontane troughs. Such deposits as seen in cross-section would pass irregularly into marginal waste slopes of coarser material and these in turn end unconformably against the sloping walls of the buried portion of the mountains. Thus their basin nature and limited extent would be evident.

Unless protected, however, by an invasion of the sea or a change to a pluvial climate such deposits as well as the intermediate rocky barriers will gradually be removed by deflation, as Passarge has shown,[1] and the desert will pass into the stages of old age as exemplified by the Kalihari. Throughout this process of erosion shallow playas play an important rôle, since the occasional rains wash the surrounding waste into them and thus tend to maintain a level

[1] "Rumpfflächen und Inselberg," *Zeitsch. deut. geol. Gesellsch.*, LVI (1904), Protokol., pp. 193–209. Review by W. M. Davis, *Science*, N. S., Vol.XXI, p. 825.

surface. But such deposits must be very shallow since as soon as insolation and deflation have lowered the surrounding tracts these in turn become playa basins and the waste of the former one suffers removal.

Thus ancient playa deposits may be of importance in certain intermontane desert basins of the Tertiary or earlier periods, now suffering stream dissection and exposure, but those of topographically old deserts can be of no importance except possibly as the occasional surface veneer of an ancient continent, such as that of the pre-Cambrian, when it passes unconformably beneath the deposits formed by a marine transgression. In such an event, however, they would doubtless be partly destroyed through marine planation.

MUD-CRACKS MARGINAL TO INTERIOR LAKES

Description.—There are many regions of the world showing all transitions between true salt lakes and fresh-water lakes with perennial outflow.

Where evaporation does not quite balance the inflow of water there may be an occasional discharge, either at the end of the rainy season or only during a series of rainy years. Such lakes without being salt show fluctuating shores, usually very flat, since the water does not stand sufficiently long at one level for the characteristic beach slopes to form. Wide expanses, therefore, may become sun-cracked and thoroughly hardened before the next rise of the lake waters occurs and deposits over them another layer of clay.

Prominent examples of this class of lakes are Titicaca in South America, 80 miles long by 40 broad, and Lakes Tanganyika and Tchad in Africa. Lake Sistan in Persia with a breadth of 60 miles and a length of 100 has been known to go completely dry, while in occasional years during times of heavy flood it sends a stream of water down the Shila.

Nature of the geological record.—In some respects the structures recorded in the formation of the successive laminæ will be similar to playas, but differ in that the exposed area is a transitional belt between a relatively permanent water body and a permanent land surface with its wind and stream-borne detritus. It is more subject to wave-action, building occasional beaches; it may not be salt and may be the seat of a considerable assemblage of living forms. The result is that the lake clays need not be saline, but are likely to be leached of iron or be even carbonaceous and fossiliferous. Footprints may also be common on the shores and the remains of land plants, and animals may become entombed in the deposits. The wash of nearby land waste and the action of waves may fill up the mud-cracks with sand and thus lead to their permanent preservation.

Interior seas are unstable bodies whose shores are ever varying, and which are finally destined to be either dried up into playas, the fate of Lake Lahontan, or to be filled up with sediment, giving rise to river flood-plains, the fate at present overtaking Lake Titicaca, or by becoming fresh to be drained by cutting down an outlet, a change at present in progress in several of the large African lakes.[1] As seen in geological section the mud-cracked margin should be transitional on any one horizon between fine-grained, paper-thin, lake clays, on the one hand, showing no mud-cracks, and the coarser slopes of land waste on the other. In ascending through the formation such mud-cracked shales should oscillate laterally and occupy but a portion of the series. They could hardly, therefore, be a characteristic feature of the sediments in general, nor even of the bodies of shales originating in the lakes of interior basins.

MUD-CRACKS OF RIVER FLOOD-PLAINS

Description of present conditions.—Over all river flood-plains inundations periodically take place, and as the flood waters gradually drain away, a large quantity of fine mud is left upon the surface, perpetually renewing the fertility of the soil. Where the climate is humid, as over the delta of the Mississippi, such regions become seats of luxuriant verdure, while on the contrary in arid or semi-arid regions, an evanescent vegetation may spring up following the flood, but as soon as the water is drained away and the level of the ground water sinks beyond the reach of the plant roots the region becomes a desert until the period of the next inundation. Such regions are abundant over the desert belt of the world, the flood plains of Egypt, of Mesopotamia, and of the Indus River being

[1] Albrecht Penck, "Climatic Features in the Land Surface, *American Journal Science*, Vol. XIX, p. 171 (1905).

familiar examples.[1] In such regions the conditions of mud-crack formation are at a maximum and may extend to the margin of the littoral zone.[2] Consequently carbonaceous deposits and mud-cracks both mark the land surfaces of aggrading rivers, the one a maximum in pluvial climates, the other in arid. Mud-cracks, as contrasted with coal beds, may thus serve as an index to ancient climates as well as possessing a stratigraphic significance.

In applying this distinction to the earlier geological periods it should be held in mind, however, that there is no evidence of an arboreal or even herbaceous vegetable covering to the land previous to the Silurian, and its surface was presumably devoid of life save possibly that of the lowest cryptogams. Under such circumstances the indications of the presence of former flood-plain surfaces by means of carbonaceous deposits or deoxidizing effects upon the ferric oxide might be entirely absent. Mud-cracks would be the safest remaining indication of the flood-plain nature of the land surface over the regions where the character of the detritus was suitable and periods of desiccation were sufficiently long for the formation of the cracks and hardening of the successive surface layers.

The necessary fineness of deposit is frequently not found on the sandy or gravelly fans of mountain streams, and hence a large per cent. of stream-built deposits could not be expected to show this feature. The necessary conditions are found, however, on all streams of small gradient which broadly overflow their channels, this being characteristically the case of the larger rivers in the lower portions of their courses and especially over the delta, where the argillaceous nature of the deposits is well known. Broadly speaking then, the formation of mud-cracks is non-essential on slopes of piedmont river waste, but is especially characteristic of the larger river plain and delta deposits of arid and subarid climates. That the phenomenon is not strictly confined to even subarid climates is, however, true since humid climates may have their seasons of dryness.

[1] See for illustration, Daniel Trembly Macdougal, "The Delta of the Rio Colorado" (with map by Godfrey Sykes), *American Geographical Society*, Jan. '06.

[2] Walther, *Das Getz der Wüstenbildung*, 1900, also mentions the occurrence of mud-cracks on arid flood-plains. See *Trockenrissen* in index.

Nature of the geological record.—Flood-plains differ from playas and the shores of interior lakes in important particulars. Playas are formed in local basins or as the ends of desert rivers, usually of limited length. Playas do not fill up valleys from which the rivers escape, but are entirely phenomena of interior drainage. They are not built out against the sea and the deposits are at least brackish from the inclosed salts.

The flood-plain of an aggrading river covers a wide area, in the case of the larger rivers measured by thousands of square miles. It is all periodically subject to inundations which may last for a few days or weeks, but leave the greater part of the surface exposed to the air during much of the year. The invading flood waters frequently sweep sand with them, but after the flood is at its height the waters drain away quietly and much of the fine clay is deposited from suspension. Thus on river flood-plains there is peculiar liability to form well-interstratified deposits of sand and clay: to fill up the last-formed mud-cracks with coarser material, and hence permanently to record them through the varying composition and structure of the formation. Such successive strata of the same nature may be indefinitely accumulated.

Such valleys even in desert regions commonly support considerable life. Drifting vegetation is liable to become buried and animals crossing the half-dried flats in search of fresh water may leave through their foot-prints a record of their visits. The periods of desiccation are seasonal and sufficient to harden this record of cracks, rain-prints, and foot-prints to such an extent that the next invasion of water does not wash it out, but by depositing upon it a new layer of sediment permanently preserves it. As the main streams or their distributaries wander over the plain from century to century they form a network of channels which cut through the preceding fine-grained layers of the flood-plains, and the channels become filled with sand or even gravel, as they are finally abandoned for new courses. They may be distinguished from the beach sands and gravels of lakes from their linear, treelike arrangement, their occasional cutting-down into the finer-graind layers, and their occurrence far from the margins of the basin.

The mud-cracked strata of flood-plains not only stand excellent chances of temporary preserval until buried, but since the surfaces upon which the fine-grained river waste is deposited are ordinarily near the level of the sea and are also in the case of the greater deposits frequently regions of subsidence, the chances for ultimate preserval of the bulk of the formation is, in such cases, as favorable as that of the true marine shallow-water deposits.

Again, flood-plain surfaces are not of a transitional or temporary geological nature, like the margins of interior lakes, or the borders of the sea, but they are the ultimate physiographic forms toward which both lakes and shallow seas tend by the filling-in of river waste. They are of broad occurrence at all times of continental extension and erosion, and should be looked for in the geological column as only second in importance to the off-shore deposits of the continental shelves and seas. But although flood-plains are most commonly built near the margins of the land and encroaching as deltas upon shallow seas, they are also found to occur over the regions of gräben or troughs of subsidence, such as those of the Rhine, and of other tectonic valleys, and also over interior basins. Murray has estimated the desert areas, that is those which do not drain to the sea, as one-fifth of the continental areas. Doubtless, at least another fifth is possessed of a climate marked by sufficient seasons of drought to allow the broad formation of mud-cracks upon flood-plains, following the subsidence of the flood waters.

This natural condition is, however, largely modified at the present time by the agency of man, since, by regulating the floods and by systems of irrigation, such regions become the seat of populous societies. It has been shown in the previous article that the deposits of flood-plains should enter more largely into the geological record than is usually appreciated. Combining this conclusion with these considerations in regard to climate it is seen that in those past times, which corresponded in general to present conditions, an appreciable fraction of argillaceous deposits should be characterized by mud-cracks formed upon flood-plains, and, on the other hand, in regions where the mud-cracks of the period are missing, another appreciable fraction should by their carbonaceous and organic contents bear witness of the verdure which prevails upon the river plains of pluvial climates.

Besides these general stratigraphical relations which should characterize the mud-cracked deposits of arid flood-plains may be mentioned other associated characteristics, some of which are pointed out by Walther.[1] Such deposits are usually rather barren of fossils of water-living forms; the latter, if present, are apt to be restricted to the lines of sandstone which mark the ancient channels[2] or to the deposits of shallow lagoons. The flood plain proper is more likely to contain the remains of air-breathing forms, but as conditions must have been frequently unfavorable for their life or for their preserval after death the strata are more usually barren.

Further, land deposits on account of the local and annual variations of conditions are apt to show various sorts of deposits—water borne, wind borne, organic, and volcanic, in close association but differentiated from each other. Marine deposits are not subject to this rapid variation and more gradual transitions are observed.

Deposits formed in rivers or in lakes and seas have usually greenish or bluish shades of color as in marine deposits. Those subjected to subaërial exposure, however, under arid or subarid conditions are apt to possess a normal content of iron owing to the absence of carbon and the opportunity for complete oxidation following the subsidence of the ground water. The river muds from which the iron has not been leached by the deoxidizing influence of vegetation may thus be yellow, brown, or red. In well-lithified but still unmetamorphosed formations, in which the iron still exists in the form of a free oxide, reds predominate, whereas in modern muds derived from the erosion of granite lands yellow or brown is observed to be the prevailing color. But Crosby[3] has shown that a gradual dehydration of the ferric oxide serves to transform colors originally yellow and brown into deep red or vermilion.

River deltas normally contain abandoned channels or lower tracts of country not yet built up which are more or less permanently flooded with fresh water. Such are usually the seats of luxuriant vegetable growth and abundant animal life, even under climates where the

[1] *Einleitung in die Geologie* (1893), pp. 719–26.

[2] J. B. Hatcher, "Origin of the Oligocene and Miocene Deposits of the Great Plains," *American Philosophical Society*, Vol. XLI (1902).

[3] "On the Contrast in Color of the Soils of High and Low Latitudes," *American Geologist*, Vol. VIII (1891), pp. 72–82.

other portions of the delta may be dry and barren during a greater portion of the year. The decaying material of such fresh-water swamps, being preserved by the water covering, will serve to deoxidize the iron to the ferrous state, and even if the carbon is not sufficient in amount to color by its balance the argillaceous strata to brown or black, its former presence will still be indicated by gray or green bands of shales. Thus delta regions of subarid climates are peculiarly liable to be forming deposits which will ultimately become variegated shales, in which maroon, deep red, or vermilion bands will pass, sometimes almost without change of texture, into bands of grayish-white or green. An example of such variegated strata recently made is described by Huntingdon as having formed in the basin of eastern Persia and Sistan.[1]

The seaward portion of the delta surface is also frequently covered between the distributaries by brackish or salt-water lagoons and bays, as in the Nile and Mississippi deltas, protected from the waves and possibly containing considerable life of estuarine types, whose decay will lead in the same manner to variegated shales.

In truly arid climates, however, such river or sea lagoons are the seats of progressive evaporation giving rise to such salt pools as front the northern portion of the Caspian Sea or the recent gypsum deposits of the Isthmus of Suez. The degree of aridity and of the severance of the lagoons from the sea will determine the kind and amount of the chemical precipitation. It would seem, therefore, that the mud-cracked red beds originating on the delta surface of an arid climate should frequently be interstratified with mud-cracked beds holding salt or gypsum, a less arid condition leading more usually to the production of variegated shales.

MUD-CRACKS OF THE LITTORAL ZONE

Discussion as to present origin.—The littoral zone is one of the most sharply delimited of the natural physiographic divisions, forming a narrow belt between the sea and the land and defined here as comprising the zone between the average highest and lowest tides of the month. To form mud-cracks the deposit must be exposed to the sun or air sufficiently long to be dried out to such a depth

[1] *Carnegie Institution Publications* (1905), pp. 285 ff.

that the underground capillary rise is no longer able to keep the surface wet. This time limit will vary with the climate and the texture of the clay, but there may be immediately excluded all that portion of the littoral which is wet twice per day; in other words, all that portion of the littoral below the upper limit of the neap tides. This may be modified to some extent by strong off-shore winds. In the temperate zone such winds, being usually of a cyclonic nature, are frequently accompanied by rain; but where not, it is possible that by this means the tidal rise may be prevented from reaching its normal level by some feet and mud-cracks formed in the meantime somewhat below the usual level. In the latitudes of monsoon winds such effects might be seasonal, as is noted in the Runn of Cutch on the southeastern side of the Indus delta. Off-shore winds, therefore, will permit a wider development of mud-cracks over the upper portion of the littoral zone, but it is not probable than any appreciable areas below the level of mid-tide should be laid bare, dried, and cracked by such means. Neither has such an effect been described.

In tideless seas the fluctuations of level due to storms are important. Where there is an open reach of water, however, the waves which develop upon its surface break off-shore at a depth which the writer has seen stated somewhere as half the height of the wave below the trough of the same. This action maintains an open sea and an effective working depth, since the waves as soon as they drag on the bottom scour it out and carry the material partly on to the beach, partly into deeper water. In order, then, that any appreciable stretch of bottom normally covered by water should be laid bare, the change of water level between the on-shore and off-shore storms would have to equal at least the height of the waves of the on-shore storms.

As an instance of changes of level under favorable circumstances may be mentioned those of Lake Erie, a narrow body of fresh water 245 miles long lying in a northeast and southwest direction and therefore subject to heavy gales blowing the length of the lake from both directions. As a result Whittlesey has noted a change of level at Buffalo of 15½ feet between flood water and low water.[1] At intermediate points such as Erie and Cleveland there is naturally

[1] Dana, *Manual of Geology*, p. 202.

but little change of level. Even at the points of extreme change a lowering of eight feet below the normal level lays bare but a narrow margin, insignificant in comparison with the total area of this relatively shallow lake. In addition it is observed that such extreme conditions are never of long continuance. Therefore, until instances are cited to the contrary, it must be considered that in all bodies of open water the normal wave action maintains such a depth that off-shore gales cannot lay bare any broad tracts of bottom. Partly land-locked lagoons may in such cases run dry, but such can only form a broader fringe within the actual limits of the land. The border flood zone of tideless seas is therefore not so much due to off-shore winds as to those which blow on-shore. Such may occasionally flood wide belts of lowland, as is seen to take place around the shores of the Gulf of Mexico. By such means in tideless seas mud-cracks may originate above the normal level of the water and therefore upon the land surface, but not to any appreciable extent below the line of mean water.

In the case of the Mississippi the possibilities for the formation of mud-cracks are doubtless somewhat increased by the presence of the mud lumps described by Hilgard, convex or low conical elevations, sometimes 100 feet or more in diameter, showing their tops at the surface. These occur in the shallow waters within one to three miles of the main channel at the mouth of the Mississippi River. They originate in upheavals of the soft but tough bottom. Once formed they discharge mud from the top, the successive layers being but a fraction of an inch thick.[1] These appear to be exceptional phenomena, however, and could hardly be appealed to to account for the structure of extensively mud-cracked formations.

Returning to the consideration of seas with notable tidal ranges it is doubtful if under any climatic conditions mud-cracks could be made upon surfaces left bare by the tides for less than thirty-six hours; but as offshore winds may succeed for a couple of days or more in preventing flooding above the line of neap-flood tide, that may be taken as the limit below which mud-cracks cannot form. Taking the relative heights of the neap and spring tides above the mid-tide line as 4 to 7, this gives 21.5 per cent. or approximately

[1] J. D. Dana, *Manual of Geology* (1895), p. 197.

the upper fifth of the littoral zone as the greatest possible limit over which mud-cracks may form. The upper fifth in level may, however, comprise much more than a fifth of the area, since the salt marshes are especially developed near this level. This indicates that the more favorable places for the development of mud-cracks are either those comprising extensive salt marshes, or regions of unusually great tidal range. As an example of the latter may be cited the Bay of Fundy as pointed out by Lyell.[1]

> On the borders of even the smallest estuaries communicating with the bay, in which the tides rise sixty feet and upwards, large areas are laid dry for nearly a fortnight between the spring and neap tides, and the mud is then baked in summer by a hot sun, so that it solidifies and becomes traversed by cracks, caused by shrinkage. Portions of the hardened mud may then be taken up and removed without injury. . . . . When a shower of rain falls, the highest portion of the mud-covered flat is usually too hard to receive any impressions; while that recently uncovered by the tide near the water's edge is too soft. Between these areas a zone occurs, almost as smooth and even as a looking-glass, on which every drop forms a cavity of circular or oval form, and, if the shower be transient, these pits retain their shape permanently, being dried by the sun, and being then too firm to be effaced by the action of the succeeding tide, which deposits upon them a layer of new mud.

In connection with fossil rain-prints this calls attention to another factor in the problem of fossil foot-prints and rain-prints, structures often associated with mud-cracks, and that is the necessity of drying and hardening before the next invasion of waters which would otherwise wash out the newly made record.

Not wishing to draw an artificial distinction, however, as mud-cracks belonging to the littoral zone may be here included those made from tides of abnormal rise, especially where the water is driven upward by powerful storms. But where flooding of erosion slopes takes place the mud deposited will be ultimately washed away. Where flooding of a river flood-plain takes place, the sea temporarily invades a region which is periodically flooded by fresh water, and therefore mud-cracks in such regions are not distinctive marks of the occupancy of the sea.

It is seen then that exceptionally high tides are not important as necessary conditions for the making of mud-cracks.

[1] "On Recent and Fossil Rains," *Quarterly Journal Geological Society*, Vol. VII (1851), p. 239

As a final exception may be noted the effect of the previously mentioned monsoon winds, as seen on the Runn of Cutch, southeast of the delta of the Indus. In this case winds blowing steadily on-shore for months at a time raise the sea-level sufficiently to flood with sea-water large tracts of marshy country which during another portion of the year become an arid desert. Such conditions are, however, very exceptional and probably are most likely to occur broadly where rivers have previously built up alluvial plains, so that this seasonal extension of the littoral zone may only take place in connection with the continental deposits of rivers.

As the season of off-shore monsoon winds, during which the mud-cracks form, should be normally a season of aridity, it is likely that saline deposits from evaporated sea-water should frequently be associated with the mud-cracks. This is notably the case in the Runn of Cutch. The two features are also associated in the saline beds of New York. If the climate on the contrary is a pluvial one, the rain which would wash off the residual sea-water would also prevent the formation of mud-cracks from the sea-water *as a cause*.

To sum up: it is seen that mud-cracks are confined to an upper fraction of the littoral zone, and where occasionally formed beyond it by inundations of the sea only attain a broad development at the present time in arid regions where continental river deposits have been previously built. In this case the mud-cracked strata should be at least frequently saliferous.

Nature of the geological record.—The nature of the geological record and the features which distinguish mud-cracks of the littoral zone from those made under other conditions may be gathered from the preceding discussion of the conditions of present occurrence. The zone itself marks the transition between a subaërial and a subaqueous surface, in the case of deltas each nearly horizontal but at different levels. When the delta deposits of these three regions are seen in cross-section, the littoral will be a transition belt between continental and marine deposits. As the seashore during the accumulation of the strata was ordinarily a shifting line, as seen in cross-section, it will pass nearly horizontally between the two. If the subsiding land was receiving no river deposits, the lower surface will be an erosive surface represented by an unconformity. If the land surface had been one of river building it may underlie or overlie the littoral and marine deposits according as to whether the delta was retreating owing to subsidence or advancing owing to river building. But in either case the physical conditions of accumulation are so different upon the land and beneath the shallow sea that there is to be expected a marked contrast in the character of the contiguous continental and marine deposits.

Not only will the littoral zone be narrow and transitional in nature compared with the regions which border it on either side, but, as shown in the preceding article, its deposits are liable to suffer much destruction from the planing effect of the waves in the case of a subsiding land and are the first to suffer from subaërial erosion upon an emerging land. Only in the case of a delta building forth into a sea is there a good chance for the preserval of the littoral record. It has been further seen that mud-cracks are not a characteristic feature of the littoral, but can only originate upon its upper fifth or tenth, and in the places most favorable for ultimate preservation there is a grading into the land surface of the delta of which in arid climates the mud-cracks are more characteristic than of the littoral.

From these considerations it is seen that mud-cracks of littoral origin cannot be a characteristic or important feature of geological formations. They are by no means excluded as of occasional occurrence, but it would seem safe, where certain formations are dominated and widely characterized by mud-cracked shaly layers, to assign them to another origin and most probably to one upon a river plain receiving fluvial deposits.

To speak more particularly of the features which will be associated with the occasional mud-cracks of littoral origin may be noted the presence of beach structures of associated sands and muds, frequently fossils characteristic of the littoral zone, leaves and other débris from the land, rain-prints and the foot-prints of such land animals as frequent the shore. These will ordinarily be restricted to animals which seek food native to the littoral or cast up by the sea, as for instance the grubbing of swine for clams upon exposed mud flats, or birds which run over the flats and beaches for annelids or other small organisms.

The mud-cracks should be most frequently developed upon coasts where the tides are high, and in this case the areas of salt marsh should be rather frequently cut up by wide and deep tidal channels filled with coarser material. Yet in most mud-cracked formations such erosion of deep channels across the mud-cracked layers is conspicuously absent.

Under the subject of mud-cracks of fluvial plains the subject of variegated shales was discussed and it was concluded that in those formed under a subarid climate the conditions were especially favorable for their production. Before closing the present topic, therefore, the subject should be again mentioned, in order to find if they may not form equally readily in the littoral zone or even in estuarine or open sea portions of the zone of marine deposits. Along the littoral somewhat the same conditions of variable exposure to the air exist as upon flood plains. Below the line of low tide, however, extensive tracts are never exposed to the air except by broad changes of level, and local variations in the amount of organic matter present, to which variegated shales are presumed to chiefly owe their origin, will depend upon conditions of current and influx of sediment. Variegated colors should therefore be associated more markedly with variations of texture and composition than is necessarily the case with the deposits upon flood plains; changes more analogous with the contrast between channel sands and true flood-plain muds.

That red muds as well as blue muds of the terrigenous zone may form on ocean bottoms is indicated by the red muds chiefly found off the Brazilian coast. "Its red color is thought to be due to the great amount of hydrous peroxide of iron brought to the sea by the rivers and which cannot be reduced by organic matter, as in the case of the blue mud. The area covered by it is, however, small, and is estimated at about 100,000 square miles,"[1] while the blue muds cover some 14,000,000 square miles.

Variegated shales may therefore originate in any zone of sedimentation and under any depth of water, but those of marine origin are due to broad and slow changes upon the land and should not show any of the local variations and partial independence between color and stratification which may mark the deposits of a flood plain. Within limits variegated shales may be considered, therefore, as rather characteristic of continental and littoral deposition.

[1] W. B. Clark, *Geological Survey of New Jersey, Annual Report*, 1892, p. 223.

CONCLUSIONS ON GEOLOGICAL SIGNIFICANCE OF MUD-CRACKS

From the preceding analysis of the origin of mud-cracks, as observed at the present time and the conditions under which they would be geologically preserved, it would seem that next to coal beds formed *in situ*, or abundance of land fossils belonging to the animal kingdom, that mud-cracks form one of the surest indications of the continental origin of argillaceous deposits. The structure is also seen most commonly to originate under climatic conditions where the other tests are apt to fail.

It may be considered, therefore, that mud-cracked shales predominantly indicate former flood-plain deposits, usually on delta surfaces which have displaced shallow seas. Removed from the vicinity of the sea and occurring in continental basins with older rock rims, they may have originated as playa deposits and indicate a formerly truly desert climate.

More rarely mud-cracked shales may be found as transitional belts separating unlike formations and indicative of the sun dried margins of former lakes or seas. In any case the associated characteristics which have been pointed out should assist in arriving at a conclusion in regard to the particular conditions of origin.

PREVAILING INTERPRETATIONS

The prevailing views upon a subject are exemplified by the statements of the current textbooks and manuals. These not only guide the formation of views of the younger students of the subject, but represent the longer-established and verified opinions of the older body of scientists. While frequently specialists in various lines would regard the presentation of their departments even in the better textbooks as not strictly up to date, this is, on the whole, not without its benefits, since it is necessary for new knowledge to become seasoned with time before its exact place and importance can be assigned among the body of well-established principles.

It will be desirable in summing up the present subject to compare the conclusions just arrived at with those statements concerning the significance of mud-cracks which are given in the standard texts, and which it is believed have been largely influenced by the habit of interpreting all sediments as marine unless there was positive evidence to the contrary. It is in no spirit of adverse criticism that this is done, but in order to call sharper attention to the degree of variance with the present conclusions and the desirability of confirming or modifying the latter by further observation and analysis.

Turning first to the work of the best known of American geologists: J. D. Dana, in his *Manual of Geology*[1] stated that mud-cracks are made on drying mud flats, but with customary insight was evidently careful not to restrict them entirely to the seashore, since on the next page he refers to them as well as rain-prints as made by "exposure above the water level at low tide, or at least a low stage of the waters." Thus Dana recognizes the possible continental origin, but places the emphasis, perhaps unconsciously, upon the sea-beach or estuarine origin.

Chamberlin and Salisbury in their *Geology* (1904), Vol. I, p. 466, state that "sediments are sometimes exposed between tides, or under other circumstances, for periods long enough to permit drying and cracking at the surface."

Sir A. Geikie in his *Text Book of Geology*, 4th ed. (1903), pp. 643, 644, speaks of mud-cracks as vestiges of shores of former seas and lakes, and one of the kinds of evidence showing that a locality was sometimes laid bare of water.

James Geikie, in his *Structural and Field Geology* (1905), p. 116, mentions the present occurrence of mud-cracks around the shores of inland seas and lakes, and states that the same action may take place on low flat beaches which are exposed to a hot sun during the retreat of the tide. Although lake shores are mentioned first, no discussion is given as to the relative geological importance of the two situations in producing mud-cracks.

In none of the preceding books is the possibility mentioned of mud-cracks being formed over flood-plains of rivers and apart from permanent bodies of standing water. Yet these authors are authorities upon the subject of sedimentation and sedimentary structures, and in Sir A. Geikie's *Text Book* especially, an appreciation is constantly shown of the importance of fluviatile formations. It remains a question, therefore, if this difference of view upon the significance

[1] P. 94; see also pp. 742, 745 (1895).

of mud-cracks is due to an inheritance of expression from the past or if undue importance has been given in the present paper to mud-cracks of continental, and especially of flood-plain, origin in arid and subarid climates.

In both LeConte's and Scott's textbooks no mention is made of mud-cracks originating by any other means save by the laying-bare of tidal flats, and in both it is used as an argument proving the estuarine nature of the Newark basins; and Scott discusses the question whether the basins were parts of one or two "continuous bodies of water," p. 445.

Recently Huntingdon[1] has spoken of sun-cracks and ripple-marks taken in connection with other features as initiating continental sedimentation of the Tertiary in Central Turkestan.

> It appears as though, after the retirement of the sea, the land was covered with great playas, on which water first stood in thin sheets, forming ripple-marks in the mud and then retired or was evaporated, allowing the surface to become sun-cracked. As time went on streams began to flow across the playas, at first slow and broad and able to cut only shallow channels which were afterward filled and covered, assuming the form of very thin lenses of a material slightly different from that of the surrounding playa strata. Then, as the strength of the streams increased, sand was deposited over the whole area, and the channels, now deep and distinct, were filled with gravel. Lastly gravel was deposited almost everywhere.

So far as the writer is aware the only attempt at a discussion of the several methods of origin of mud-cracks and the relative chances of their preserval is by Penck,[2] who points out that they, as well as foot-prints and rain-prints, occur on sea-beaches, over the flood-plains of rivers and the shores of interior seas, but that the surface bearing the markings must to a certain degree have hardened and consequently have remained as a land surface for a certain length of time in order that the impressions should not be washed out by the next invasion of waters. For that to be accomplished he states that the sea-coast is less favorable than the flood-plains of rivers and the margins of lakes. In the latter cases the exposed floor dries for weeks or months and attains a considerable hardness before being again overflowed.

[1] "Explorations in Turkestan," *Carnegie Institution of Washington* (1905), pp. 164, 165.

[2] *Morphologie der Erdoberfläche* (1894), Vol. II, pp. 25, 26.

ILLUSTRATIVE GEOLOGICAL APPLICATIONS

In the preceding paper under the heading of "The Relations of Continental and Marine Sedimentation through Geological Time," it was concluded, not from a detailed study of the strata, but entirely from the broader relations at present prevailing, that at certain times in the past continental sedimentation should have played an important rôle, especially in the form of fluviatile deposits filling interior basins or displacing epicontinental seas. Having made this present examination of the different methods by which mud-cracks may originate, together with some of their associated characteristics, it will be well to apply it as a test to the conclusions of the preceding paper. If the result is a confirmation, there will thus be two largely independent lines of reasoning which arrive at the same result; a result in which therefore correspondingly more confidence may be placed.

MUD-CRACKED FORMATIONS OF THE PRE-CAMBRIAN

In both northwestern Montana and northwestern Arizona occur a series of predominantly arenaceous and argillaceous formations of great thickness which are distinctly older than the Middle Cambrian, since these lower formations were gently folded and base-leveled before the transgression of the Middle Cambrian sea. Yet these terranes are remarkably free from metamorphism and still retain their original characters. For this reason they are selected for illustration and briefly described. It was suggested in the preceding article that on account of the general nature of the deposits and the fact that the early Cambrian as well as the immediately pre-Cambrian were periods of great continental extension, the hypothesis of subaërial and fluviatile origin for certain formations should be at least entertained until disproved. It is now proposed to describe certain features of these formations in detail in order to arrive at some conclusion in regard to their continental, littoral, or marine origin, the conclusions being drawn after the presentation of the details.

PRE-CAMBRIAN FORMATIONS OF MONTANA

These are described by Walcott under the title of the "Belt Terrane"[1] and by Willis as the "Algonkian of the Lewis and Liv-

[1] Pre-Cambrian Fossiliferous Formations," *Bulletin Geological Society of America*, Vol. X, pp. 201, 215.

ingston ranges."[1] The two districts described above are about 150 miles apart in a general north-northwest and south-southeast direction; and as the intermediate region has not been studied in detail, Willis does not pretend to correlate closely the several formations described by him in the northwest with those described by Walcott from the district near Helena, but the similarity of sequence is sufficiently striking to warrant placing them in juxtaposition as is done below.

BELT FORMATION, HELENA REGION—WALCOTT	Thickness in feet	ALGONKIAN OF NORTHWEST MONTANA, LEWIS AND LIVINGSTON RANGES—WILLIS	Thickness in feet
Marsh shales	300	Kintla argillite / Sheppard Quartzite	800+ / 700±
Helena limestone	2,400	Siyeh limestone	4,000
Empire shales	600		
Spokane shales	1,500	Grinnell argillite	1,000 to 1,800
Greyson shales	3,000	Appekunny argillite	2,000+
Newland limestone	2,000	Altyn limestone	1,400+
Chamberlain shales	1,500	(Bottom of limestone not exposed)	
Neihart quartzites and sandstone	700		
	12,000		9,900 to 10,700

Brief descriptions of these formations are quoted as follows, those of the equivalent formations of the two localities being placed together:

Neihart quartzite and sandstone Helena region, Little Belt Mountains.—In this formation are included the reddish, coarse sandstones, with interbedded dark greenish layers of fine-grained sandstone and shale, beneath the Chamberlain shales. The lower 400 feet of the formation is a massive, sometimes cross-bedded quartzite, which, in some of its members, where unaltered, is a compact, hard sandstone. The prevailing color is pinkish-gray on the freshly exposed surface, with dark and iron-stained weathered surface. Occasional layers of a fine conglomerate occur in some portions near the contact with the gneiss.[2]

About 300 feet above the base the character of the formation changes. The pink and white pure quartzites are replaced by more thinly bedded rocks, no longer of pure arenaceous material, but containing an admixture of greenish mica, which higher in the group forms the layers of mica shales interbedded with the quartzite. The higher strata are still more impure and the quartzite beds are but six to twelve inches thick, blackened by carbonaceous material that now forms a prominent feature of the intervening shales, becoming increasingly abundant until the latter rocks are true black shales in which the green mica no

[1] "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *ibid.*, Vol. XIII, pp. 316–24.

[2] *Bulletin Geological Society of America*, Vol. X, p. 204.

longer shows. At the same time the quartzite beds decrease in thickness and purity, while the interbedded shale increases in thickness and purity, so that an arbitrary line must be drawn separating the two formations.[1]

Chamberlain shales, Helena region, Little Belt Mountains.—This formation is composed of a series of dark silicious and in places arenaceous shales. Ripple-marks, mud-flows, and sun-cracks were occasionally seen, but no traces of life were observed. The dark shales frequently form low cliffs along the canyon side, near the beds of the streams.[2]

Newland limestone, Helena region, Little Belt Mountains.—At the typical locality on Newland Creek the limestones are thin bedded, the layers averaging from two to six inches, with shaly partings of variable thickness between them. In the section of Sawmill Canyon, near Neihart, the layers are somewhat thicker, more impure, and with a greater number of beds of interbedded shale. The prevailing color of the limestone is dark bluish-gray on fresh fracture, and buff to straw color on the weathered surface.[3]

Altyn limestone, Lewis and Livingston Ranges.—Limestone, of which two members are distinguished; an upper member of argillaceous, ferruginous limestone, yellow, terra-cotta, brown, and garnet-red, very thin-bedded; thickness about 600 feet; . . . . and a lower member of massive limestone, grayish-blue, heavy-bedded, somewhat silicious, with many flattened concretions, rarely but definitely fossiliferous; thickness, about 800 feet.[4]

Greyson shales, Helena region, Little Belt Mountains.—Dark-colored, coarse, silicious, and arenaceous shales, passing above into bluish-gray, almost fissile shale, which, when broken up, weather to a light gray fissile shale, resembling a poor quality of porcelain. These in turn are succeeded by dark gray silicious and arenaceous shales, with interbedded bands of buff-colored sandy shales and occasional layers of hard, compact, greenish-gray and drab silicious rock. At the base of this series, in Deep Creek Canyon, a belt of quartzites occurs, interbedded with shales, the base of the quartzites showing ten feet of interformational conglomerates, composed of sand and pebbles up to eight inches in diameter, and derived from the subjacent Belt rocks.[5]

Appekunny argillite Lewis and Livingston Ranges.—The Appekunny argillite is a mass of highly silicious, argillaceous sediment approximately 2,000 feet in thickness. Being in general of a dark gray color, it is very distinct between the yellow limestones below and the red argillites above. The mass is very thin bedded, the layers varying from a quarter of an inch to two feet in thickness. Variation is frequent from greenish-black argillaceous beds to those which are reddish and whitish. There are several definite horizons of whitish quartzite from fifteen to twenty feet thick. The strata are frequently ripple-marked, and occasionally coarse grained, but nowhere conglomeratic.[6]

[1] W. H. Weed, *Geology of the Little Belt Mountains*, pp. 281, 282.

[2] *Bulletin Geological Society of America*, Vol. X, p. 206.

[3] *Ibid.* [4] *Ibid.*, Vol. XIII, p. 317. [5] *Ibid.*, Vol. X, p. 206.

[6] *Ibid.*, Vol. XIII, p. 322.

Spokane shales, Helena region, fifteen miles east of Helena.—The Spokane shales occur as massive beds of silicious and arenaceous shales of a deep red color. The arenaceous shaly portions frequently thicken up into thin layers of sandstone. The shales break down on exposure, but they are usually sufficiently firm to resist erosion and form strongly marked slopes and cliffs.[1]

The present writer had an opportunity in 1901 of examining the Spokane about 20 miles northwest of Helena and found the shaly layers frequently mud-cracked.

Grinnell argellite, Lewis and Livingston Ranges.—A mass of red rocks of predominantly shaly argillaceous character is termed the Grinnell argillite from its characteristic occurrence with a thickness of about 1,800 feet in Mount Grinnell. These beds are generally ripple-marked, exhibit mud-cracks and the irregular surfaces of shallow water deposits. They appear to vary considerably in thickness, the maximum measurement having been obtained in the typical locality, while elsewhere to the north and northwest not more than 1,000 feet were found. It is possible that more detailed stratigraphic study may develop the fact that the Grinnell and Appeknuny argillites are really phases of one great formation, and that the line of distinction between them is one diagonal to the stratification. The physical characters of the rocks closely resemble those of the Chemung and Catskill of New York, and it is desirable initially to recognize the possibility of their having similar interrelations.[2]

Empire shales, Helena region, twenty miles northwest of Helena.—These are greenish-gray massively bedded, banded, silicious shales.

Helena limestone, Helena region, Helena.—The Helena limestone formation is composed of more or less impure bluish-gray and gray limestone, in thick layers, which weathers to a buff and in many places to a light gray color. Irregular bands of broken oölitic and concretionary limestone occur at various horizons. Bands of dark and gray silicious shale and greenish and purplish argillaceous shale are interbedded in the limestones. These bands are from half an inch to several feet in thickness. There are also beds of thinner bedded limestones, especially toward the top of the formation.[3]

Siyeh limestone, Lewis and Livingston Ranges.—Next above the Grinnell argillite is a conspicuous formation, the Siyeh limestone, which rests upon the red shales with a sharp plane of distinction, but apparently conformably. The Siyeh is in general an exceedingly massive limestone, heavily bedded in courses two to six feet thick like masonry. . . . . Occasionally it assumes slabby forms and contains argillaceous layers. It is dark blue or grayish, weathering buff, and is so jointed as to develop large rectangular blocks and cliffs of extraordinary height and steepness. Its thickness, as determined in the nearly vertical cliff of mount Siyeh, is about 4,000 feet.[4]

[1] *Bulletin Geological Society of America*, Vol. X, p. 207.

[2] *Ibid.*, Vol. XIII, p. 322.

[3] *Ibid.*, Vol. X, p. 207.

[4] *Ibid.*, Vol. XIII, p. 323.

Sheppard quartzite, Lewis and Livingston Ranges.—A distinctly sandy phase of deposition succeeding the extrusive rhyolitic eruption capping the Siyeh limestone has resulted in a quartzite which is very roughly estimated to have a thickness of 700 feet.[1]

The present writer has observed a basal quartzite to the Marsh shales in a similar stratigraphic relation upon Greenhorn Mountain, sixteen miles northwest of Helena. But the occurrence of the quartzite was lenslike and not persistent for many miles.

Marsh shales, Helena region.—At Helena there is a thickness of about 250 feet of shales and thin-bedded sandstones of the Belt Terrane above the Helena limestone and beneath the Cambrian sandstones. The same bed, on the north side of Mount Helena, is reduced to 75 feet in thickness, but to the northwest the formation increases in thickness to 300 feet or more.[2]

Kintla argillite, Lewis and Livingston Ranges.—Argillite and quartzite, thin-bedded, maroon red, ripple-marked, and sun-cracked, containing casts of salt crystals; also occasional beds of white quartzite and some calcareous; thickness 800 feet; no upper limit seen.[3]

The Kintla formation closely resembles the Grinnell, and represents a recurrence of conditions favorable to deposition of extremely muddy, ferruginous sediment. The presence of casts of salt crystals is apparently significant of aridity, as the red character is of subaërial oxidation. The formation has an observed thickness of 800 feet, but no overlying rocks were found. Its total thickness is not known, and the series remains incomplete.[4]

Discussion.—The very similar general nature of these formations at a distance of 150 miles from each other indicates similar conditions of accumulation over wide areas, though it is possible of course that the stratigraphic cycle was not strictly contemporaneous in the two regions. The volume of material which must have been eroded to supply these sediments was far greater than the volume of the sediments, since the one kind of sediments of any epoch, occurring at *both* localities, represents but a portion and, in the case of the limestones and quartzites, but a small portion, of the rock masses whose erosion supplied the material.

Taking Clarke's figures[5] of the average amounts of the oxides and common minerals in the "primitive crust of the earth" it is seen that an approximately pure dolomite which should contain all of

[1] *Ibid.*, p. 324.

[2] *Ibid.*, Vol. X, p. 207.

[3] *Ibid.*, p. 316.

[4] *Ibid.*, Vol. XIII, p. 324.

[5] "Analysis of Rocks, Laboratory of the U. S. Geological Survey," *Bulletin U. S. Geological Survey No. 168* (1899), pp. 14, 16.

the lime and magnesia of a primitive rock mass would contain but about one-tenth of the original, and in volume, allowing for the carbon dioxide in combination with bases, would roughly represent about a fifth of the original. In this case, however, since the material has been deposited from solution, it does not signify a necessary origin from contiguous land masses.

The average igneous rock, containing, according to Clarke, 10 per cent. of quartz, a pure quartzite will represent less than one-eighth of the original rock mass, but an argillite, containing variable amounts of the original quartz and additional water and carbon dioxide combined with the bases, represents a far higher, but indefinite, proportion of the original rock mass. Quartzites and argillites, however, since they cannot be transported across deep bodies of water imply contiguous land. The great thickness and similarity of the arenaceous and argillaceous formations over a wide area point to an originally still more widely spread character, since there is no indication that these districts were near the original limits. But their volume indicates deep erosion of a correspondingly extensive contiguous land. The formations do not show the local variations and conglomeratic nature which would indicate the erosion of a nearby mountain range, and therefore the denudation must have taken place from a wide area. The similar formations which are known to exist in British Columbia, Utah, Nevada, California, and Arizona emphasize still further the profound erosion of widespread adjacent land masses of late pre-Cambrian time.

Thus a detailed examination of the composition and texture of these Montana formations allows inferences confirming *for this region* the statements made in the previous article from more general grounds concerning the wide development of the continents in the later pre-Cambrian times.

In regard to the topographic and sedimentary cycles expressed by the succession and character of the formations it is seen that the two great limestones represent long-enduring incursions of the sea, while the quartzites and argillites represent the uplift and erosion of neighboring lands of large area.

The Neihart quartzite.—The cleanness and partially deferrized character of the basal formation, the Neihart quartzite, indicates shallow water off-shore deposit, subject to the prolonged sorting and attrition characteristic of the work of currents and waves or of desert winds resulting in the accumulation of dune sands. The latter idea is perhaps made improbable by the transition into, and alternation with, the deoxidized and carbonaceous lower members of the Chamberlain shales.

The Chamberlain shales grade, on the one hand, into the underlying quartzite and, on the other, into the Newland limestone. These relations, in addition to the dark silicious and occasionally arenaceous character and occasional ripple-marks, suggest a quiet offshore formation. The mud-cracks noted by Walcott may be either of littoral or fluvial origin, but in either case imply a nearby land. The lack of a more arenaceous character may be due, therefore, to a topographic old age and lessened stream gradients of the land, or to the river material having been borne from a great distance.

Newland and Altyn limestones.—The inauguration of the era of the Newland and Altyn limestones may be due as much to the lack of supply of mechanical sediments as to subsidence and incursion of the sea.

Greyson and Appekunny argillites.—Following the limestone came some 2,000 to 3,000 feet of Greyson and Appekunny argillites. The generally dark gray color, thin-bedded lamination, occasional ripple-marks, and quartzitic strata suggest the submarine deposits poured into a sea as a result of the re-elevation of a contiguous land.

The association with the limestone below, the absence of conglomerates and observed mud-cracks, and the contrast in color with the deep-red and mud-cracked formation above all tend to confirm this interpretation.

The Spokane and Grinnell argillites, from 1,000 to 2,000 feet in thickness, on this view represent subaërial delta deposits over a region where sedimentation had gained upon subsidence to such an extent as to fill up and exclude the sea. In contrast to the inferior argillites are to be noted the highly oxidized character indicated by the deep red color, the frequent alternations of sandstone strata, and especially the widespread occurrence of mud-cracks. These are not sparingly present and developed in strata transitional between two distinct types, as would be characteristic of mud-cracks of the littoral zone, but on the contrary are developed in the normal red shales. Furthermore, the exposed sections show throughout a marked sameness in color and a similar repetition of argillaceous and arenaceous beds. The areal extent, the fineness and evenness of grain, combined with the evidences of aridity, bespeak an extensive delta fan, comparable in size and climatic environment to those of certain of the larger Asiatic rivers of the present time.

The lack of knowledge as to the extent and relations of the formation will not allow of a closer comparison, but it is seen that it represents the continental culmination of the sedimentary cycle as the preceding Newland and Altyn limestones represented the opposite or marine phase.

The cycle appears to be less dependent here upon a mere transgression and recession of the sea as the active agent, than upon the wasting-away and the rejuvenation of adjacent land masses, which, upon being re-elevated, supply such a flood of sediment as to crowd back and dispossess the sea, the subsidence of the geosyncline going forward more or less continuously but at a variable rate.

The succeeding formations of this terrane indicate a repetition of this cycle, the Empire shales, showing greens and grays and passing into the upper limestones, doubtless represent the submarine deposits made during the transgression of the sea across the subsiding former delta surface. Then followed several thousand feet of limestone formation. This is largely thin bedded and shaly in the upper portions in the Helena region and various features described elsewhere suggest that it was largely accumulated in a shallow sea. This limestone was succeeded in places by quartzites which suggest wave-sorted deposits, and finally by a deep red mud-cracked series of argillites, somewhat similar to the Spokane-Grinnell formation, suggestive once more of land deposition under conditions of aridity. The thickness of this formation varies widely, the upper surface being a base-level erosion surface upon which is superimposed the Middle Cambrian marine transgression across a far-reaching and topographically ancient land.

THE GRAND CANYON SERIES OF ARIZONA

Leaving the preceding region and passing to the Grand Canyon of Arizona, some 750 miles south of Helena and some 950 miles south of the international boundary, a different series of rocks is found to occur, but one holding a similar stratigraphic position, being embraced between the metamorphic formations of the Vishnu and Archean below and the unconformable Middle-Cambrian above. Walcott gives the series a total thickness of 11,950 feet, divided into two terranes, the upper or Chuar containing 5,120 feet of strata of which 285 feet are limestones and 4,835 feet brown to black or variegated shales and some reddish-brown sandstones. The lower or Unkar terrane attains a total thickness of 6,830 feet of which from 110 to 210 feet are limestones and the balance brown to vermilion sandstones and shaly sandstones with a basal conglomerate 30 feet in thickness. The Unkar is characterized by a great thickness of reddish-brown sandstones. The detailed section of the Unkar as given by Walcott follows, the italics being introduced:[1]

SECTION FROM THE SUMMIT DOWNWARD	FEET
1. a) Massive bed of gray to reddish magnesian limestone, passing below into a calciferous sand rock	50–150
b) Light gray, shaly sandstone	25
c) Irregular, massive beds of yellowish-brown sandstone	50
d) Partially crossbedded, fine grained, purplish-brown sandstone.	50
e) Reddish-brown sandstone and sandy shales, ripple-marked.	200
	475
2. Lava beds:	
a) Nine lava flows aggregating	770
b) Interbedded sandstones	30
At Chuar lava hill the lava beds are 1,000 feet thick.	
	800
3. Sandstones (upper)	
a) Shaly, vermilion, rather fine-grained sandstones, with intercalated bands of greenish-gray, followed below by 700 feet of vermilion beds of a uniform character, and massive beds with arenaceous, shaly partings, the massive beds breaking up into shale and sandstone on the talus slopes. *Ripple-marks and shrinkage cracks characterize the upper, shaly beds*	1730
b) The vermilion sandstones of a) pass into chocolate colored sandstones, that for 125 feet down unite in the general slope of the beds above. Below, a cliff is formed of five massive bands of chocolate-colored, slightly micaceous sandstone, separated by shaly sandstone partings of a greenish color below and a chocolate color above	925
c) Reddish-brown to chocolate, more or less shaly sandstone, 125 feet, underlain by 300 feet of friable sandstone and arenaceous and micaceous shale	425
d) Irregularly bedded, compact sandstone:	
Curiously twisted and gnarled layers	15
Massive, grayish layer	10
Light gray layer with reddish spots, friable, shaly in places	125
	3230

[1] "Pre-Cambrian Igneous Rocks of the Unkar Terrane," *Fourteenth Annual Report* (1894) U. S. Geological Survey, Part II, pp. 510–12.

4.		Sandstones (lower):	
	a)	Compact, quartzitic, gray sand rock, 25 feet, with 65 feet of hard, compact sandstone	90
	b)	Massive, compact, cliff-forming, brown, buff, and purplish-brown sandstone	1200
	c)	1. Reddish-brown to vermilion, friable, shaly sandstone	200
		2. Brick-red, shaly sandstone	250
		3. *Brown, friable, shaly sandstone, ripple-marks and shrinkage cracks*	300
		4. Same in more massive layers, with fine, siliceous conglomerate	80
		(10 feet) at the base	80
			2120
5.	a)	Light gray limestone with interbedded laminæ of quartzitic shale	8
	b)	Brown sandstone with a bed of silicious conglomerate, 2 feet	30
	c)	Reddish cherty limestone	10
	d)	Reddish-brown limestone	2
	e)	Dark, reddish-brown slate	5
	f)	Light gray, compact shaly limestone	14
			69
6.		Dark, compact basaltic lava in one massive flow	80
7.		Light gray, compact shaly limestone with pinkish tinge between the laminæ; it is a little cherty near the base, or with thin, hard, interbedded layers of sandstone	26
8.		Silicious conglomerate formed largely of pebbles derived from the upturned edges of the pre-Unkar strata, upon which it rests unconformably	30
		Total thickness of the Unkar terrane	6830

Discussion.—The basal silicious conglomerate derived from the upturned edges of the underlying beds and followed by 175 feet of limestones containing a lava bed and some sandstone may be taken as a good indication of the invasion and continued presence of the sea.

It is noticed, however, that beginning 205 feet above the base are 10 feet of a fine silicious conglomerate which suggests a possible origin as a wave-sorted beach sand. Above this follows 370 feet of brown, friable, shaly sandstones showing ripple-marks and shrinkage cracks. These could be explained as of littoral origin by supposing that the subsidence and sedimentation remained exactly balanced so that this zone was the transition between the subaërial and submarine portions of a delta during the entire time of the deposit of the 370 feet. Even assuming a littoral origin, however, the immediate vicinity of a shore is implied and it seems a much simpler hypothesis to suppose that the mud-cracks were of flood-plain origin. Under this assumption the cracks could be more readily accounted for and it is not necessary to postulate an exact balance between the subsidence, the marine planation and the delta building during all the time of accumulation, it being only necessary to assume that sedimentation remained in excess of subsidence and that the shore was a fluctuating line, of which this locality was continually on the landward side. These mud-cracked strata form the basal portion of the lower sandstones. Above them are 1,650 feet of red buff, brown, and vermilion sandstones and shaly sandstones similar in character, but not noted by Walcott as characterized by mud-cracks. The similar characters and especially the color of the iron oxide implying complete subaërial oxidation either before or after deposition suggest a continuance of the continental conditions. If deposited beneath the sea it would be expected that the continued wave action which affects the sandy deposits of shallow seas would, at least, in part, have separated the clay and iron from the grains of sand, producing cleaner gray quartzitic layers. Such a change is, in fact, noted in the compact, quartzitic, gray sand rock which separates the lower from the upper sandstone of the Unkar.

The question arises as to why the mud-cracks should be absent from the 1,650 feet of lower sandstones, if the latter were really of subaërial origin. The answer is that, even if the necessary periods of desiccation were present between the river inundations, mud-cracks need not necessarily arise. A sandy nature is unfavorable for their development, and the strata are much more sandy, on the whole, than in the case of the Spokane and Marsh shales of the Belt terrane. Again, a canyon wall is not a favorable place upon which to observe the bedding surfaces of gently dipping strata. It is furthermore possible that mud-cracked strata which could be observed by careful search were not noted, since Walcott was not conducting the examination with that end in view as a principal object. Finally mud-cracks which were noted were not always recorded in this necessarily brief synopsis of the strata, at least if they were off the line of the section, since on p. 515 of the article cited it is stated that at Chuar Lava Butte numerous ripple-marks and mud-cracks occur among the sandstones and shales covering the uppermost lava flow, yet mud-cracks at this horizon are not mentioned in the synopsis which has been given.

Returning to the description of the Unkar stratigraphic section, the upper sandstones below the lava beds comprise 3,230 feet, nearly all being again vermilion, reddish-brown, or chocolate in color. Occasional partings of a greenish-gray are noted, and the upper shaly beds are characterized by ripple-marks and shrinkage cracks. It would seem from this that if the gray quartzite separating the upper and lower sandstones is, indeed, a beach and marine deposit, that the transgression was but temporary, the beach was pushed back and subaërial deposition continued.

Following this stage occurred a series of outpourings of lava, thin layers of sandstone separating most of the flows. The lava beds aggregate from 770 to 1,000 feet in thickness, varying this much in a distance of about four miles. The partings of shale and sandstone are widely distributed and of uniform thickness over considerable areas (p. 517) and on Chuar Lava Butte it is noted that the upper lava flow is capped by 35 feet of cholocate-brown sandstone and sandy shales with numerous ripple-marks and mud-cracks occurring among the layers (p. 515).

A study of the relations of the traps and interbedded sandstones with respect to the alternative hypotheses of marine or continental origin would probably offer some evidence in support of one view as against the other. The widespread character of the lava flows indicates that they were poured out over a level surface. The subaërial portion of a delta with a slope of normally not more than a foot per mile is more broadly level than the submerged portion, but, on the other hand, is also more cut by stream channels.

The more or less viscous nature of lava would cause the upper surface of the flows to depart from a true plane. If above the sea level the streams would tend to erode the upper surface to some extent and result in thicker deposits of sand and clays in the hollows of the upper surface, leveling it once more to grade. These effects might be less marked if the lava flows were poured out beneath the sea.

In the absence of field study with these points in view it seems best to leave the problem as an open question, but the mud-cracked layers covering the upper lava flow indicate rather strongly the subaërial origin of at least that particular sheet.

Above the last lava flow are found 250 feet of these apparently land-deposited beds followed by 50 feet of irregular massive beds of yellowish-brown sandstone and 25 feet of light gray shaly sandstone. These by their contrast in color presumably represent the off-shore deposits of a transgressing sea and are followed by 50 to 150 feet of massive, gray to reddish magnesian limestone, closing the deposits of the Unkar terrane.

The detailed section of the following Chuar terrane is not quoted in full as the beds are not described by Walcott as mud-cracked, nor do most of them by their other characters strongly suggest subaërial deposition. As previously noted, they embrace 5,120 feet of strata of which 285 feet are limestones. The greater portion of the balance consists of brown to black, gray, or variegated shales, with some reddish-brown sandstones, often shaly. Deposition in off-shore waters beyond the reach of beach action is suggested as the mode of origin of much of the formation by the prevailing difference in color, the more shaly character, and the beds of limestone scattered at intervals through the entire terrane. Occasional transitions to shore deposits of an arid climate are similarly suggested by the variegated shales, and especially masses of white and pink gypsum found in a few localities in one horizon which consists of black argillaceous shale with chocolate and greenish, sandy and argillaceous shales beneath, carrying hard layers of sandstones.

A classification of the Chuar section into appreciably calcareous and arenaceous portions suggests three movements of subsidence with invasions of the sea and four periods of halting or possibly elevation with approach of the littoral to this region, the series ending with 125 feet of massive, reddish-brown sandstone, with irregular layers of similar color and containing numerous fragments of sandstone-shale of lighter color.

The thorough and accurate observations of Walcott have made it possible to give this discussion of continental as opposed to marine origin both for the Belt and Grand Canyon series, although the problem of a possible continental origin is not discussed in the original papers and possibly was not seriously in mind, since such a question had never been raised in regard to them. Since the facts have been freely quoted, however, it is also desirable to give the observer's interpretation, which is throughout that of a marine origin. In regard to the upper lavas of the Unkar terrane Walcott states:

> The first coulée flowed over the level ocean bed, in which 5,000 feet of sediment, that now forms a reddish-brown sandstone, had accumulated on the upturned and eroded edges of the Archean, the few layers of limestone and the one flow of lava, 150 feet in thickness near the base scarcely serving to break the great sandstone series.[1]

Again the author states that

> The wide distribution of thin layers of sandstone, shale, etc., of uniform thickness over considerable areas indicates a relatively smooth sea bed at the time of the spreading of the first sheet of (the upper) lava over it; and that the sea was shallow, is shown by ripple-marks and the filling of sun-cracks.[2]

CONCLUSION ON THE NATURE OF THE PRE-CAMBRIAN SEDIMENTATION

In the absence of personal observation with the particular problem in mind any other interpretation than that given by Walcott should be held with reservation, but it has been shown that in view of the highly oxidized character of the sandstones of the Unkar terrane, and mud-cracks frequently found in the shaly beds, that the presumption is in favor of a continental origin and the burden of proof is rather upon those who would give the marine interpretation.

The discussion of these pre-Cambrian deposits but especially of the Montana occurrences, shows how completely in accord is the hypothesis of the dominant flood-plain origin of mud-cracks with the other marks of subaërial deposition in an arid climate. The mud-cracks are confined to just such formations as from other characteristics suggest a flood-plain origin and these formations are usually separated from the deposits of limestone by transitional formations which differ in color, in character, and in the absence of mud-cracks, suggesting the true submarine deposits originating between the shore and the open sea.

Assuming that a strong case has been made out for the continental origin of certain of these pre-Cambrian formations, it is seen that in the two regions examined the conclusion is justified which was reached from general considerations in the preceding paper—that the late pre-Cambrian being an aeon of wide continental extension should show in its epicontinental deposits a considerable proportion

[1] P. 504. [2] P. 517.

of subaërial origin. The two regions are unusually favorable for study in this particular, since, as previously noted, the deposits have been relatively little disturbed by later earth movements and the original sedimentary record has not been obliterated through the processes of metamorphism.

A general conclusion should be founded on a far wider study of occurrences, but such would run beyond the limits of this paper. It may be noted in passing, however, that the Montana region shows an unusual proportion of carbonate rocks, while the pre-Cambrian deposits over the world as a whole apparently are characterized by minor amounts of carbonates, rocks whose presence in notable proportions are usually the surest indication of truly marine conditions. Such a poverty in limestones may in a small measure be accounted for by a possible dominance of disintegration over decomposition in the erosion of those times, the lime thus in part not being set free and the disintegrated products giving rise upon metamorphism to a large proportion of gneisses, graywackes, and feldspathic schists, instead of quartzites, argillites and marbles.

Highly silicious rocks are, however, not uncommon, and the question arises as to where the corresponding quantities of salt, gypsum, and dolomitic limestones are to be found. In the long time elapsing since their origin these might have been completely leached out by subterranean waters, as Rutley has shown,[1] if they had remained near the surface in the zone of circulating waters. But the pre-Cambrian rocks are usually highly metamorphic and have been buried deeply in the zone of anamorphism during a considerable proportion of their existence, so that such an explanation can hardly apply to them in very much greater measure than to the Eopaleozoic limestones which remain in such abundance.

The bulk of the salt is doubtless still in solution in the sea and is a measure of the volume of erosion in those early ages in addition to that of later times. The corresponding dolomites, however, since they are apparently not found in proportionate abundance upon the continents must presumably repose within the limits of the present ocean basins.

[1] "On the Dwindling and Disappearance of Limestones," *Quarterly Journa Geological Society*, Vol. XLIX (1893), p. 372.

But as carbonate deposits are characteristic of the open sea, so are silicious, feldspathic, and argillaceous deposits dominant upon the land surface, and thus a separate argument is derived for the view that in pre-Cambrian times the continents possessed at least their present extension, an argument, however, which requires further testing in regard to the premises as to the poverty of limestones.

It would seem, therefore, that the 12,000 feet of the Belt terrane, consisting, as it does, of from 37 to 50 per cent. of dolomitic limestones is far from being an occurrence holding an unusual proportion of continental deposits and that the conclusion derived from its study in regard to their presence in important quantity is therefore susceptible of wider application.