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ART. XXX.—*The Formation and Distribution of Fluviatile and Marine Gravels;* by HERBERT E. GREGORY.

Outline.

Introduction.

THE absence of criteria for the interpretation of consolidated and unconsolidated gravels is a particularly serious obstacle to work in the Colorado Plateau Province, where a confusing variety of structure and the extreme scarcity of fossils render the usual means of differentiation of secondary value. During an excursion across the Colorado Plateau in 1900, the importance of the problem thus presented was pointed out by Professor Davis,* and at his suggestion an attempt was made to analyze the physiographic features resulting from ocean and river work, in so far as they are related to the deposition of gravel, with the hope that some constant features characterizing conglomerates of various modes of origin might be recognized. Because of the lack of quantitative data obtained from field investigations, the results of this study are unsatisfactory: they have, however, been found useful in field work, in directing increased attention to thickness, extent, and stratigraphic position of beds of gravel and conglomerate, and for this reason the original manuscript has been revised and the conclusion here presented as a contribution to stratigraphy from the viewpoint of physiography.

Fluviatile Gravels.

Although the importance of rivers as agents of erosion and deposition is widely recognized, the methods and results of stream work as conditioned by changing environment have yet to be formulated. The fluviatile deposits which have been studied in detail are too few in number and too exceptional in character to serve as a basis for generalizations founded on induction. Until many streams and typical streams have been examined with reference to habit induced by volume and gradient and load as affected by temperature, precipitation, crustal movements, regolith, bed rock, valley form, and physiographic age, we must be content with an outline sketch drawn largely by the blunt-pointed pen of deduction.

Comparative rates of subaerial and marine erosion.—Even a superficial examination indicates that in preparing and distributing waste, rivers, assisted by the atmosphere, are distinctly more effective than marine agents. A narrow zone of water takes part in marine erosion; the atmosphere reaches all land permanently or temporarily above water. The atmosphere and the rivers may arrange the order in which their work is to be taken up; the sea has little choice. In developing subsequents on less resistant rocks, thus carving inner lowlands as well as reducing highlands, rivers are unimpeded; the sea on the other hand has no opportunity to reach more easily eroded materials except by cutting its way through intervening strata. For the world as a whole, therefore, the estimates of rates of subaerial erosion are many times greater than those for marine erosion.

On the basis of study of the Mississippi drainage basin, subaerial erosion for the United States is placed at 1/4500 of a

*Davis: An Excursion to the Grand Canyon of the Colorado, Bull. Mus. Comp. Zool., vol. xxxviii, 1901, pp. 107–201.

foot a year, by Reade,* and 1/3500 of a foot a year by Salisbury.† By using the latter figure, and assuming that the conditions within the Mississippi basin are representative for the 55,000,000 square miles of the earth's lands, 300 cubic miles of land are removed each century by subaerial denudation. The estimate of R. B. Dole, Chemist of the U. S. Geological Survey, that "the surface of the United States is now being removed at the rate of 0·06 cubic miles a year,"‡ is probably a fair representation of existing conditions, since the estimate is based on a study of all the rivers of the United States. If this rate be applied to the entire earth's surface, the figure becomes in round numbers, 110 cubic miles a century. The estimate of Murray§ is 370 cubic miles a century. The discrepancy between these estimates is to a certain extent the measure of our ignorance of the régime of running water under various conditions. It is obvious that the average rate of removal must include landslides as well as old-age streams whose action in denuding the land is excessively slow, and must include tropic and arctic lands as well as those of the temperate zone. The lack of data for most of the world's rivers gives to all estimates a very low degree of accuracy.

The rate of cliff recession varies with the strength of waves and the nature of the shore. Recession of shore line probably reaches its maximum on the Yorkshire coast of England. At Kilnsea the rate is 12 feet a year, and for 34 miles of coast from Bridlington to the mouth of the Humber 9·75 feet a year, or 975 feet a century. Rates of 300 to 600 feet a century are not uncommon for portions of the English coast exposed to vigorous waves.‖ On the other hand the west coast of England recedes under wave attack probably less than one foot a century and the recession of the world's shore line is probably to be measured by a few feet per century. It is believed that the estimate of 10 feet per century¶ is safely within the average. It is obvious that the rates attained under exceptionally favorable conditions no more represent coast erosion than does the rapid denudation incident to cloudbursts and forest removal represent subaerial erosion. On the other hand it should be borne in mind also that the decreased supply of waste furnished by streams of old-age lands relieves the waves of work in distributing and grinding debris and renders them free to attack the land. If the rate of recession be taken as 10 feet per century, the length of the coast line at 125,000 miles (including

* Presidential Address, Liverpool Geol. Soc., 1884–85.
† Physiography, p. 154, 1907.
‡ Personal communication.
§ The Ocean, p. 44.
‖ Wheeler, The Sea Coast.
¶ Geikie, Textbook of Geology, 1903, vol. i, p. 567.

bays in which wave work is negligible), and the height of cliffs at 50 feet (a generous estimate), there will be removed from the coast each century 2·24 cubic miles of material. The contrast between rates of marine and subaerial denudation is well brought out if the lowest estimate for subaerial erosion is compared with the generous estimate of cliff recession. It is thus seen that rivers are approximately fifty times more effective than waves in paring down continents.

The relative proportions of gravel in total marine and fluviatile sediments is an attractive problem awaiting discussion, but there is no reason to believe that at any given time the relative amount along shore exceeds that in valleys on the land, and the figures given above may be taken to indicate that the conditions for the accumulations of gravel for conversion into conglomerate are much less favorable within the coastal belt than over continental areas.

Summary Analysis of River Work.

The net tendency of the work of subaerial agents of erosion is to reduce the land surface to a featureless plain. While many essential and conditional factors are involved in peneplanation, for the purpose at hand subaerial erosion may be considered as consisting of weathering and river transportation, the former supplying the waste, the latter distributing it. Rivers, to be sure, furnish their quota of waste by direct corrasion, but as shown by Westgate,* weathering is an important factor in valley deepening as well as in valley widening. With a constant climate, weathering in comparison with stream corrasion progressively increases throughout a cycle, reaching its maximum in old age.

Since weathering must be relied upon to furnish the supply of gravel, and since both chemical and mechanical phases of weathering are conditioned by climate and rock composition and structure, it follows that the maximum amount of coarse materials is favored by resistant jointed rock in an arid region. On the other hand, where readily decomposed rocks lie on flat surfaces, and chemical activity is facilitated by climate, no gravel may be formed at the surface. Under suitable conditions residual gravel of siliceous materials may accumulate and the regolith may consist of rounded and subangular pebbles and bowlders to a depth of several feet. The origin of such deposits is revealed by the gradation in amount of chemical decomposition from surface to bed rock.

Throughout the larger part of a cycle gravel removal is believed to follow gravel formation without much delay and the products of weathering are furnished to streams to be

* Journal of Geology, xv, p. 114–122, 1907.

transported and arranged in a manner determined by the resultant effect of all the factors conditioning the work of running water. The method of transportation by suspension need not be considered in the present discussion, for pebbles make their way down stream by saltation, rolling and sliding. For this method of transport, *entraînement** of the French engineers, the basal portion of a stream obviously must be utilized, hence the action of water at the bottom of a current and the nature of the bed of a stream are matters of prime significance. Unfortunately these are features with which we are relatively unfamiliar and which are least susceptible to direct observation. Since, under the influence of a current pebbles advance in large part by saltation, the ability of a stream to transport gravel is fundamentally affected by slope and discharge, two factors whose relations to capacity are, as shown by Gilbert, essentially parallel, with the exception that capacity is slightly more sensitive to changes of slope than to fluctuations in volume.† Another significant result of the Berkeley experiments is the demonstration of the fact that fragments of a single size are moved by river currents less freely than mixed debris, and that if fine material be added to coarse, not only is the total load increased but a much greater quantity of coarse material may be carried.‡

For a complete analysis of gravel production and gravel distribution, the factors concerned in stream traction which require evaluation are the amount and classification of the load, the discharge, the stream profile, the character of the bottom, and the valley form. The last-named factor includes form ratio as defined by Gilbert,§ and the alignment of the channel. The relative quantitative effects of these various factors as operative in natural streams remains to be determined, but for preliminary physiographic studies only their qualitative influences, conditioned by climate and topographic age, need be considered.

Distribution and Preservation of River Gravels during a single Physiographic Cycle.

During the course of a physiographic cycle the landscape passes through a brief period of rapidly increasing relief, followed by a period characterized by strong relief and great variety of form. This stage is followed by a period of relatively rapid decrease in relief, replaced in turn by a very long

* The well chosen term "traction" is suggested by Gilbert as an English equivalent of *entraînement*. All hydraulic transportation may thus be classified as suspension and traction.

† Gilbert, U. S. Geol. Survey, Prof. Paper 86, pp. 145, 149, 1914.

‡ Loc. cit., p. 11, 184.

§ U. S. Geol. Survey, Prof. Paper No. 86, p. 36, 1914.

period during which the relief is increasingly faint. At the beginning of a cycle the features of youth in a landscape may be superposed upon features indicating adolescence, maturity, or old age. But whatever the initial topographic expression, streams of youth start at the long and arduous task of establishing and maintaining grade. If youth follows maturity, gravel is ready at hand; if youth follows old age, gravel must be prepared and furnished to the stream before distribution can be effected. The production of gravel is an accompaniment of vigorous erosion and accordingly its proportion in total land waste is greatest in youth and early maturity. Moreover gravels prepared during youth normally contain a large amount of undecomposed material since rapid down-cutting of channels favors mechanical agents of erosion.

At the beginning of a cycle, the stream finds itself out of adjustment and at once undertakes to remedy this defect. If the initial stream profile is over-flat, grade is established by building steeper slopes beginning at headwaters and, until a profile suitable for carrying gravel with a given volume of water is developed, gravel accumulates in the upper parts of a stream course. If the profile at the beginning of a cycle is over-steep, coarse waste is distributed along the valley to depths required to bridge the concavities and establish grade. If young and mature stages of the stream's history be of long duration, gravel may thus accumulate to great thickness. With fluctuating stream volume in response to seasonal or cyclical flooding, gravels are carried farther and farther down valley. In maturity streams are competent to carry the load furnished; i. e., grade has been established. But probably no stream is in a graded condition throughout its entire course, and the adjusted profile of short stretches changes frequently and at times abruptly. With the continually changing conditions of volume discharge, grade is maintained by shifting the load laterally and distally but with net movement downstream. It is important to bear in mind that pebbles are carried in one direction by rivers, whereas waves and wind transport sediment back and forth. On the gentle slopes of old age the maximum amount of material is carried in solution and gravels are normally absent.

The arrangement of gravel deposits on the stream bed may be observed at stages of low water. As displayed on the floor of certain ephemeral streams on the Navajo Reservation, the masses of gravel are irregular in distribution and yet conform to a poorly defined pattern. For stretches of a few tens, rarely of a few hundreds feet, the entire bed is paved with pebbles or cobbles. More commonly the deposits have the form of lenses 10 to 100 feet long, 3 to 20 feet wide, with gentle slope at the upper end and terminating in an abrupt or in a gentle slope downstream. These lenses are roughly parallel with the axis of the immediate valley and are separated by bands of sand or of silt in places underlying shallow pools of water. In addition to the lenticular masses mentioned there is another set of bars which traverse the channel obliquely joining the inner banks of two successive curves. In several places these oblique bars are the only gravel deposits present and the dwindling stream was observed to cross these bars from one pool to another. The pattern woven by these sets of bars is a net stretched in the direction of stream flow. In the meshes of the net are areas of sands and muds of various textures. Between floods the net appears to migrate down stream without substantially altering its pattern. By wading in the stream at flood stage it was found that the position of pool and bar with references to each other was unchanged. One characteristic feature, which I have not observed in sediments of non-fluviatile origin, is the presence of lines of detached pebbles embedded in the sand and arranged like widely-spaced beads on a string. In places an isolated pebble is found resting on sand a foot or more from its nearest companion. In streams with widely fluctuating discharge the pattern of gravel lenses is believed to be maintained and if carried below base level the gravel may be preserved throughout a cycle, and is likely to become consolidated into conglomerate. If stranded above base level these deposits are subject to mutilation or destruction in response to modification of grade induced by tectonic or climatic changes, as is abundantly illustrated by streams of Plateau Province.

When preserved in the sedimentary record inland stream conglomerate deposited during a single cycle lies conformably or unconformably on older deposits. The conglomerate, prevailingly crossbedded, is arranged in long, roughly parallel bands or courses, in the direction of dip or displayed as strands in an interlacing pattern as shown by Johnson.* Along the strike lenses and belts of conglomerate irregularly alternate with lenses of sandstone. Lenticular deposits of shale and even of peat or lignite may be present since quiet water bodies of small extent are normal features in regions of uneven stream deposition particularly where winds are active. Lenses of conglomerate in roughly parallel or interlaced order a few tens, or at most a few hundreds, of feet wide, and tens or rarely a few hundreds of feet thick, suggest fluviatile origin. Such deposits as shown in section exhibit no regular gradation in coarseness. If the streams are provided with distributaries in the zone of gravel deposition the width of the combined

*U. S. Geol. Survey, 21st Ann. Rept., 1899–1900.

strands may be tens of miles; and if a group of parallel streams are working under similar conditions the gravels may extend laterally for greater distances. The length of the overlapping and branching gravel lenses will be determined by the net result of all the agents concerned with the transportation and deposition of coarse material.

Observations of modern rivers indicate that gravel in quantity is carried 30 to 40 miles by streams of high gradient and under favorable conditions portions of a gravel bank may be transported a few hundred miles. Thus 60 per cent of a gravel bar examined on the Urubamba River, Peru, consisted of pebbles up to 3 inches in diameter which had been ferried down stream for a distance of 33 miles. Twenty per cent of the pebbles and cobbles in certain bars along Chinli Creek in Arizona have their source 36 miles distant, and scattering pebbles were found 50 miles from their parent ledge. In front of the Rocky Mountains gravel is distributed for distances of 300 miles, and pebbles in the Nile delta "have been river-borne for at least 400 miles."* Grabau† states that extensive deposits of river gravels in the Triassic of England are found 300 miles from their source and that pebbles of the Pottsville conglomerate have made a journey of 400 miles.

Distribution and Preservation of Gravel during Interrupted Cycles.

Tectonic Interruptions.—Within a single cycle, as discussed above, climate is assumed to be substantially uniform, and the earth's crust stable. The effect of regional or local downwarp or upwarp with constant volume of water is to modify all factors concerned with the distribution and preservation of gravel. In consequence of crustal movement the stream's gradient and consequently carrying power is changed; the area from which gravel is collected may be increased or decreased in size and the area over which gravel is deposited may be modified as to extent and position. Since with general regional uplift streams begin to deepen their valleys and to localize their channels, gravel is left on terraces and on interstream spaces. The thickness of such deposits is obviously some fraction of the amount laid down during the previous cycle. With the development of drainage the removal of these fringing terraces is favored and the gravel stands little chance of preservation. General regional downwarp results in flattening of stream profile since deposition is facilitated on flood plains in the lower portions of rivers while the headward portions of the valleys are still subjected to erosion. On such over-flat profiles gravels tend to

* Wade, Quart. Jour. Geol. Soc., vol. lxvii, 1911.
† Principles of Stratigraphy, p. 594.

accumulate along the entire valley and may be brought below base level and thus preserved.

If the downwarp be geosnyclinal in character, accumulations of gravel are favored. The material from the rim of the newly formed basin is readily removed since the increased stream gradient gives added power of traction. The process of deposition may go on indefinitely, since transference of load favors sinking of the floor of the trough, and the rising of the bordering lands. Under such circumstances gravel may accumulate to thicknesses of thousands of feet and will bear variable relations with sands, clays, or adobe forming along the axis of the geosyncline. All such deposits may be carried well below base level and hence may be preserved throughout several cycles of erosion.

Fault valleys, or graben, in which a narrow zone of land is subsiding, furnish conditions for gravel accumulations comparable with geosynclines. If subsidence is long continued, overlapping gravel fans may reach thicknesses of hundreds or even thousands of feet, and in the absence of regional uplift and peneplanation may be preserved for indefinite periods.

Climatic Fluctuations.—Changes in climate by modifying discharge affect stream gradients and hence gravel deposition in much the same manner as tectonic movements. Change from a humid climate to an arid may result in the formation of gravel deposits comparable to terraces incident to upwarp. Decreased supply of water finds the grade of streams formed under humid conditions too flat and gravel accordingly accumulates near headwaters. Change of climate from arid to humid produces opposite effects, for in such a case stream gradients are found steeper than necessary for the effective transportation of load; gravels may be removed from headwaters and the filling of concavities along stream may proceed at rapid rates. So far as cyclical fluctuations in temperature are concerned a change from temperate conditions to extremes of heat or of cold tends to hasten the formation of gravel, and, as shown by Barrell,* oscillations toward cold favor transportation of coarser materials.

As regards the place of deposition of the coarser materials, particularly along stream courses, the working rule that pebbles increase in size and degree of angularity toward their source is subject to important exceptions. In fact, the only conditions under which this hypothesis is wholly applicable are equable climate, perennial streams, and the early stages of an uninterrupted physiographic cycle. If the present arid climate of the Plateau Province became humid, with evenly distributed rainfall and perennial streams, the gravels abundantly

* Jour. Geol., xvi, p. 381, 1908.

strewn along the present stream channels would probably be rapidly eroded or swept entirely away into the master stream. The supply of waste, on the other hand, would probably decrease in amount because of the newly developed cover of vegetation and the decrease in concentration of runoff resulting from desert showers. Decrease in amount and increase in fineness of waste furnished at the headwaters would result also in an increasing ability of streams to erode their beds and grind up bowlders. The area of deposition of coarsest material would, therefore, probably not be nearest the source of supply but would be followed, upstream, by deposits of waste distinctly finer in texture. An upwarp which steepens grade might produce the same result.

Gravel at River Mouths.

The interstratifications of river gravels with marine sediments is not a normal relation. Gravels are prevailingly associated with young or mature topography and the seaward reaches of streams, especially those of large size, are characterized by fine waste. Deltas of rivers, therefore, may contain no gravels resulting from erosion within a single cycle. The inauguration of a new cycle as the result of climatic or tectonic changes may produce, at river mouths, a stratigraphic series, the origin of whose various members may not be definitely determined on the basis of published field study.

In this connection the deltas of vanished lakes are worthy of consideration. In cases which have come under my observation the deposition of gravels over finer lake muds appears to be a normal feature of river work conditioned by crustal upwarp or its equivalent in climatic change. By analogy it follows that conglomerate overlying marine sandstones and shales may be of fluviatile origin.

In a section of an abandoned lake bed in Kayenta Valley, Arizona, a stratum of gravel is embedded in lacustrine deposits, which suggests that fine-grained marine sediments may both overlie and underlie conglomerate of continental origin. Likewise if the finer-grained beds in a series of shale, sandstone and conglomerate show evidence of fluviatile origin, there is little reason to assume that the conglomerate has a different mode of origin. Fans of steep gradient immediately at the lake shore, whose building is conditioned by fluctuating stream discharge and changing lake level, would be expected to show various combinations of coarse and fine strata, both of lacustrine and fluviatile origin. The same conditions doubtless exist on certain marine deltas.

Gravels of Marine Origin.

Definitions.—For the sake of uniformity in the discussion of coastal physiography it seems advisable to retain the terms suggested by Gulliver,* viz: *Shore line* is the line of intersection of sea and land, the region landward of the shore line is the *coast*, and the region seaward of this line is the *shore*.† *Coastal belt* is the zone formed of coast, shore line and shore. *Wave base* is the controlling plane of marine levelling—a mathematical plane toward which the mature profile of marine denudation tends but does not reach. The submarine platform (or subaqueous shore terrace, or plain of marine denudation) bears the same relation to wave base that a peneplain does to river base level. *Initial* is a technical term defining the form at the beginning of a physiographic cycle. Forms developed at later stages are *sequential*. The term *shifting* is used in the present paper for change in position of a shore line resulting from crustal movements, *recession* for the change in position due to wave cutting, and *migration* for the total movement of the shore line regardless of causes.

Physiographic Development of a Coastal Belt.

The formation, distribution, and preservation of marine gravels are controlled by marine currents conditioned by rock structure and physiographic age. A brief analysis of marine action within a coastal belt may therefore serve as an aid in the interpretation of conglomerates.

The net result of the combined work of waves and currents is to establish maturity of outline within the two zones which comprise the coastal belt, namely the coast and the shore. Maturity of outline of the *coast* is attained when erosion, transportation and deposition are so adjusted with reference to each other that all portions of the shore retreat at equal rates; that the landward migration of the shore line in areas of resistant materials is the same as for the less resistant portions of the coast. Under these conditions the shore line tends to straightness and retains that quality so long as sea level remains constant. Development of the coastal contour of continents cannot proceed further so long as any land remains above sea level. On many small islands, however, landward migration of the shore line has continued until all land has been consumed. In such cases a mature coast is succeeded by no coast; land

* Shore line Topography, Proc. Am. Acad. Arts and Sciences, vol. xxxiv, p. 152, 1899.

† This use of the term "shore" is obviously technical. The common practice is to consider the "shore" as part of the land. Satisfactory discriminating terms are needed for the loosely used words "coast," "shore," and "strand."

becomes a shoal without the intervention of significant old-age forms other than the "flying bars."

The *profile of the shore* also advances to maturity as the result of normal shore erosion, transportation and deposition within a single cycle. Shore maturity is usually reached after coastal maturity has been attained, and in fact is made possible in large part by the establishment of coastal maturity, for the simplification of the coast line by cutting off headlands and building bay bars is to be considered not as a phase of the contest between sea and land as is frequently stated, but rather as a stage in the process of development of shore equilibrium. Like the coast contour, the shore profile does not advance past maturity on continental borders where land remains unconsumed; but on shoals representing former islands, old age may be attained and the surface of the underwater land may continuously progress toward wave base. The normal shore profile both on cutting and building coasts "is a compound curve which is concave near the shore, passing through a line of little or no curvature to a convex front." * The attainment of this profile of equilibrium is accomplished only after the expenditure of an enormous amount of energy on a complicated piece of work, but the advantages are correspondingly great, for in consequence of previous establishment of coast maturity the coast is now openly exposed to the attack of the waves for long stretches of straightened shore line and wave energy may now be concentrated within the zone where it is most effective. The position of the profile changes with the migration of the shore line; with constant sea level it moves landward. The form of the profile appears to remain constant, but its relative dimensions change in response to the type of initial coastal belt, wave power, and mass of materials provided for transportation.

Steepness and regularity of slope are factors which affect the distances to which materials may be carried, for waves tend to establish conditions where their greatest abrasive energy is concentrated along a narrow belt, the breaker line, and where the profile is of such steepness as to allow for ready seaward transportation of materials provided. An initially over-steep slope retards wave action in carrying material seaward, for the materials worn from cliffs are deposited near the shore line until the profile is placed in adjustment. An initially over-flat profile likewise retards coast erosion, for under such conditions the locus of wave attack is some distance off shore, and before the waves may reach the coast a notch must be cut on the bottom, and a bar, or a series of bars, as the waves again and again rerecover their form, be thrown up. The net result is that much

* Fenneman, Jour. Geol., x, p. 27, 1902.

material and particularly the coarser stuff is carried landward, thus defeating the object of wave attack. The highest efficiency is reached when a profile of equilibrium adjusted to the strength of the waves of a given shore is established; for under these conditions materials of all grades of coarseness may be carried the maximum distance.

The shape of the shore profile of maturity is directly related to the force of waves. Fenneman has shown* that "there is a certain minimum slope for the bottom upon which the waves may be propagated as a shallow water wave" and "a certain maximum slope for the bottom upon which the wave may be propagated without breaking." Wind acting on waves tends to diminish both the minimum and maximum slope required for normal swells. At and coastward of the line of breakers the work of a normal wave of oscillation (waves of the second order) may be modified or entirely counteracted by water movements of various sorts, primarily waves of translation, undertow, and long shore currents. Waves of translation, or waves of the first order, move toward the shore line both at bottom and surface and transport materials landward, not backward and forward as in the case of waves of the second order.†

The effect of the undertow associated with waves is to carry water and sediments seaward and thus offset the work of waves of translation. In the contest between these two sets of forces the waves under average conditions are more effective since their activity is concentrated within a short time, whereas the work of the undertow is more evenly distributed in time. The result of these opposing agencies is to carry materials back and forth over a narrow zone with a net tendency landward. Fenneman‡ calls attention to an exceptional type of returning bottom current, that developed in bays where water has been heaped by wind-made or wave-made long shore currents. The current developed under such conditions is regular and powerful and may carry sediments or even erode below the point of maximum wave agitation. Thus in Lake Michigan, where waves disturb the bottom to depths of 60–70 feet, "a sand-covered or gravel-covered bottom concave upward extends outward to several times this depth with little or no evidence of change of slope at wave base."§ A similar case is cited from

* Jour. Geol., x, p. 17, 1902.

† This view of the relation waves of the first order bear to those of the second order as presented by Russell, Trans. British Assoc., 1837, is discussed by Hunt (Sc. Proc. Roy. Dublin Soc., vol. iv, pp. 251-254, 1883–85), who reaches an opposite conclusion: that there is "no evidence that a wave of oscillation is transformed into a wave of translation on passing into shallow water."

‡ Journal of Geology, vol. x, pp. 31–32, 1902.

§ Loc. cit., p. 31.

Lake Mendota and examples along sea shores might be mentioned.

Long shore currents, which coöperate with waves and undertow, travel in one direction or another in response to wind. The incoherent materials of the coastal belt are accordingly ferried to and fro or deposited in bays or on the lee sides of headlands. If winds of equal strength blow alternately in opposite directions the shore materials may be continually in transport. If winds are of unequal strength, materials make their way in one direction since the weaker currents are unable to return shore debris, particularly that of coarse texture, brought by the stronger current. Materials deposited by currents are thus distributed irregularly but in all cases near the shore line. When waves are present with currents "shingle must go with the wave, sand must go with the strongest current."* Coarse and fine material may thus move in opposite directions.

The shape of the profile of shore maturity is significantly modified by the load furnished from the coast; in fact, the development of the normal compound curve of equilibrium involves the deposition, transport and sorting of the coastal load. In the absence of a renewed supply of sediment the shore profile of maturity would be a steep descent from shore line to the outer limit of effective work of the undertow, continued outward as a gentle slope.† When sediment is supplied deposition will take place at the base of the steep descent leading down from the shore line until a grade suitable for transportation of material is established and the debris is carried seaward ending on a slope with convex front. A concavity in the profile is now formed at the junction of the plain of deposition with the plain leading landward over which material is transported. The resultant profile is the curve of equilibrium. With deficient initial slope of subaqueous profile, barriers may be built, thus steepening the profile. In both these ways the shape of the normal curve may be modified. The outer limit of the convex portion of the curve and hence the width of the shore belt of combined erosion and deposition is determined by the distance to which materials are ferried seaward by the forces acting along a given coastal belt. For the Atlantic coast of the United States Fenneman has shown that the depth to which the *whole load* can be carried is 50 or 60 fathoms; that is, 40 to 80 miles from shore; and at 100 fathoms or less nothing can be carried except in suspension. It is obvious that the coarse materials may be transported for but a fraction of this depth and distance.

* Hunt, loc. cit., p. 282.

† Fenneman, loc. cit., p. 26.

Application to the Formation and Distribution of Gravels.

On an excursion to Marblehead and Nahant in 1898 my attention was called to the tendency of sediments, particularly those of coarse texture, to remain near shore. Observation of shores of New England, California, North Carolina, and Peru have produced a sympathetic attitude toward the erroneous view of Rear Admiral Davis that the sea "rejects or repels" the debris of continents.* While this statement is obviously an exaggerated figure of speech, the coastward urging of coarse materials during the process of coast erosion, has, to my mind, been too little emphasized in texts for students' use. Without taking an extreme view, it follows from the above summary analysis of the development of coast contour and shore profile, that clastic marine deposits laid down during a single physiographic cycle have no great extent or thickness, and that their limits may be roughly calculated. If the coarser materials, gravel and cobbles, are alone considered, the belt of marine and lacustrine sedimentation is narrowed to a degree not generally recognized. If we could determine the thickness and extent of marine gravel deposits laid down under average conditions upon various types of shore and at different stages in their physiographic history, a useful criterion for the recognition of ancient conglomerates would be established. This I believe may be done with a fair degree of approximation on the basis of the physiographic studies outlined above.

Distribution and Preservation of Gravel during a Single Physiographic Cycle.

Whatever the initial topographic expression of a coastal belt, the coast contour and the shore profile experience a series of changes leading from youth through adolescence to maturity following a defined order. The nature and amount of the work to be performed within a cycle and the time required to reach maturity depends upon the initial form, the strength of the ocean forces and the composition and structure of the coast. Gravel is supplied from stream sediments, from older coast gravels or from wave-beaten cliffs, and in the absence of supplies from these sources the sea may expend its power for long periods upon fine stuff alone. In general, however, youth is the time of maximum erosion and maximum deposition for all classes of material. Two types of shore may be distinguished: over-flat, and over-steep initial profiles.

Initial over-flat profile.—If the initial shore profile is too flat for the most effective wave work, a nip is cut in the sub-

*Quoted by Mitchell, U. S. Coast and Geodetic Survey, 1869, Appendix 5, p. 85.

aqueous platform and a barrier beach thrown up. After recovering their form, waves of translation urge material coastward from the barrier, and the barrier itself aids in preventing the return of coarse sediments. The maximum width of gravel is, therefore, found in youth when barriers of no great thickness are farthest off shore, the gravel being confined to the zone between the breaker line and the shore line. As the cycle advances and the barrier progresses landward the zone of gravel is narrowed, and the pebbles are continuously ground to sand. During adolescence, when the barrier is pressed close to shore and currents and tides and oblique waves express their activity in bay bars, spits, tombolos, cuspate forelands and winged beheadlands, gravel in decreasing amounts is kept progressively nearer the shore. At maturity gravel may be absent except at points of origin, for effective shore work in maturity requires that gravel be limited to such amounts as can be ground up by waves and ferried away by currents.

If the above analysis holds for the normal coastal belt it follows that youthful forms on an over-flat profile, if preserved in the sedimentary record, would be represented by a belt of sediment which may include conglomerate, a few miles at most in width and a few tens of feet thick, rather sharply limited seaward and interbedded landward with bands of various materials brought to the coast by streams. If adolescent features were preserved along the ancient shore, the bulk of the coastal gravels would be represented by a band, a few hundred (or at most a few thousand) feet in width and a few tens of feet thick, of crossbedded conglomerates and sandstone unevenly distributed and showing great variation in texture vertically, transversely, and longitudinally. In exceptional cases where strong off-shore bottom currents are initiated by excess of water piled in bays, gravel may be carried to depths beyond the reach of waves and thus preserved. These exceptional accumulations are doubtless small in extent and thickness. If mature features were preserved in the sedimentary record, a narrow band of conglomerate with water-worn pebbles on one side and unassorted debris on the other may mark the plane of unconformity.

It is believed that all flat subaqueous profiles favor landward transportation of coarse sediments. Observations of a group of pebbles on the Long Island Shore and of another on Lake Whitney, near New Haven, showed that in the course of a year about 40 per cent of the fragments had moved landward and none seaward. These experiments were abandoned because of the impractibility of evaluating the effect of ice work. On a reservoir at Tuba, Arizona, of 26 pebbles 1/4 to 1 inch in diameter, in a position unaffected by ice, 19 were found to have moved coastward 1 to 5 inches, 5 had not moved, 2 had gone farther into the lake, during the lapse of four years. Hunt observed that shingle is traveling toward the head of the shallow Lyme Bay.*

Initial over-steep profile.—If an over-steep shore profile is presented to waves at the beginning of a physiographic cycle, the conditions are favorable for the accumulation of thick but narrow bands of gravel and also of thin bands of greater extent. In early youth of the cycle the wave-cut nip and the wave-built barrier, if present, are near the coast. If the initial steepness is such as to preclude the building of a barrier the breaker line may be immediately at shore line. Longshore drift may be negligible at the beginning of the cycle and the materials worn from the upper portion of the cliff may be deposited directly at cliff base. The thickness of the gravel deposited under such circumstances is limited only by the depth of the water. An examination of coast charts indicates that the bases of few if any sea cliffs are submerged in more than 50 feet of water. If, in order to include doubtful examples, this figure be increased to 100 feet the outside limit of thickness of gravel deposited during a single cycle is believed to be indicated. As the cycle advances, a rock platform is developed at first by building and cutting, later chiefly by cutting. Before the profile of maturity is established a platform must be built to a point where grade adjusted to the waves and debris of a particular coast is established. It is conceivable that in certain cases all gravel may be worn to sand before being carried beyond the edge of the wave-cut bench. Recession of the cliff involves the continuous attrition of the materials on the platform, as well as the abrasion of the rock platform itself; otherwise the attack of the waves on the coast is greatly decreased in vigor. Since the newly-cut platform is likely to be of gentler slope than the outer portion of the profile, the coarse debris tends to remain on the shelf rather than to be transported seaward. During adolescence the shore line migrates landward, the coastward portion of the profile is already too gentle for the most effective seaward transportation of debris, but the conditions are favorable for the attrition of pebbles and their landward transportation. When maturity is attained and the profile becomes adjusted to the waves and currents, a thin sheet of gravel may be deposited over the upper concave portion of the slope, but with a net tendency coastward. The gravels deposited in youth may be buried by later, finer deposits as the shore line advances toward the land.

Evidence from maps.—As a check on the above conclusions that gravel is deposited within a few miles of the shore line

* Loc. cit., p. 283.

and in relatively shallow water, the distribution of gravel along existing shores may be examined following the list based on age and initial form, as given by Gulliver.

Initial Profile Over-flat.

1. Youth.—On the Argentine shore at Bahia Camarones, gravel is charted in 23 fathoms of water at distances of 4 to 8 miles from shore.

2. Adolescence.—On the south shore of Long Island gravel is indicated on the Hydrographic Charts at depths of 15 and 13 fathoms at a distance from the shore line of about 10 miles and at points nearer the coast. Off the New Jersey coast at Barnegat, gravel is charted 9½ miles from the shore in 15 fathoms of water, and at Cape Henlopen, 13 miles from shore at a depth of 17 fathoms.

3. Maturity.—The material on the shore adjoining the west coast of France is indicated as prevailingly sand, but gravel is indicated off the mouth of the Loire in 26 fathoms of water. The character of sea bottom is not shown on the maps of eastern Italy examined.

Initial Profile Over-steep.

1. Youth.—On the California shore, off San Pedro Point, gravel is found in 15 fathoms of water at a distance of less than 2 miles from the water's edge. Off the coast of Southwest Ireland sand covers the bottom except at the immediate shore line. Gravel in 60 fathoms of water at one point off Loop Head is interpreted as belonging to a previous cycle.

2. Adolescence.—On the Pacific coast of Lower California, the outermost gravel is shown off Lagoon Head Anchorage, 4½ miles from shore, at a depth of 20 fathoms; between Playa Maria Bay and Rosalia Point no gravel is indicated beyond depths of 28 fathoms, and 4 miles from shore. On the Baltic shore of Germany gravel is indicated at depths of 30 fathoms and less.

3. Maturity.—On the Italian shore near Leghorn, no gravel is shown beyond a depth of 7 fathoms; between Brindisi and Ortona gravel is found inside the 30-fathom contour and one mile from the shore line.

The facts deduced from these shore profiles are not in themselves conclusive, since "gravel" is not a definitive term, and also because soundings have obviously not been made for the benefit of physiographers. Moreover, probably all these shores have experienced more than one physiographic cycle. The measurements, however, indicate that gravel derived from existing coasts is rarely found in more than 20 to 30 fathoms of water, and they gain added significance from the fact that they are in harmony with results of exhaustive studies on the English coast, where wave and current work attain maximum proportions.

Austen* concludes that "the moving power of the sea at 60 fathoms is limited to fine sand" and that gravels below this depth date from previous cycles. This author also remarks that "no abrasion has been effected over ledges (in the English Channel] under depths of not more than 17 fathoms." Cornish† states "I reckon that they [the waves from the English Channel) would move shingle at 10 fathoms, hardly at all at 20 fathoms, and probably not at 30 fathoms." The researches of Douglas, Stevenson, Winder and other harbor engineers‡ indicate that 30 fathoms is about the depth of effective movement of shingle even by heavy swells. That the bed of the English Channel is not traversed by violent currents of translation of any sort is indicated by the unworn state of flints and other pebbles and by the presence of an extensive fauna. If the figures for the English coast be considered as representing the average, 30 fathoms may be taken as the depth to which gravel under normal conditions may be deposited during a single physiographic cycle. The distance from the shore line at which this depth is attained in selected localities is as follows: San Pedro Point, California, 8 miles; Rosalia Point, Lower California, 3 miles; Atlantic City, New Jersey, 30 miles; Shinnecock Bay, Long Island, 30 miles; Argentine coast, 40 to 70 miles; southwest Ireland, 1 to 3 miles; northeast Ireland, 10 miles; east Scotland, 12 miles; western Italy, 1 to 10 miles; Finland, 30 miles. On those shores where the 30-fathom contour is more than 20 miles distant from the shore line gravel is rarely indicated at that depth; in most cases the outermost gravel is shown less than 10 miles from the coast.

On the basis of data available it appears therefore that gravel deposited during a single physiographic cycle is limited to a narrow zone, probably not exceeding 15 miles in width—a statement in harmony with the conclusions derived from the analysis of marine erosion. Moreover, the proportion of gravel to finer sediments in this belt of 15 miles is not necessarily large, since the coarse materials are not continuous. As preserved in the sedimentary record, a stratum of marine conglomerate exceeding 15 miles in breadth and 100 feet in thickness would be anomalous. As compared with marine action vigorous streams may carry gravel during a single cycle 3 to 300 times farther and distribute it much more widely.

If the above analyses properly represent the methods of river and ocean work, it follows that inland fluviatile gravels

* Quar. Jour. Geol. Soc., vi, pp. 69–97, 1850.
† Geog. Jour., xi, p. 541, 1898.
‡ Discussed by Hunt, loc. cit., p. 285.

and their ancient representatives, the conglomerates, are in general much thicker and many times greater in extent than are those of marine origin. To a greater degree than streams, the tendency of marine agents during a cycle with constant sea level is to destroy rather than to accumulate and preserve gravel.

Distribution and Preservation of Marine Gravels during Interrupted Cycles.

Effect of Coastal Downwarp.—Coastal downwarp or its equivalent, the rise of sea level, introduces a new physiographic cycle. The work of the waves and currents is put out of adjustment with the coastal contour and the shore profile. Unless the crustal warping were abnormally localized it includes wide subaerial areas and increasing amounts of land are brought within range of the destructive work of the sea. Conditions are favorable for marine planation at rates depending upon the nature of the initial coastal belt and the efficiency of waves in eroding the cliffs. Because of the amount of material to be removed planation is favored by an initial coast which has attained old age and consequently possesses slight relief; while a rugged coast of mature topography is unfavorable for coastal migration of the shore line.

Since the depression of a coast does not materially modify the force of waves, the conditions affecting deposition are directly related to the degree of adjustment of the former shore profile to the supply and transportation of coastal material at the beginning of the cycle initiated by downwarp. If the profile is over-steep it must be reduced by filling; if over-flat, it is cut by waves and bars are developed. With a coastward migrating shore line the section of the compound curve of shore maturity most directly concerned is that part between the outer edge of the concave portion and the shore line; for this is the part of the underwater slope over which gravel is normally deposited. The depth at which the concave curve merges with the plane of deposition is, as shown by Fenneman, 10 or 12 fathoms on the Atlantic shores and 20 to 30 fathoms on the Pacific shores of the United States.

So far as the thickness of gravel deposits is concerned the conditions associated with downwarp are essentially like those in a cycle marked by an initial over-steep shore profile. As in other cases, the work of the waves at any stage of downwarping is between the breaker line and the shore line; but waves during subsidence are effective at continuously higher levels and the gravel of successive submerged beaches may be preserved as a mantle covering the continuously expanding platform. The thickness and width of the gravel deposit, as well as its final place of deposit, varies with the stage reached in the cycle. Gravel below the depth of wave agitation at the beginning of a cycle may be indefinitely preserved. Gravels formed in youth will constitute a thick but narrow vertical wedge comparable to the accumulation of talus and further distinguished by the unworn character of its materials. The deposits of maturity will be thin and limited in extent to the area of the platform.

If this analysis is correct, the evidence of a rising sea preserved in the sedimentary record will be an unconformity between older rock and marine sediments. Conglomerate may be absent, but in most cases a basal conglomerate passing down dip slopes into sandstone and overlain by finer marine sediments will mark the ancient shore. The conglomerate may form a narrow thick band or a widespread sheet of variable thickness.

As regards maximum thickness the conclusion of Barrell is affirmed : " marine conglomerates, except under local and exceptional circumstances, [are] limited to considerably less than 100 feet."*

Effect of Coastal Upwarp.—Upwarp of a coastal belt or its equivalent, a sinking sea level, gives to the coast a simple contour with swinging curves whose shape is determined by the original inequalities of the shore. The new shore profile presented to the waves is in general over-flat. Under these conditions the forces of the sea tend to crowd gravel landward, and if no other agents were at work a series of abandoned gravel or sand beaches would mark the retreat of the water. The depth of the stranded marine gravel obviously equals the thickness of deposits on the beach slope. In the youth of the newly inaugurated cycle, particularly if the sea level sinks rapidly and intermittently, beaches may be preserved and notches cut by waves may be present as terrace fronts. The new-born subaerial landscape would therefore be characterized by ridges of gravel and well-marked steps or terraces in approximate parallelism to the shore line and at a high angle to general surface slope. In the absence of subaerial erosion and deposition the land surface would be veneered with a superficial sheet of marine gravels of great durability because highly porous and composed of resistant materials. On most coasts, however, rivers are at work and their extension over the exposed shore results in the redistribution of beach material and the accumulation of land sediments. The abandoned shore becomes a coastal plain,—a youthful landscape on which, if the climate be humid, streams and lakes and later swamps will de-

* Bull. Geol. Soc. Am., 1908, p. 620, abstract.

velop. If the climate be arid, streams of fluctuating discharge score the slopes and construct terraces among which dunes may be found as illustrated by the coast of Peru. The stranded gravels may be destroyed by a readvance of the sea or dissected by streams or preserved by burial under delta or river deposits.

When preserved in the sedimentary record the evidence of a receding sea is a widespread stratum composed of lenses of conglomerate usually much less than 100 feet in thickness underlying, with marked uniformity, fluviatile deposits frequently coarser in texture. Within the conglomerate, lacustrine shales and peat or coal and evidences of æolian action may be preserved.

This analysis of gravel deposition conditioned by coastal upwarp is readily checked by an examination of existing coastal plains, of which Patagonia is a typical example. As interpreted by Hatcher,* the coastal plain of Patagonia extends from the base of the Andes to the sea and is covered by the "Shingle Formation," with an average thickness of 30 feet. The marine gravels consist throughout of a heterogeneous mass of water-worn stones with but a slight admixture of sand and clay and unconformably overlie the Cape Fairweather beds of marine origin. The ancient beaches and sea cliffs are in places still preserved.

Conclusion.

There are doubtless more gravel and bowlders strewn over the surface at present than at any time in the earth's history. Youthful and mature landscapes are common, old age forms are rare. Vigorous waves and rivers are supplying gravel in maximum amounts, and the extensive coarse deposits from Pleistocene and recent glaciers are still in place. Of the gravel now in process of deposition by far the greater amount is furnished by the continental agents, rivers and glaciers. Marine erosion yields relatively little. The proportional efficiency of these agencies was doubtless not essentially different at any previous geological period. Thickness and extent and position of gravels and of conglomerate are therefore factors of much significance not only for the reading of the life history of existing rivers and coast lines but also for the interpretative description of ancient landscapes.

Yale University, New Haven, Conn.,
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* Princeton Univ. Exped. to Patagonia, vol. i, p. 221, 1903.