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[F O U R T H S E R I E S .]

ART. I.—*Factors in Movements of the Strand Line and their Results in the Pleistocene and Post-Pleistocene*;* by JOSEPH BARRELL, New Haven, Connecticut, *including a letter on Botanical Evidences by M. L. Fernald*, Cambridge, Massachusetts.

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Introduction.

THE problems of the nature of the Pleistocene and post-Pleistocene movements of the strand lines and their causes are important from a number of standpoints. They constitute one of those common fields in which stratigraphy and physical geology meet. The evidence shows a complex series of movements, indicating a complexity of causes. Each locality may give indications of the existence in the recent geologic past of both higher and lower stands of the sea, recorded by such unlike features as elevated seaplain and cliffs, on the one hand, by drowned river valleys on the other. Minor rhythms of movement are superposed upon larger rhythms. What is the proper sequence, what the relative duration, and what the correlation of successive stages of emergence and submergence between different localities? As the last phase in this series of oscillations, what is the direction and amount in different regions of the last movement of the strand line?

* Written at the suggestion of Dr. T. Wayland Vaughan and presented with lantern slides at the meeting of the Geological Society of Washington, on March 24, 1915.

But after the complexities of the record have been correctly deciphered there come the questions of interpretation. The making and unmaking of the great ice sheets must, by deduction, have been the cause of very appreciable fluctuations in the volume of ocean water. To what extent does the record of movement coincide with this cause, or to what extent does the evidence show inductively that there are other equally important or more important causes? The weight of the ice sheets depressed the crust beneath them, but what was its effect on the zone of crust immediately beyond? Among other questions, if it is found that the Pleistocene and post-Pleistocene movements are to a considerable degree unrelated to glaciation, to what degree are they due on the one hand to isostatic movements, including possibly intermittent changes in the volume of ocean basins, movements merely toward crustal equilibrium; to what degree are they due to deep-seated radial shrinkage of the earth, generating rhythms of tangential compression in the crust? These factors, together with the effects of changes in crustal density, the effects of erosion, of sedimentation, and possible changes in the volume of ocean water have operated through all past time, but their effects can be most minutely studied and correctly evaluated for the recent geologic past.

When, in the future, comprehensive answers can be given to these questions, much will have been learned in regard to the nature of crustal movements, and, as the present is the key to the past, better detailed interpretations will be possible for the stratigraphic record of previous geologic periods.

Within recent years new points of view have been developed by a number of geologists in regard to present and recent movements of the sea level. Among them, D. W. Johnson has shown the necessity for a re-examination of the supposed evidences of present continuing submergence of the Atlantic shore. Daly has suggested that the rise of sea level with deglaciation may account for the appearance of subsidence of coral islands, without requiring any real movement of the crust. Vaughan has come to the view that the development of recent off-shore reef corals is closely related to a recent rise of sea level and that, in general, reef corals flourish broadly only during and immediately following submergent phases of movement. W. M. Davis has developed especially, through a critical re-examination, the evidence given by the topography of the Pacific Islands.

The writer has not entered upon this subject as a special problem for research, but in the pursuit of other investigations has several times come into contact with it. But coming unexpectedly upon a subject from an angle is apt to give new sug-

gestions and somewhat novel points of view. It is from this standpoint that the following consideration of the subject may be of value. These points of view must be followed further and tested, however, before their results can be correctly and finally evaluated. In that brief treatment which is necessary in order to compress a large subject into the space of a short article detailed demonstrations must be avoided. The article is planned to be suggestive rather than conclusive. The purpose is to outline the controlling factors, putting the emphasis upon those aspects which have presented themselves to the writer as somewhat novel. It is not the plan here to demonstrate fully any single thesis, nor to treat in proper proportion all of the composite factors.

The Interpretation of Composite Rhythms.

The movements of the strand show a rhythmic nature. Smaller are superposed as undulations upon the larger oscillations, as, on a smaller and far briefer scale, are superposed the rhythms of waves due to wind upon those produced by tidal forces. In the interpretation of these rhythms, as Gilbert has so clearly shown, attention has been focused upon the marks of previous inroads of the sea, not upon the limits of its retreats, for these are now concealed.* To extend the analogy used by Gilbert,—if at any time we stand upon the shore and look at the lines upon the sand which mark the arrest and turning of previous waves, we see that the highest is the oldest and the successive marks form a descending series in time and intensity. We might generalize from this that the motion of the water was subsiding and the sea would therefore soon be at rest; but no sooner might this conclusion be announced than greater waves roll in, each obliterating the marks of the lesser waves preceding it, effacing also a part of the previous descending series and beginning the record of a new descending series. If we visited the shore at those rare times when a combination of spring tide and heavy on-shore storm raised the water level highest, we would at the moment of culmination see no series but only the single line of the highest wave. A visit at another time would show highest and faintest, as lines of shells and wrack, the marks made long previous during combined highest tide and storm. Below this would be the record, weeks or months younger, developed during the more moderate spring tides. Below this and still younger would be seen the marks of the waves made during the last high tide. Below this would be the series made by the combination of larger and smaller sets of wind-caused waves, the sequence recorded by

* G. K. Gilbert, *Continental Problems*, Bull. Geol. Soc. Am., vol. iv, pp. 187-189, 1893.

each descending series, destroyed and covered up while we watched by the following ascending series. The tide and storm might meanwhile be rising higher, and yet the writing of the past would appear as of a subsiding nature. The lesson to be drawn is that the record of a descending series measures only the descending sequence from the last maxima of the greater rhythms. It does not in itself tell the present trend of the oscillations.

Since the end of the Oligocene the strand has, on the whole, been retreating, the continents rising higher, the climates growing colder. There seems, in the Pleistocene, to have been a culmination of crustal and climatic oscillations, closed by a descending series. Men have taken hope that the ice age is past and have looked upon the Quaternary revolution as closing. But the study of the rhythm of the waves robs us of that assurance. At several times in the Pleistocene that view, as based upon apparent subsidences of crustal and climatic movements, would have been far better justified by the evidence than it is at the present moment. The high latitudes, unlike their state through the most of geologic time, are still mantled with glaciers. The shore lines are now in a stage of earliest youth. We live in fact within the Age of Ice, within an age of crustal unrest and revolution; the geologic morrow may bring forth greater and more compelling changes than the geologic yesterday. With this understanding of the nature of composite rhythms, always seen in retrospect as ending with a descending series, we should study the record of the ocean waves made on "Time's great continental strand."

Indications of Oscillations given by Subaqueous Profiles.

The first line of investigation which led the writer to an intersection with the problem of recent strand-line movements was in a study of present shore action as a basis for the development of "Some Distinctions Between Marine and Terrestrial Conglomerates."* The pressure of other work and the desirability of making quantitative measurements has prevented the publication of more than an abstract of this article, which led up to the conclusion that "the truly terrestrial forces produce vastly more gravel, spread it far more widely, and provide more opportunities for deposition than do the forces of the littoral zone." This conclusion was reached by a re-examination of the data used by Geikie, de Lapparent, and Penck for determining the relative rates of erosion. The result was to diminish still further the ratio of marine to terrestrial erosion as given by those authors. It was estimated, by multiplying the length of shore line by the thickness

* Abstract, Bull. Geol. Soc. Am., vol. xx, p. 620, 1908.

eroded, that marine denudation for the whole earth at present amounts to probably between .02 and .10 cubic miles per year, whereas the rivers bring to the sea annually probably between 1.50 and 3.00 cubic miles of rock material. These wide limits must be used, since for the earth as a whole the data are as yet not on a quantitative basis. But to have any application to the geologic past the variation in rates of erosion of both marine and subaerial agencies, and the high or low values of the present rates, must be considered. Now an examination of present shores shows that they are characteristically young and the sea work is mostly erosion at certain parts of the shore, not upon the bottom. Beyond some miles off shore, deposition is in general taking place. In the oscillations of sea level the last movement therefore has, on the whole, been one of submergence and this phase is favorable for a large proportion of gravel in the marine deposits now in evidence near the shores.

Turning to the application to the present subject, it appears, by reversing the argument, that recent movements of the strand line may be elucidated by a method of study which analyzes the place and character of marine degradation and aggradation; a study pursued in a somewhat similar fashion to that study of fluvial degradation and aggradation which has thrown such great light on the succession of crustal movements. Both rivers and sea work with respect to a base level. Their first effort is to bring a profile to a graded slope, eroding in some places, depositing in others. For the one as for the other, the nature of the work shows the direction, amount, and relative duration of recent changes of level. Valuable studies on the principles controlling the character of the shore *line* have been made by Davis and Gulliver, but what is here emphasized is the study of the water *bottom*, both near shore and offshore, its sedimentary character and its form. The basis for study consists especially of the hydrographic charts issued for the use of mariners. The writer has used particularly those published by Great Britain and the United States. The form of the bottom may be advantageously studied, not only from the plan, but by means of the projected profile. For this a section plane is taken at right angles to the submarine contours, and, to smooth out the minor effects of currents and waves and to make up for the scantiness and possible errors of the data, all soundings within a certain width are projected upon it and located as dots. A smoothed curve is then drawn through the soundings. These profiles are illustrated in figures 1 and 2.

In such studies distinction must be drawn between the subaqueous profiles of aggradation and degradation. Although in the course of unlimited time the two would tend to approach

each other, yet the recurrent movements of the crust tend to eliminate this mark of old age, by creating new base levels of planation. The profiles for various grades of sediment will also be of unlike depth. Sand derived abundantly from active shore erosion may build out a subaqueous terrace at the same time that finer sediment, partly of river origin, may not be permitted to settle on the older and deeper platform beyond.

After a profile is graded, then the advance of the sea inland or the retreat of the sea, provided the level is constant, requires erosion or deposition on all parts. This graded profile is

FIG. 1.

FIG. 1. Projected profile of the Argentine coast, South America. Section 50 miles wide, 25 miles on each side of a line, bearing S. 24° E. through lat. S. $38^{\circ} 45'$, long. $59^{\circ} 20'$. Vertical scale 890 times the horizontal scale.*

concave upward and may be called the profile of equilibrium. The depth of the profile varies greatly according to the power of the waves. Off the flat shores of quiet seas it ranges, at a distance of about ten miles, between ten and twenty fathoms. Vaughan, from his experience in the West Indies, reaches similar conclusions and considers that about ten fathoms is there the depth to which submarine erosion is vigorous. Off abrupt coasts exposed to on-shore heavy winds the profiles make it clear that it reaches to thirty or forty fathoms at the same distance.

As observed off many continental shores these slopes at the present time may continue almost flat for twenty or thirty

* Mr. Willis has noted in the discussion of this paper that the land surface of Argentina has been greatly affected by warping in late geologic time and that the possibility of warping should also be entertained in considering the significance of the subaqueous terraces. This is a valuable suggestion and no doubt has controlled the general form of the coast line. The development of these upper terraces at uniform levels over broad regions, however, at approximately 30 and 50 fathoms appears to indicate that their surfaces have been controlled by wave action working at these two levels at two different times later than the warping.

miles from shore. Then comes a convexity and a descent, in places to great depth, in other places, as illustrated by the shelf seas of Argentina, to broad flats about twenty fathoms deeper. Daly has been independently following the very same line of investigation, and he states in a personal communication that he has reached the conclusion that effective wave action stops much above the one hundred fathom line, notwithstanding that this has become conventionally accepted as the limit. With this conclusion the writer is in accord. Vaughan also has called attention to precisely the feature of

FIG. 2.

FIG. 2. Subaqueous projected profiles, coasts of Madagascar. Most of the coast shows graded, subaqueous profiles in adjustment with the present level of the sea, the wave action being relatively weak on the western side, strongest on the southeast. The figure shows how the different exposures of a coast must be considered together in order to eliminate the varying effect of the waves according to their intensity. This permits a conclusion regarding the relation of the profile to present and past water levels. Vertical scale 100 times horizontal.

the ocean profiles here described, noting the steep descent from about the 30-fathom to the 50-fathom curve, with gentler slopes above and below, as seen especially on the North American and Australian platforms.* E. C. Andrews, a

*Sketch of the Geologic History of the Florida Coral Reef Tract, and Comparison with Other Coral Reef Areas, Jour. Wash. Acad. Sci., p. 33, 1914.

The Platforms of Barrier Coral Reefs. Abstract, Bull. Am. Geog. Soc., vol. xlii, p. 427, 1914.

pioneer in thought in many fields of Australasian geology, showed in 1902 that the Great Barrier Reef of Australia stands on a platform which marks a former lower sea level. As Vaughan has stated, "The problem of the depth of barrier platforms is a world-wide one, for it is only an aspect of the general problem of the history of continental shelves."*

The study of the form of the subaqueous profiles shows, then, that they are not generally in equilibrium with wave action throughout their length. The character of the departure indicates a recent submergence. Where the shore is abrupt, as off the coast of Maine, the profile is overdeepened and the power of the waves is concentrated upon the exposed shore. Where the coast lands are very flat, as on the coastal plain, the submergence has inundated a strip which was previously land. The waves spend most of their energy on the flat bottom, miles off shore; they drag and throw up bars, partially recover their form and advance farther inshore to where barrier beaches are thrown up and cut off farther advance. The overflat bottom profile thus becomes undulatory by the shifting of material which is finally swept in part to the beach, in part to deeper water, and a normal profile becomes established. Thus it is seen that according to the form of the land submerged the profile may be overdeepened or overshalloved and the wave work becomes opposite in trend. But the cause,—submergence, may be equally clear in each.

Vaughan has developed additional criteria from the study of the shore and offshore physiography of the West Indies. He has pointed out that solution wells in the limestone show former emergence. These were made by fresh waters, and in the Bahamas are now submerged to a depth reaching 33 fathoms. There was also a still-stand of the land with the shore about ten fathoms below present level, as shown by the levels of the submerged terraces on the outside of the barrier reefs at from 8 to about 13 fathoms, with solution wells inside the barrier showing a depth from 6 to 7.5 fathoms. The filled channels of Havana harbor further substantiate the conclusion. Here there is a concurrence of evidence. From many regions, however, the other lines of evidence will be absent. There the conclusion must rest upon the testimony of the sea floor alone. When understood it is as convincing, however, as are any of the more familiar lines of evidence.

As an implication from the detailed evidence of the subaqueous profiles, it appears that the outer flats of the continental shelves still preserve to a greater or less degree the form determined by a sea level about twenty fathoms below

* Sketch of the Geologic History of the Florida Coral Reef Tract, p. 33, 1914.

that existing at present. Still farther out there are probably terraces cut still lower. But such older steps must be commonly mantled over by the terraces of later construction, their forms would tend to become smoothed out and they are not developed by sufficient soundings to permit as yet of a detailed study. In regions where rivers do not bring much sediment from the land, however, such fossil terraces may be best preserved. For the study of the negative phases of oceanic movements,—that side of the rhythms of which, as previously pointed out, so little is known,—they should be of high importance and be best developed where the evidence given by drowned river valleys is wanting.

Pliocene and Pleistocene Marine Terraces.

The second line of investigation which has led the writer toward the problem of recent movements was in connection with areal geologic work in southern New England. An examination of the topography indicated that there were in this region a series of descending baselevels, more than could be fitted to the so-called Cretaceous, early Tertiary, and late Tertiary baselevels. The necessity of determining the number, the slope, and the age of these, as a key to the post-Jurassic history of the region led to a development of methods the results of which have been published in abstract.* Each baselevel would be recorded in the interior by surfaces of subaerial denudation, on the seaward side by surfaces of marine planation. The latter were cut as benches across the harder rocks and are consequently better preserved than the former. They were most strongly developed at the maximum elevation of the sea during each oscillation. A method of projected profiles restores these ancient levels and hides the later dissection carried on by subaerial agencies. The length of the several profiles of marine planation is related to the duration of the baselevels; their difference in elevation gives, on the other hand, the amount of elevation of the land as the result of each cycle of motion. It is thought that the Goshen level, attaining an elevation of 1380 feet in northwestern Connecticut, dates from probably the earlier Pliocene. The terraces below, facing the sea, descend by steps which are a little over 200 feet apart in elevation and many miles broad. The series resembles a flight of stairs, but one in which the rises and treads are both gently sloping and the whole so dismantled by subaerial erosion that what the eye sees in viewing the landscape is almost wholly the dissection due to later cycles of destruction. The

* *Piedmont Terraces of the Northern Appalachians and their Mode of Origin*; *Post-Jurassic History of the Northern Appalachians*, Bull. Geol. Soc. Am., vol. xxiv, pp. 688-696, 1913.

shore lines of the terraces give the maximum elevations, the five Pliocene terraces reaching approximately to 1380, 1140, 920, 730 and 520 feet respectively. The Pleistocene terraces below were, in comparison, very imperfectly developed, but planation can be traced at stages whose mean elevations on their inner margins are 360, 220, and 100 feet. That at 220 feet is best developed, but none show the clear character of the Pleistocene terraces farther south on the coastal plain, since the Connecticut terraces were developed on formations of resistant rock. Furthermore, all are older than the last glaciation and have been obscured by that event. Their narrow breadth and originally imperfect development in comparison with the older and higher terraces appears to be a measure of an acceleration of the diastrophic rhythm in Pleistocene time. This crustal unrest is continued to the present; the present is diastrophically as well as climatically a part of the Pleistocene.

The broader Tertiary rhythm shown by the wide terraces facing the sea must be complicated in the Pleistocene by the special effects of the weight of the ice sheets, the changes in volume of ocean water related to glaciation, and the perception of the briefer minor diastrophic movements whose records are lost to sight among the larger movements of the past. These complications do not hide the facts, however, which lead to the conclusion that an abnormal crustal unrest beginning in the Pliocene has marked especially the entire Pleistocene period. The record which has been described shows the rhythmic oscillation during the upwarping and emergence of the Atlantic shore of the United States between latitudes 38 and 43 degrees. The record is different on the Pacific shores. There it is doubtless more largely related to the orogenic forces existent in latest times in the Pacific mountain system. On the eastern shore the deposits older than the Pliocene show a seaward tilt, greater for each older formation. This is a mark of progressive crustal warping. For the Pliocene and Pleistocene levels this warping, however, diminishes progressively. These later changes are more largely broad and parallel movements of level. They represent apparently more largely movements of the sea itself. To what extent, however, the net result is due to local movements of the crust cannot be determined until the series of strand lines has been studied on many shores and their resemblances and differences compared.

These high-level terraces represent the height of successive submergences. Let attention be turned next to the other side of the rhythm, that of the record of emergences, as shown by river valleys which now are drowned. Reaching far back into the Pliocene each shore line is found to be marked by large embayments developed upon regions of softer rocks. The

shore lines represent therefore the rhythmic rise of the sea upon a land surface previously dissected by subaerial erosion. The baseleveling on the softer rocks near the larger streams each time during the emergent phase had reached to an advanced stage, but upon the broad formations of harder rocks it had not progressed beyond the stage of youth. The submergent phase, however, lasted long enough for the sea to produce notable planation against the outstanding harder masses. Subaerial baseleveling at these stages seems also to have made notable progress, marking times of diastrophic rest. The submergence was in each cycle great enough to permit concentration of marine erosion against the headlands, the waves not spending their force upon the bottom. The motion of the sea-level was therefore cyclic, but not smoothly undulatory. If time be laid off as a horizontal axis, the curve of sea-level was nearer to the form of the common cycloid than to the sinusoid. The variety of the cyloidal curve suggested approaches that described by a point on the circumference of a rolling wheel. This curve is characterized by a nearly flat top and a cusped bottom. Conceive the point to be somewhat within the wheel and the pointed bottom of the curve would be somewhat broadened out. Conceive the wheel furthermore to be rolling down an irregular grade. Such a more complicated curve as would now be generated by the motion of the point may be nearer to the actual record of the sea-level movements against the Atlantic shore. It does not quite represent the discontinuous nature of the movements, but it does make graphic the conclusion that the emergent phases of the oscillations are relatively rapid and brief, the submergent phase prolonged, and marked by a slowly rising level of the sea. The retreats of the sea are thought to have been more rapid than the advances.

In Maryland broad and gently sloping terraces of Pleistocene age face the sea, bounded on the land side by low escarpments. They mark submergent phases of rhythmic crustal movements and show planation at levels of 220, 100 and 40 feet respectively, in descending order of age. The gentle seaward slopes are more or less in adjustment with the slope of the subaqueous profile of wave-worked bottoms. Within the valleys the deposits are regarded as fluvial. Facing the sea they are doubtless marine, though the porous nature of the thin mantle of deposits has not permitted the preservation of marine fossils. The terrestrial fossils fix the age as Pleistocene. The oldest and highest deposits are known as the Sunderland formation, and are apparently of early Pleistocene age. The youngest, known as the Talbot, are judged to be late Pleistocene. The materials of all three, Sunderland, Wicomico,

and Talbot, carry a large proportion of ice-borne bowlders, too large to be transported by the moderate development of river-ice now carried by the streams. They indicate thicker ice and a much colder period than at present.* These stages correspond in general to what in New Jersey, Salisbury has named the Bridgeton, Pensauken, and Cape May formations.

The oldest glacial deposits of New Jersey, represented by the patches of extra morainic drift, over the Triassic area are preserved on flat hill tops which range from 200 to 220 feet or more, in elevation. Some attenuation of the drift, ascribed to creepage, is observed below these levels, but it is inferred that the drift was laid down when the Triassic Plain was a gently undulating surface, corresponding with that whose dissected remnants are now 225 to 275 feet above the sea. The larger streams now flow at levels more than 100 feet below.† The combination of evidence from Maryland and New Jersey suggests strongly, though it lacks perhaps actual demonstration, that certain early Pleistocene stages of cold climate and glaciation occurred when the ocean level stood at the higher parts of the phases of cyclic oscillation. The statement fails of complete demonstration because the glacial deposits of New Jersey may be somewhat different in age from the Sunderland deposits of Maryland. The development of the plains at this level by subaerial erosion during crustal rest had been accomplished, at least in large part, when the ice sheets ended considerably north of their present limits, since the writer has identified baselevels of erosion at these levels in Connecticut. But the glaciation took place either before these baseleveled surfaces of soft Triassic rock had been uplifted at all or had been uplifted long enough to become dissected. The important point, however, is that the development of the cold climates, culminating in glaciation, does not appear to have required a low level of the sea, or high elevation of the land of this region. Such abstraction of ocean water as took place at these times was, therefore, more or less compensated for by occurring at the long submergent stages of the diastrophic cycles. Nothing is said here as to the attitude of the land in the centers of glacial accumulation. It is true that the central regions of glaciation are now in a depressed condition, as shown by the drowned topography. This may be the result of a lack of complete isostatic recovery after the removal of the ice load. This permanent depression is a factor, however, which would not have operated in Maryland. In conclusion, therefore, the evidence of the region marginal to gla-

* G. B. Shattuck, *The Pliocene and Pleistocene Deposits of Maryland*; Maryland Geological Survey, p. 85, 1906.

† R. D. Salisbury, *The Glacial Geology of New Jersey*, Final Report of the State Geologist, vol. v, pp. 755-760, 1902.

ciation leans toward the view that the amount of water abstracted for the formation of the ice sheets was not a major factor in the control of Pleistocene sea levels. From the estimates which have been given by Woodward, Penck, and Daly it would seem necessarily to have been a true and important factor, but the evidence of the Pleistocene oscillations of the Atlantic shore suggests that the diastrophic rhythm continuing with accelerated movement from the Pliocene constituted a more controlling factor.

Post-glacial Emergent Cycle Marginal to the Glaciated Areas.

The third line of investigation which led to an intersection with the problem of Pleistocene and post-Pleistocene crust movements is that connected with the Strength of the Crust, a subject now in progress of publication in the *Journal of Geology*. If the hypothesis set forth there is valid,—that a thick and strong lithosphere rests upon a thick zone of comparative weakness, an asthenosphere; then the weight of a continental ice sheet should tend to depress the crust into this weak zone. The crust up to a certain limit would yield as an elastic plate, the asthenosphere would reach its elastic limit at a far earlier stage and from that point yield by flowage, a flowage, it is thought, which is akin to the recrystallization which explains glacial flow. But as this subcrustal zone is not a fluid, it cannot transmit the excess pressures to unlimited distances. Broad and low pressure ridges would tend to be raised therefore beyond the limits of the ice sheets. A railroad embankment sinking into a marsh and elevating slightly the adjacent portions of the marsh offers an instructive analogy. Upon the removal of all of the embankment, including that which had sunk below the marsh level, a re-elevation of the central tract toward the original level would occur. The lateral pressure ridges might rise at first with the central part and then subside. This double motion would be favored if the deeper levels of the marsh were the more nearly fluid and if the removal of the load was very rapid, exceeding the rate of readjustment for the upper levels.

Does the expectation raised by this hypothesis correspond with the known depression of the crust under the Pleistocene continental ice sheets and the recovery from that depression which followed the retreat and disappearance of the ice? The question serves in a measure as a test of the validity of the initial hypothesis regarding the distribution of strength in the outer earth. As giving such a test the problem was investigated, though, as it is somewhat apart from the principal subject, it is not intended to publish the results as a part of the series on the Strength of the Crust, but rather later as a separate article.

The results of that investigation in so far as they bear upon the post-glacial crustal movements may here be touched upon, but within a short article the detailed arguments cannot be given. These results cannot therefore logically be used here as proofs regarding the nature of recent movements, but may serve as suggestions: the deductive conclusions from a hypothesis must be subordinated to the direct inferences from established facts, but the deductions may serve, nevertheless, to emphasize, explain, and coordinate such inferences.

This theory of the distribution of crustal strength was applied to the data regarding water levels during the retreat of the ice, and their correlations as given by Woodworth for the Champlain and Hudson valleys.* The accuracy and clearness of presentation of this difficult subject by Woodworth when combined with this theory permitted the determination of the sea level in latitude 40° north for each stage of the ice retreat. This is at a distance where the weight of the ice should have had no direct influence and represents the movements in a belt beyond the terminal moraines. As previously noted, however, the results of such an investigation are to be regarded as suggestive rather than conclusive. When the ice had retreated about to lat. $42^{\circ} 45'$, some 150 miles back from the terminal moraine, the sea level near the ice front stood 430 feet above the present level. The projection of the curve of flexure points to a sea level at latitude 40° 40 feet lower than at present. When the ice had retreated to lat. $43^{\circ} 30'$ the sea level there stood at +560 feet; at latitude 40° the appropriate curve suggests a sea level at -90 feet. When the Champlain marine water body existed, its slope and the appropriate curvature point to a water level of -220 feet south of the terminal moraine. These figures have of course no exact value, but if they are in the direction of the truth they mean that south of the limit of glaciation the coastal plain of the Atlantic shore was higher than at present and rising, the sea sinking, during the retreat of the ice, and that in later post-glacial time a marked submergence of this region has taken place to the present level. This emergence and submergence are of an opposite character to the effect of the addition of water to the ocean by deglaciation and are distinct from the marked isostatic rise of the glaciated region toward the present level, a rise which accompanied the removal of the load of ice.

Are there independent lines of evidence pointing in this direction, evidence strong enough to make a real case and not depending upon the grist of a mathematical mill, grinding out

* Ancient Water Levels of the Champlain and Hudson Valleys, Bull. 84, N. Y. State Education Department, 1905.

the results of certain hypotheses? Such independent evidence will now be considered.

Woodworth has called attention to evidence that at some time since the retreat of the ice the land has stood higher than at present. South of Albany many of the tributaries appear to be now filling up excavations below sea level which at some previous time they had cut into post-glacial deposits.* In the gorge of the lower Hudson River silt extends to variable depths, 280 to 320 feet at New York City. At the Storm King Crossing of the Hudson River, borings for the new aqueduct encountered the highest stratum of boulder beds at a little over 200 feet in depth. These appear to be deposits not excavated by river action since the ice retreated. The evidence shows, therefore, that a stage of emergence has occurred since the retreat of the ice but that this emergence above present level was not over 200 feet as a maximum. It may have been less.

Evidence that a minor cycle of emergence and submergence has occurred since the retreat of the ice is also found along the shores of southern New England and the south. The submergence to present level appears not to date back more than a few thousand years at the most, as is shown by the extreme youth of the shore line. Headlands have barely begun to be cut into, embayments have only begun to be filled. Sediment carried in by the tides forms salt marshes which are still flooded at spring tides. Deltas at drowned river mouths have barely begun to form.

It happens, however, that near the margins of glaciation the latest submergence has brought the present sea level only slightly above that which existed at the beginning of the retreat of the ice. The physical evidence for a rapid cycle of post-glacial emergence of considerable amount, involving a tract beyond the limits of glaciation, is therefore drowned and the amount and importance of the emergence is perhaps best given by the distribution of plants along the Atlantic shore from New Jersey to Newfoundland. Britton, Hollick, and others have discussed the significance of plant distribution, especially of southern types of the Coastal Plain, but the most important contribution on this subject has come from Fernald in his analysis of the flora of Newfoundland.† He points out that 118 species of plants belonging to the Pine Barren and Coastal Plain floras of New Jersey and the south are known from remote outlying stations along the coastal strip of New England and the Maritime Provinces. Most striking, however, is the evidence from Newfoundland. He shows that 60

* J. B. Woodworth, *loc. cit.*, pp. 229-234, 1905.

† M. L. Fernald, *A Botanical Expedition to Newfoundland and Southern Labrador, Rhodora*, vol. xiii, pp. 109-162, 1911.

per cent of the plants are boreal types. Only a few plants are present out of the hundreds which constitute the flora typical of Canada in the same latitude. On the other hand 35 per cent of the plants of Newfoundland are southwestern types and 7.7 per cent of these are plants characteristic of the coastal plain of New Jersey and the south. Fernald shows, by means of the evidence of the flora, the ineffectiveness of winds and currents to transport across the Gulf of Saint Lawrence to Newfoundland the typical Canadian plants, though the boreal types may have entered across the comparatively narrow straits which separate the island from Labrador. Fernald argues that it would be still more difficult for winds and currents to act as agents for the migration of the Coastal Plain flora. Not only are the distances vastly greater, but the winds and currents move actually in the wrong direction to carry plants from the southwest.

Migrating birds can hardly be invoked. The nearest land to the southwest of Newfoundland is Cape Breton Island at a distance of 70 miles and many of the species of plants which are concerned are rare and local at all points northeast of New Jersey, a distance of over 850 miles. Studies of migrating birds, especially in connection with the flora of the Farøe Islands, have shown that they reach the end of their flights with intestines empty.

A remaining hypothesis is, that after the last retreat of the ice, the Coastal Plain stood higher and offered northeastward a line of passage broken only at a few places by channels of deep water. A climate warmer than the present would favor this migration of the flora of the southern Coastal Plain. An elevation of at least 100 or better 150 to 200 feet, enduring for some thousands of years, would apparently be needed to give the necessary conditions for plant migration. An elevation of 200 feet would still involve, however, the crossing of 70 miles of water in Cabot Strait. An elevation of the Coastal Plain seems the readiest way of explaining the existence of such isolated stations of southern plants as that of *Magnolia virginica* at Cape Ann, Massachusetts, but migration from the southwest is difficult to apply to Newfoundland. For this it may be necessary to invoke another aspect of the same hypothesis of elevation.

The Great Banks extend 200 miles southeast of Cape Race, to latitude 43 degrees. The Gulf Stream flows past not far distant on the south and must serve to ameliorate the climate. Nearly to the margin of the Banks the depths range no deeper than from 30 to 40 fathoms. If, during and for a time following glaciation, this region was above sea level and unglaciated, it may have served as a haven of refuge for plants of the Coastal Plain, requiring a temperate climate.

In his first publication Professor Fernald had given much weight to the suggestions derived from Penck and Daly,—that the ice of the continental glaciers abstracted so much water from the ocean that an emergence would be expected of part of the continental shelves. But against this cause as an agent operative in this instance it is to be noted that in direct proportion as the climate became warmer and the ice withdrew such an emergence would have disappeared. The character of the flora suggests, however, that the migration to the present isolated localities must have taken place during a period of climate even warmer than the present and at a time after the ice sheets had given up their water. This aspect tends to rule out the availability of the hypothesis that emergence was controlled only by the level of the ocean water as controlled in turn by glaciation. In response to questions by the writer regarding the indications of the plants as to the climatic conditions which would favor their migration and successful competition with other floras, Professor Fernald, under date of January 15, 1915, wrote a letter, which because of its great value on the problem of recent crustal movements is quoted here nearly entire.

Botanical Evidences.—A Preliminary Statement of Results of Studies on the Northeastward Distribution of the Coastal Plain Flora, by M. L. Fernald :

The question you raise, of the probable period and climatic conditions of the migration of southern coastal plain plants to Newfoundland, is one on which there is now accumulating a vast amount of evidence. Since I published a preliminary statement of the case I have had parts of two seasons in Newfoundland where I secured much more similar material, a season divided between Prince Edward Island and the Magdalen Islands, which have a flora much more southern than boreal, with many New Jersey Pinebarren species, a summer on Cape Cod and Black Island, where there are still larger proportions of such cases. One of my research students, Mr. Harold St. John, has spent a season on Sable Island, getting evidence in the same line, and another season on the Magdalen Islands, and he is now working on the results as his doctor's thesis. Another graduate student, Mr. Sidney F. Blake, has spent a season on Northumberland Strait and the sands of northeastern New Brunswick, where he secured further material upon which his thesis will be based.

Briefly, we have in southern Newfoundland (south of the North Peninsula) a large number of species of southern origin, some even of tropical affinity. Further, on the shores of Dawson's warm Acadian Bay (see Dawson, *Canadian Nat.*, ser. 2, vii, p. 277, 1875), including the region from Cape Breton to the south side of Baie des Chaleurs, i.e., eastern Nova Scotia, eastern New

Brunswick, Prince Edward Island, and the Magdalen Islands, we find many such species, some identical with, others different from those reaching Newfoundland, and on Sable Island there are some similar cases, some of the species from the south getting to Sable Island but not to the other areas. Now it is inconceivable that these southern types should have extended to these remote outlying areas under conditions much colder than at present, and judging from their present very restricted occurrence in these northern regions it looks as if they must have reached them during a period somewhat warmer than at present. They either migrated northward on the continental shelf prior to the Wisconsin glaciation and persisted outside the subsequently glaciated area, finally taking possession of their present isolated habitats on the receding of the ice or, as seems to me perhaps equally probable, the continental shelf, including the present southwestern half of the Gulf of St. Lawrence, must have been considerably elevated after the Wisconsin, long enough for the migration—including some mammals, and even fresh water and land snails.

The question is complicated by a mass of evidence not yet published upon: briefly that in the regions above enumerated, there is also a remarkable proportion of the flora, quite unknown elsewhere in North America, which is strictly identical with the flora of the Atlantic area of Europe, even including the Azores. We have startling cases (several scores of them) of species strictly indigenous in Newfoundland and known otherwise only in the region from the North Sea to Portugal, or to western France, and in some cases also on the Azores or even Madeira. Similar and very striking cases have come to light on Sable Island, the Magdalens, Prince Edward Island and eastern New Brunswick, indicating pretty clearly a large flora (and snail fauna, too) which must have crossed on the mid-Tertiary land and been stranded at the present margins of the Atlantic. Now these cases imply some tract along the coast, especially of Acadia, and Newfoundland, which held this flora and fauna continuously through the Pleistocene.

Another point: in a few cases plants clearly indigenous on these isolated areas, Newfoundland, Sable Island, Prince Edward Island, etc., are species identical with, or representative of, the Australasian flora, and seem to be harking back to the Eocene. So you see, that it is not very easy to give an offhand brief answer to your inquiry about the botanical evidence. My students, Messrs. St. John and Blake, and I are wading about in a flood of such evidence, trying to work out the exact identities and affinities and come to safe anchorage, but it is a vast problem and every species has to be studied intensively, often requiring a complete monographic study of a world-wide group before we are sure of our ground.

It will be a long time before we are able to publish our detailed results. If you wish to use the above as a preliminary statement you may do so.

Evidence somewhat similar to that which has been so strikingly presented by Fernald is found on the shores of north-western Europe, of land emergence above the present level involving regions beyond the limits of glaciation and occurring in a warm stage following the retreat of the ice. This is presented in comprehensive form by W. B. Wright of the Geological Survey of Ireland in his recent book on "The Quaternary Ice Age." Before the glacially depressed region had recovered in Scandinavia all of its present elevation, there was a rapid uplift to the south which cut off the connection of the Yoldia (enlarged Baltic) Sea with the Atlantic and produced the Ancylus lake. The climate was notably warmer than at present, as recorded by the advance of the hazel (*Corylus avellana*) and other plants to regions well beyond their present northern limits. The same climatic optimum has been proved in Finland, for at a certain floral horizon (the upper portions of the Birch-Fir zone) certain warmth-requiring plants made their appearance in localities far north of their present northerly limits.* In southern England forest beds which are correlated with this stage are found submerged now to a depth of 55 to 60 feet, indicating a post-glacial uplift of land to a height well above the present sea level.

Wright considers the breadth of this movement as indicative of a general lowering of sea level and seeks its cause in a recrudescence of some one of the ice sheets, possibly that of the Antarctic continent.† But the general warmth of climate existing at that time does not favor such a view. So far as the evidence goes two other hypotheses are preferable.

One of these hypotheses is that the post-glacial emergence and following submergence represent a diastrophic emergent cycle entirely unrelated to glaciation, one of the movements in the complex rhythms which have been traced in southern New England through Tertiary and Quaternary times. If so, it should be in part a sea-level movement, and traceable widely over the earth.

The other hypothesis involves less widespread effects. It is that which was discussed in the pages leading up to the botanical evidence. This hypothesis is, that the weight of the ice sheets caused crustal depression directly below the load, but moderate elevation in a wide zone beyond the load. Upon the removal of the ice it appears the first isostatic upwarping carried up higher this marginal upwarped zone with it. Being already an upswollen tract the broader regional movement carried it up to a level where it became unstable and a slow settling back occurred as an after effect, coincident with the

* W. B. Wright, loc. cit., p. 437, 1914.

† Loc. cit., p. 417, 1914.

last stages of upwarping over the centers of glacial load. The actual evidence at hand does not decide between these hypotheses. The association with the close of glaciation appears to favor a genetic connection with deglaciation, but on the other hand it remains to be demonstrated why the extra-marginal zone should rise together with the region directly glaciated, or that the cycle was restricted to such an extra-marginal zone.

Possible effects of radial shrinkage.

The fourth line of intersection with the problem of recent movements was the result of a query raised by Professor Schuchert in 1909 as to the quantitative effect of earth shrinkage in producing an increased speed of diurnal rotation, and a greater oblateness of the earth's figure; tending to raise the level of ocean waters toward the equator, and to depress the ocean level near the poles. Calculations made by the writer for Schuchert in regard to the possible magnitude of this effect suggested that it might be of very real influence.* A radial shrinkage of a mile, it was estimated, would increase the difference between equatorial and polar radius by about 90 to 100 feet. If this difference were taken up wholly by adjustment of ocean level and not by internal earth adjustment, a supposition which can be true to only a limited degree, then a shrinkage of a mile in radius would raise the water level at the equator about 35 feet, while at the poles it would sink about 60 feet. In latitude 35 degrees the water level would suffer no change.

The rigidity of the earth in an east-west direction is also found to be different from that in a north-south direction and may have some influence on mode of crustal yielding.

But to be of influence in a result, a factor must not only be real; it must, furthermore, be of quantitative importance. Such great folding and thrusting movements as have occurred in the later Tertiary suggest that earth shrinkage is an important factor. Schuchert has called attention to the greater persistence of equatorial epeiric seas and the readvance of waters more frequently from lower toward higher latitudes.

The southward bends of certain rivers such as the Delaware and Susquehanna along the strike of soft formations has received various explanations. In so far as land emergence is produced by sea-bottom subsidence or is coincident with movements of crustal shortening, the retreating sea should also slightly change its slope. It is possible that such a slight change in slope of sea level at the time the lower river courses were established on a newly emerged coastal plain may be at

* Charles Schuchert, Paleogeography of North America, Bull. Geol. Soc. Am., vol. xx, pp. 505-508, 1910.

least a partial cause of the southward deflections of rivers which were established along the Atlantic margin in late Tertiary time. Such a possibility should at least be added to the group of multiple hypotheses which have been brought to bear upon the problem. In the emergence of a sea bottom, the more important control of the slopes is due to the slope of the previous surface of sedimentation and the later local warpings of the crust, but a component tending to make for deflections toward the equator may be due to more broadly acting forces, and at certain times and places it may rise to the rôle of an important factor.

Conclusions.

To review in conclusion the factors which appear to enter to a greater or less degree into Pleistocene and recent crust movements,—First, we must recognize the *climatic factors* connected with Pleistocene glaciation. These consist in the abstraction of the vast quantities of ocean water which accompanied the development of the ice sheets; the direct depression under the load of ice; a possible compensatory elevation in a somewhat broad zone beyond; a deferred, intermittent, and possibly oscillatory readjustment upon the removal of the burden of ice.

But these factors related to glaciation must not be used alone. There are other factors unrelated to climatic causes which may be of equal importance. The second group of causes includes the movements which tend to maintain the equilibrium of large sections of the crust, affect the whole ocean level and locally warp the lands, but do not involve earth shrinkage. It is thought that they find their cause in a lack of equilibrium of pressures upon that zone of the earth's body which lies just below the level of isostatic compensation. They are then the *isostatic factors*. The general rise of lands which has marked the later geologic times may most probably be placed in this category, due either to changes of external load, or to changes in crustal density. This would include a possible enlargement or deepening of portions of the ocean basins. As continental rejuvenation is the chief effect, these adjustments toward the maintenance of isostasy may be called *epeirogenic factors*.

The third group of causes are thought to be found in great compressive movements in the lithosphere, which seem to be due in turn to a shrinkage of the centrosphere. Locally they may work against isostasy, more broadly they may start isostatic movements. As their ultimate expression is in mountain building along lines of weakness they may be classed as *orogenic factors*.

Fourth are the *planation factors*, working in opposition to isostasy. They are the forces which tend to erode the lands, fill the seas with sediment, and raise their surface level. Added to this is whatever slow and secular gain the ocean makes in the volume of its water.

The combinations of isostatic and compressive forces have together operated through geologic time. The causes are complex and the result is seen in the composite diastrophic rhythms which are expressed in all ages but which can be studied best and more definitely in the record of the latest times.

To sift apart the factors, comprehensive investigations must be prosecuted over different parts of the earth. The sequence and amount of oscillations in the tropics must be linked to those of higher latitudes. Changes of sea level must be separated from local changes in the level of the crust. Multiple working hypotheses must be tested by the application of new and significant facts.

When, as Gilbert says in the introduction to his monograph on Lake Bonneville, "the work of the geologist is finished and his final comprehensive report written, the longest and most important chapter will be upon the latest and shortest of the geologic periods".