CHAPTER SIXTEEN

THE PERIODICITY OF OCEANIC SPREADING, MOUNTAIN-MAKING, AND PALEOGEOGRAPHY

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The writer has been asked by Doctor T. Wayland Vaughan to write for this symposium on oceanography a brief outline of the principles of paleogeography, or the former distribution of land and sea, and of the explanations proposed for such changes. For those who may desire to go more deeply into this matter, a short bibliography is appended, giving some of the readily accessible literature on the subject.

INTRODUCTION

The Greeks and Romans knew that the lands had been partially invaded by the oceans, but after the time of Leonardo da Vinci (1452-1519) this fact became all the plainer. When, at a still later date, fossils of sea animals were found farther and farther inland, in fact in the very hearts of the continents and at great heights in most of the mountain ranges of the world, geognosts taught that the whole earth had once been covered by a universal ocean and that the lands, as we now see them, emerged through subsidence of these oceanic waters, which in great part were swallowed by the inbreaking of huge cavities into the earth's interior. That such vast cavities actually existed seemed to them proved by the highly inclined strata of the fold-mountains. Accordingly, they held that the universal ocean hid the submerged topography beneath, and that the present land sculpture was revealed ready-made as the oceanic level gradually subsided in a few thousand years to its present stand. Then came the knowledge that locally the lands are even now actually subsiding slowly beneath the sea in some places, and at other places are rising above it. And when geology accepted the fact that whole mountain ranges, with their folded structures, along with large parts of continents, had actually risen out of former seas, and even out of the Mediterranean and the Pacific, there arose two schools of thought. One of these, led by Sir Charles Lyell, concluded that both the continents and oceanic areas are inconstant as such, and that the lands go beneath the marine waters, even to abyssal depths, while the ocean bottoms become dry land and even mountains. The other school, led by James D. Dana, believed in permanency of these major features; that the continents and oceans have always been where they are now, but not necessarily with their present detailed outline, size, elevation, or abyssal depth. The school holding to the permanency of the continents and oceans is now almost universally in ascendancy. These conclusions led to the further one that the earth's surface in all of its parts moves either up or down, and that the average of the movements of the continents is upward or positive in respect to sea-level, while the sum of the oceanic bottom movements is downward or negative.

As the sequence of geologic history was gradually worked out, and it was seen that some of the floodings of the continents are indeed very extensive, and others very small, the old theory of universal oceans with their universal formations was abandoned. Now we are agreed that almost all marine deposits accessible to geologists, and of whatever age, are more or less local in deposition, and that only some of the transgressions are of very wide distribution. These facts teach that the continental surfaces in relation to sea-level are to a certain extent inconstant, and that they may be warped above or below the average oceanic level of any given time. But now we also see that it is not the lands alone that move, since the study of coral islands has demonstrated that the oceanic bottoms have moved at least locally up or down and as much as 5,000 feet. Not only all this, but the further grand fact has come into general recognition that the crustal movements are periodic in their occurrence. In other words, the evolution of the earth's surface is cyclic in nature. Most often the movements of the lands are local, affecting now this and now that portion, or two or more parts of the same continent at a given diastrophic time, and even the continents become more or less mobile at about the same time, or in sequence. These crustal movements may continue through millions of years. This mobility is greatest near the continental margins and may be common to the two sides of an ocean or a mediterranean, or may alternate on either side of an oceanic basin (see Fig. 1).

PALEOGEOGRAPHY

Geography describes and maps the present earth's surface and other features that have to do mainly with human relations. Paleogeography, or ancient geography, on the other hand, treats of the succession of geographies of the past, i. e., the prehistoric geographies as revealed by geologists and paleontologists. In other words, paleogeography is the synthesis of the earth sciences, based on the record of the rocks of the earth's surface and the fossils in them. All sedimentary strata come as detritals, or solution materials, from older rocks of like or unlike nature, and in the last analysis from igneous ones. Therefore it is the province of geologists and paleogeographers to seek for the lands that have furnished the sediments of any given time. In this examination of the marine deposits, shorelines are discovered, and the nature and depth of the sediments reveal something of the topography of the adjacent lands, and likewise a little of the temperature of the water and the climate of the land; and more of the same sort of information is gleaned from the entombed fossils.

Descriptively, paleogeography is far easier to state than to depict on a map. Such maps have been made since 1832, and now number more than one thousand, but their accuracy is good only along broader lines. This branch of geology is still in its infancy, and most of the paleogeographic maps embrace far too much geologic time, none less than one or more million years and many based on the known events that transpired during tens of millions of years. Accordingly, the shorelines of paleogeographic maps must be more or less hypothetic, and are drawn in sweeping curves, unlike those of geographic maps with their bays, headlands, and islands. The lands are usually drawn as featureless, and only rarely do they indicate the probable drainage. In the course of time, the maps will also show the probable relief of the lands, such as the mountain ranges and volcanoes, something of the climatic zones as well, and of the distribution of the life of the time depicted, while the seas will show probable depths, currents, temperatures, and nature of bottom deposits.

As yet, no one has attempted to picture the geographies back of the Cambrian—a vast time of about two-thirds of the earth's history that is almost devoid of recognizable fossils. This means that all of our attempts are limited to about one-third of geologic time, with its abundance of formations that have usually not been obscured by the dynamic and igneous forces of the earth.

Principles of Paleogeography. The paleogeographer, in his work of deciphering the past, uses mainly eight sets of facts, as follows: (1) The law of stratal *superposition* says that the lowest bed of rock in any undisturbed exposure of the earth's surface is older than those above; and superposition is also of prime importance in determining the stage of evolution attained by the entombed organisms. (2) *Fossils* are the basis of most geologic chronology, because all life is in the constant state of change comprehended under the term organic evolution. Through the discerning of this genesis, fossils have also become the automatically-placed time cards, since the "guide fossils" tell the geologic age of their entombment. They also yield much information about the environment in which they lived, whether in the seas or fresh waters, in the swamps, lowlands, or highlands, and whether the temperature was warm or cold, temperate or tropical. Fossils are actually "life thermometers." (3) The units in paleogeography are the *geologic formations,* masses of rock of like or variable kinds formed on the dry lands or in the rivers and lakes or in the seas and oceans. The present geographic distribution of the formations is the first basis for deciphering the geographies of the past. (4) The nature of the formation, or its *petrology,* tells whether it was formed in water or was wind-blown, laid down in wet or dry climates in the seas and oceans, or is of igneous origin. Sediments are also climatic indicators. In other words, the environment automatically impresses itself upon the accumulating sediments, just as it brings about the evolution of all living things. (5) The record of crustal movement, or *diastrophism,* tells of the variability of the environment and of the absence of deposition or recording. These absences are the "breaks, unconformities and disconformities" of stratigraphers, which show that the recording goes on now here and now elsewhere, and that recording, diastrophism, and erosion are periodic and cyclic in appearance. (6) *Geologic time* is exceedingly long, and on the basis of radium disintegration the earth has a record of not less than 1,500 million years. (7) The greater geographic features of the earth's surface are essentially permanent (=*permanency*). The entire surface of the earth moves variably in the course of geologic time, but the lands are the most mobile parts and are either marginally or in large sectors breaking down into the oceans; the ocean basins are the most permanent features, slowly deepening and enlarging with time. As a result of diastrophism the surface of the earth changes its altitude and in consequence alters the sea-level in respect to the lands; thus, in the main, is brought about the transgression of the marine waters over the lands, and their emergence. (8) The *geographic map* is at present the necessary base upon which are drawn the paleogeographies.

CYCLIC NATURE OF TRANSGRESSIONS AND EMERGENCES

We now know that the oceans flood each continent in definite and recurring patterns, and that the areas of greatest marine persistence are the geosynclines—waterways that last through one or more geologic eras (see Fig. 1). Stated in years, some of these troughs have lasted but a small part of a geologic era, say 20 million years, while the most persistent ones have endured, though with much change, through 500 million years and even longer. These geosynclines are narrow, slowly subsiding, negative tracts from 200 to 500 miles wide and from a few hun-

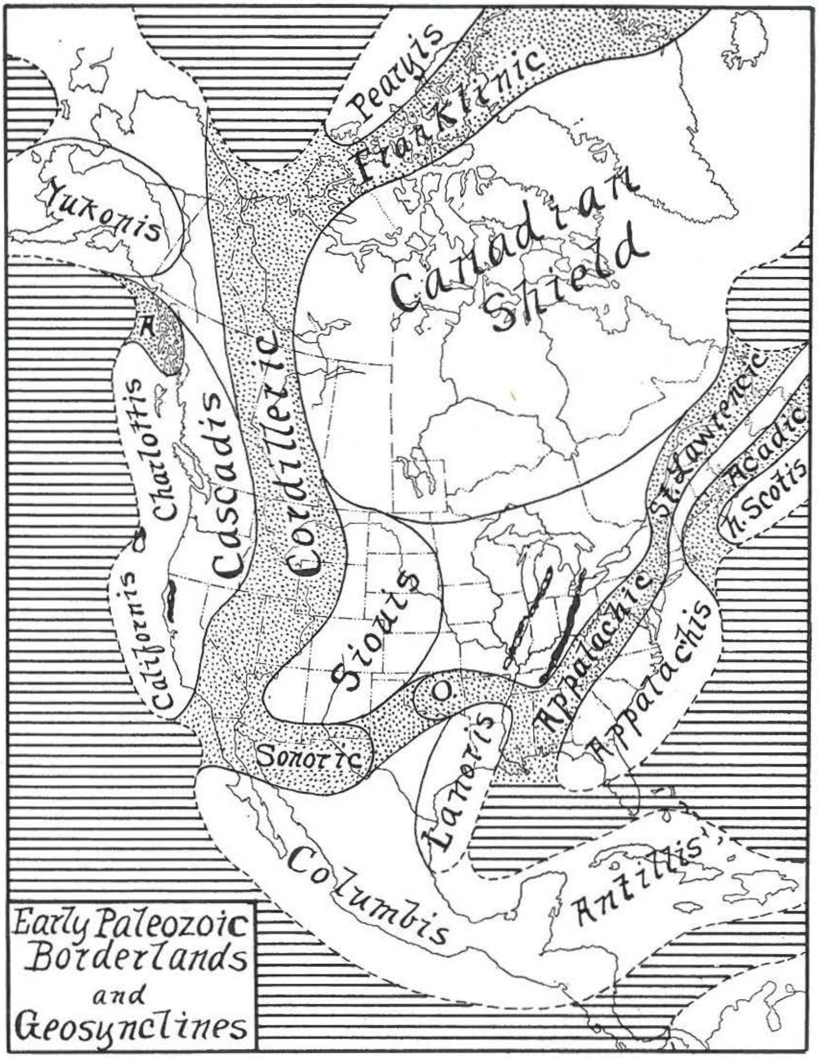

FIG. 1.—The North American borderlands, the rising areas, are the most mobile parts of the continent. The geosynclines (dotted) are the sinking areas, and eventually go into fold mountains. A, Alexandric embayment. O, Ouachitic embayment, at times continuous with the Sonoric embayment.

dred to several thousand miles long, situated along the inner sides of the outer, most mobile parts of the continents, called borderlands. In other words, the frame of the great interior basins consists of two compensating parts situated along the continental margins, an outermost rising or positive borderland that furnishes nearly all the sediments for the inner subsiding geosynclinal part of the frame. Eventually the geosyncline also becomes positive, and then it slowly undergoes folding with some elevation, and finally the two parts of the frame are elevated together vertically into a broad arch that is eroded into a mountain system. Some of the smaller geosynclines have subsided 20,000 feet before being transformed into a mountain system, but the largest one of western North America, the Cordilleric, which is about as old as the continent, went down in general anywhere from 30,000 to 50,000 feet, and locally even to 70,000 feet, before it was folded into the Rocky Mountains, which later were raised to greater heights and are now mountain ranges that extend from Alaska to southern Mexico.

Inside the geosynclines of North America, the continent has always had a shallow basin shape (see Fig. 1), and previous to the Cenozoic generally stood but a few hundred feet above sea-level. With the greater rising of the Rockies during Pliocene time the whole interior was elevated two or three times higher than it stood during the Paleozoic era. This vast inner region, known as the neutral area, warps in a recurring, more or less similar pattern, and over the lower parts of it the geosynclines spread their marine waters as variably extensive epeiric seas.

The oceanic floodings always begin in small transgressions, usually first in the geosynclines, and then grow larger by spreading over the neutral area (see Fig. 2). Finally, each flood retreats, generally from the geosynclines last, and eventually most of the waters leave the greater part of the continent emergent. In three of the greater floods of early Paleozoic times, however, the waters from the Arctic Ocean spread widely south across the neutral area of North America, and all of the larger spreadings occur in the middle part of each period. During the first and last third of each cycle, when the lands are highest, erosion is most active in levelling the lands, and thus it facilitates the oceanic spreadings during the middle third when the marine transgressions are also greatest.

The sands and muds and the solution materials carried by the rivers are but the fragmented and dissolved mountains and high lands in transit to the oceans. For every grain of land transported into the marine waters, there is just so much water displaced. The result is that during the long quiet middle part of the cycles, when the earth's surface also

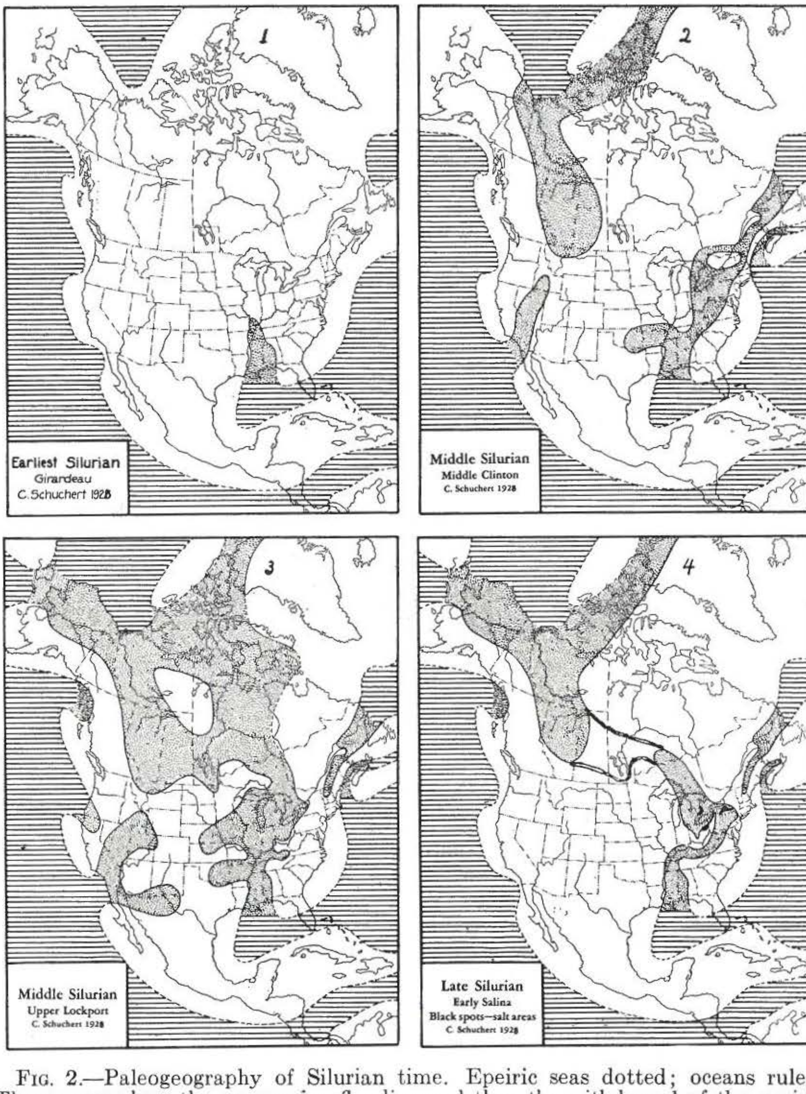

FIG. 2.—Paleogeography of Silurian time. Epeiric seas dotted; oceans ruled. These maps show the progressive flooding and then the withdrawal of the epeiric seas. At the close of the Silurian the continent was almost entirely emergent.

moves least, the oceans are constantly rising, as it were, and flowing ever more widely over the continents. It is during the closing part of the cycles (close of periods) that new mountain chains arise or old ones are re-elevated. These upliftings of the earth's surface are commonly of restricted occurrence, now here and now there, but after long geologic intervals (toward the close of eras) the upheavings and sinkings of the past appear to leave the crust in a state of unbalance, and then the time comes for general readjustments, and the grandest mountains are made in almost all the continents. The present relief shows the completion of the latest of these crustal readjustments. In other words, each cycle of oceanic spreading over North America begins with a small flood that grows larger, though it may oscillate back and forth variably over the neutral region. Eventually, however, the flood retreats more or less completely off the continent, and more quickly than it came (see Fig. 2). The lands are then most elevated in relation to the strand-line, while the ocean bottoms have subsided, thus increasing their capacity as basins, a volume increase that is enhanced through the downwarping or fracturing of parts of the continental shelves.

At least seventeen such cycles are recorded in the geologic history of North America. Of these ten have been large inundations, varying between 1,660,000 and 4,675,000 square miles; the smallest flood has 235,000 square miles (see Fig. 3, curve of oceanic invasion). All are inland shallow waters, and nothing of marginal overlaps or shelf seas is known until late Mesozoic times, when the Atlantic spreads over its western margin from Massachusetts south to Florida (see Fig. 5). During Cenozoic time there are almost no interior seas at all, but instead, narrow shelf seas along the margins of the Atlantic and the Pacific. The Gulf of Mexico, however, came into existence during the Cretaceous period and then spread north to Illinois, continuing thus into early Cenozoic time, but with the Oligocene began a retreat to its present configuration. These facts show how greatly the geography of North America has varied in the geologic past. To-day we are living in the beginning of a new cycle, when the continents are largest, highest, and scenically grandest. The oceans, however, have begun another invasion upon North America, as seen in the shelf seas, the Saint Lawrence embayment, and most widely in Hudson Bay.

In 1910 the writer produced a chart showing the cyclic nature of the North American marine floodings, and a more generalized form of it is given in Figure 3—curve of oceanic invasion. Since then his paleogeographic mapping has been continued in manuscript form, but no new recalculations have been made. The new maps will be published two or three years hence, but for the present it may be said that although the curves of 1910 are not correct in detail, they are not fundamentally wrong. They still give fairly correctly the cyclic sequence, and in general the amount of land covered by the inland seas during each flood.

This chart shows seventeen lows or inundations, separated from one another by as many highs, or emergent periods. Of these, eleven are Paleozoic, four Mesozoic, and two Cenozoic. In the following table is given in square miles the amount of North America and the United States that was submerged. The names in italics represent the marked submergences, ten of which covered between 20 and 57 per cent of North America, and from 24 to 61 per cent of the United States.

TABLE OF NORTH AMERICAN INUNDATIONS (1910)

Time of greatest inundation	Area of North America =8,200,000 sq. miles		Area between 30° and 50° =3,530,000 sq. miles	
	In sq. miles	In per cent	In sq. miles	In per cent
Cambrian				
Middle Lower Cambrian ...	1,451,000	17.6	421,000	12.0
Middle Cambrian	2,587,000	31.6	1,648,000	46.7
Late Upper Cambrian.......	1,775,000	21.7	1,016,000	28.9
Ordovician				
Lower Ordovician	1,663,000	22.7	1,065,000	30.3
Middle Ordovician (Trenton)	4,676,000	57.2	2,158,000	61.2
Upper Ordovician (Richmond)	3,340,000	40.0	1,560,000	44.3
Silurian				
Middle Silurian (Louisville).	2,940,000	35.9	1,246,000	35.7
Devonian				
Middle Devonian (Hamilton)	2,881,000	35.2	1,126,000	32.0
Lower Carboniferous				
Mid. Low. Carboniferous (Burlington)	2,664,000	20.1	874,000	24.8
Upper Low. Carboniferous (St. Louis)	620,000	7.6	348,000	10.0
Upper Carboniferous				
Early Mid. Up. Carboniferous (Pottsvillian)	2,270,000	27.7	1,283,000	36.4
Late Triassic	1,261,000	15.4	292,000	8.4
Late Jurassic	1,130,000	13.8	646,000	18.4
Lower Cretaceous				
(Fredericksburg)	1,559,000	19.0	433,000	12.4
Upper Cretaceous (Niobrara)....	2,778,000	33.9	1,354,000	41.3
Early Oligocene	236,000	2.9	154,000	4.5
Upper Miocene	360,000	4.4	234,000	6.7

CLIMATES OF GEOLOGIC TIME AND OCEAN TEMPERATURES

The paleometeorologic studies of the writer are summed up in Figure 3. Two marked glacial climates are now clearly established, namely, those of Pleistocene and of Permian time. The former is the best known one and is the standard for recognizing the others. In addition, there is a great deal of evidence showing at least two and probably three other times of world glacial climates; these are all of the time back of the Paleozoic. One of them was at or near the close of Proterozoic time, and another at the very beginning of this era. Hence glacial climates have recurred at rare and irregular intervals almost throughout the geologic history of the earth.

These world climates reduced the mean air temperatures sufficiently to allow vast accumulations of snow and ice, not only at high altitudes, but even markedly at low levels, with the glaciers in many places attaining the sea. Pleistocene glaciation was dominant in polar regions, whereas that of Middle Permian time had its greatest spread from 20° to 40° south of the present equator, and to a far less extent between 20° and 40° in the northern hemisphere (see Fig. 4). Accordingly, we see that Pleistocene glaciation was general in far northern and southern latitudes, whereas that of the Permian was mainly in the south temperate zone with scattering known occurrences in tropical and north temperate regions.

A glacial period does not appear to remain constantly cold, but fluctuates between glacial climates and warmer interglacial times of varying duration. During the Pleistocene there were, according to the leading glaciologists, at least three, if not four, such warmer intervals. That of the Permian also had its warmer times, and the interbedded red strata of the Proterozoic tillites seem to point to the same variability. It is this decided temperature fluctuation during the glacial periods that is so difficult to explain.

We now know that during almost the whole of geologic time the earth has periodically undergone more or less widespread glaciation, and that the cold climates have been of short geologic duration. Seven periods of decided temperature changes are known, and of these at least four had glacial climates. The latter occurred during or directly after times of intensive mountain-making. On the other hand, the very marked and world-wide mountain-making period, with decided volcanic activity, during late Mesozoic and earliest Eocene times, was not accompanied by a general glacial climate, but only by a cooled one with at least one local area of piedmont glaciers (Colorado). The cooled period of the early Jurassic also followed a time of mountain-making

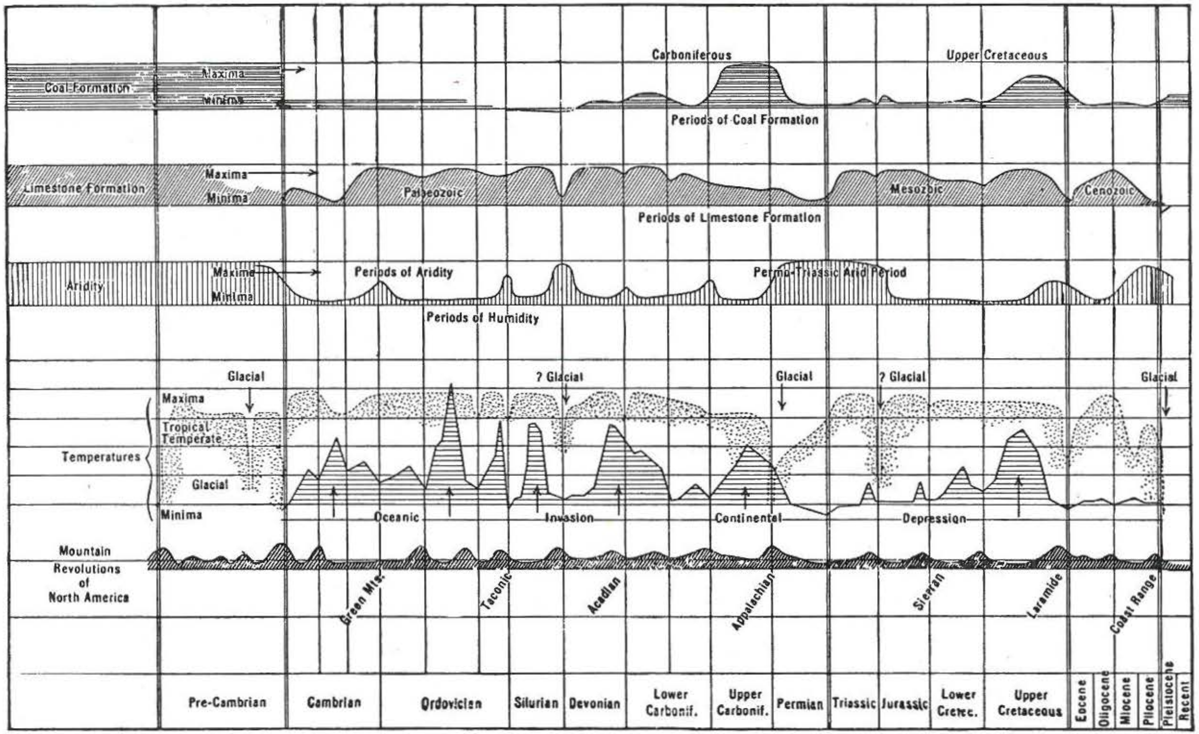

FIG. 3.—Diagrammatic geologic vista of the earth's changing surface and atmosphere. Here the times of maximum coal, limestone, and mountain-making are correlated with those of maximal variations in temperature, aridity, and oceanic spreading. After Schuchert, from Osborn's *Origin and Evolution of Life*, 1917.

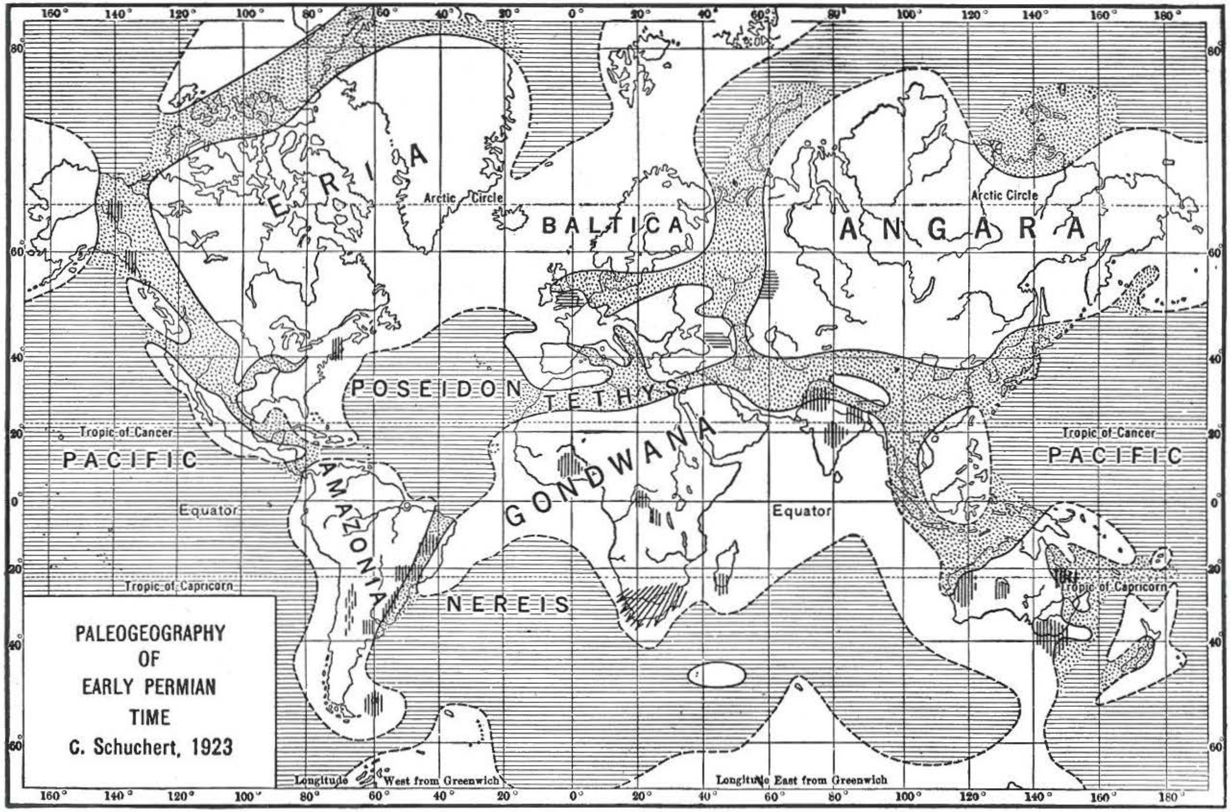

FIG. 4.—Glaciation of Lower Permian time. Oceans are ruled, epeiric seas dotted, and places of glaciation lined (vertical, areas of proved glaciation; horizontal lines, of uncertain glaciation). Note the transverse shape and connected condition of the continents of this time.

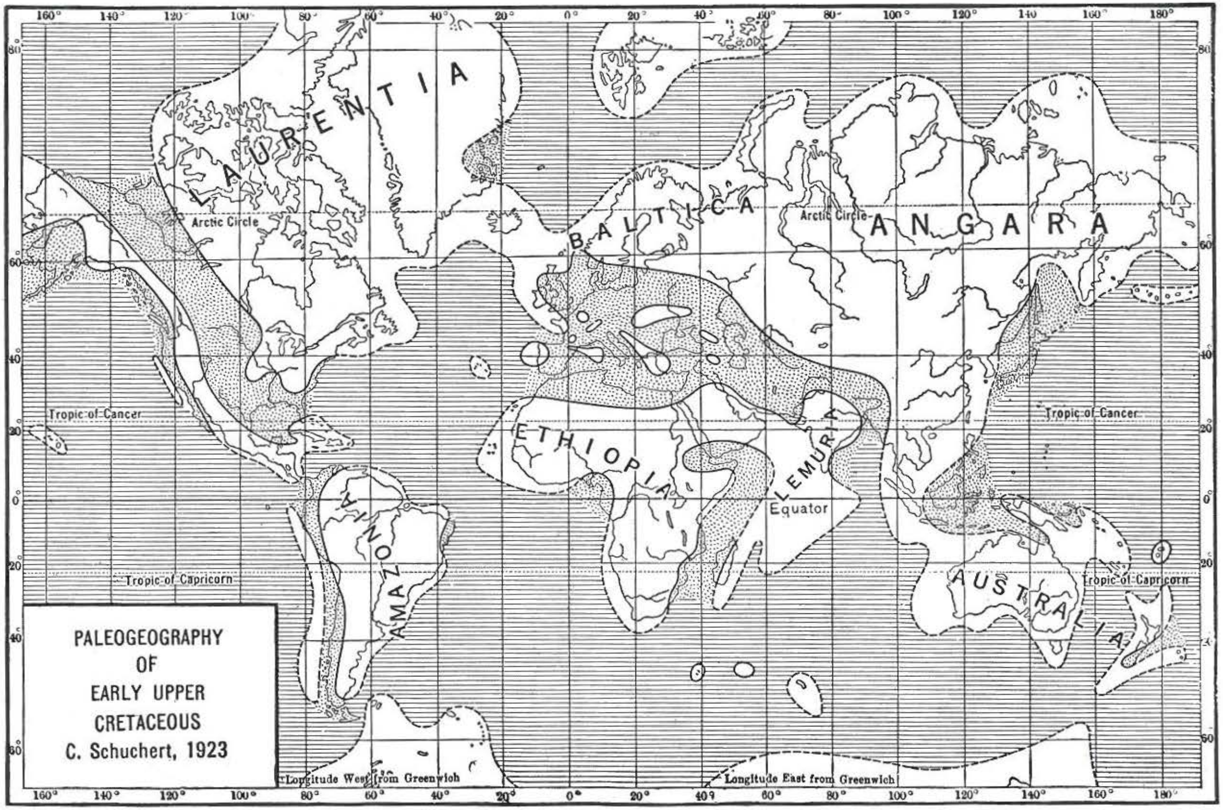

FIG. 5.—The great Upper Cretaceous transgression (dotted) of the oceans (ruled) over the lands. The time is upper Benton or Turonian. This was probably the greatest submergence that ever befell the continents. Laurentia, Baltica, and Angara make the Holarctic continent also known as Eris.

in the late Triassic. There were no cold climates when the continents were flooded by the oceans, and we may add that the periods of widespread limestone making preceded and followed, but did not accompany, the reduced climates. On the other hand, the times of greatest coal-making (Upper Carboniferous and Upper Cretaceous) accompanied great continental flooding and preceded the appearance of cooled climates (see Fig. 5). There were earth movements of considerable magnitude at the close of the Lower Cambrian, the Ordovician, and especially the late Jurassic, but none was accompanied by glacial climates. At all of these times there appears, however, to have been a drop in temperature, slight for the two first-mentioned periods and more marked for the third one, for here we find in the austral region, during earliest Cretaceous times, winters alternating with summers. We may therefore conclude that cooled and cold climates, as a rule, occur during or immediately after periods of marked mountain-making.

As is well known, the deep oceans now have very cold waters, and this reduced temperature is constantly renewed by the slow flowage of polar waters into the depths. If, then, the polar climates are replaced by warmer ones, it seems to follow that the slow drifting of abyssal waters will gradually bring about an increased temperature. Accordingly, cold abyssal waters like those of the present can lag a million years more or less behind the vanishing of continental glaciers.

The marine "life thermometer" indicates vast stretches of time of mild to warm and more or less equable temperatures, with but slight zonal differences between the equator and the poles. The great bulk of marine fossils are those of the shallow seas—areas that best simulate the climatic conditions of the lands—and the evolutionary changes recorded in these "medals of creation" are slight throughout vast lengths of time. These long periods of slightly varying climates are, however, punctuated by short but decisive intervals of cooled waters and climates, which bring on, through lack of adaptation, greater mortality, quickened evolution, and the rise of new stocks.

On the land the story of the climatic changes, as interpreted in the main from the entombed plants, is more variable and decided, but at times the equability of the temperature simulates that of the marine areas. In other words, the lands also had long-enduring life assemblages that indicate mild to warm and but slightly variable climates.

In general, we may say that the temperature fluctuations seem to have been slight throughout vast stretches of time, but geologically the climates varied between mild to warm pluvial, and mild to cool arid or even glacial. This variability of climate appears to be largely governed by the periodic changes of the earth's surface; by the changing of lowlands and seaways into depressed mountain ranges, followed by the greater broad and high uplifts of large portions of the continents like those of the present Americas; also by the spread of the oceans more or less widely over the continents; and by the making and unmaking of land-bridges between continents, like those of Panama or Tehuantepec, which may greatly change the oceanic currents and the distribution of life on the lands and in the oceans. A look back through the geological ages appears to reveal the earth's surface and its climates as in ceaseless flux, but after all, since geologic time is exceedingly long, the mean condition of any given time lasts very long indeed.

CAUSES OF OCEANIC TRANSGRESSIONS

Why do the oceans periodically transgress the continents? This question has been partially answered in several places in the previous pages—namely, it is primarily due to the movements of the earth's surface, or, technically, to diastrophism (see Fig. 3). This conclusion has long been acceptable to geologists but it is not a complete answer, since there are other and very important factors that enter into the problem. These are: (1) the amount of water on the surface of the earth has increased with time; (2) the wash of the lands brings tremendous amounts of materials to the seas and oceans, which displace about an equal quantity of water; (3) volcanic growths occur on the ocean bottoms; (4) the lands according to their variable masses attract water toward them; and (5) changes are brought about by the subtraction of water during glacial climates. We will now examine these various factors that are constantly changing the oceanic level.

(1) *Increase in the amount of water.* According to the Laplacian theory of earth origin, which holds that the planet was originally very hot and had a liquid surface, the ocean waters were primordial and originated with the primal atmosphere. Following this view, the assumption would be that the original oceans were not only as large in volume as they are now, but even larger, for all of the circulating water in the outer shell of the earth must have soaked into it from the oceans and directly or indirectly through rains falling upon the lands. The Laplacian theory and that of the primordial oceans are no longer acceptable. It is now held by most geologists that the ocean waters have been gradually added to the surface of the earth through volcanic action and hot springs. In other words, most of the oceanic water was originally occluded or dissolved in the deep earth, and through volcanic action this *juvenile water* (steam), as Suess calls it, has been liberated and added

to the already accumulated or *vadose water*. It is not yet well demonstrated how much of this steam and thermal water is vadose and has been returned to the surface of the earth, but the evidence appears to be convincing that certain volcanoes are liberating juvenile water. Furthermore, deep mines and very deep wells demonstrate that circulating vadose waters become less and less with depth.

The writer believes that all waters upon the face of the earth were originally liberated from the earth's crust, but what the percentage of liberation has been during each geologic period is of course wholly unknown. It is demonstrated, however, that at the very beginning of the geologic processes, Archeozoic time begins with water-laid and igneous rocks. Therefore oceans existed at the beginning of the known geologic record. Barrell states it as probable that from 25 to 50 per cent of the present oceanic waters were added during Archeozoic and Proterozoic times, and from 5 to 10 per cent more during the Paleozoic. This therefore seems to mean that about 50 per cent of the water now present on the surface of the earth had its origin previous to the Archeozoic, that possibly from 25 to 45 per cent was added in Pre-Cambrian times, and that from 5 to 25 per cent came after the stratified rocks began to have an abundance of fossils, that is, since the beginning of the Paleozoic. As volcanoes are most active when the earth's surface is in motion and when the lands are least flooded, we see that the juvenile waters of any time of transgression can not be the cause of oceanic spreading.

(2) *Waste of the lands transported into the seas and oceans.* Ever since the time of Humboldt, attempts have been made to ascertain the mean height above sea-level of the various continents, and the mean of all continents. Geikie in his well known *Text-book of Geology* (1:48-49(1903)) goes into the history of this problem and then presents "the latest general results of the various estimates as to the area and height of the continents," which are embodied in the subjoined table:

Continent	Area in square miles	Mean elevation	Greatest height in feet
Europe	3,700,000	330 meters = 1032 feet	18,500
Asia	16,400,000	1010 " 3313 "	29,000
Africa	11,100,000	660 " 2165 "	18,800
Australia	3,000,000	310 " 1017 "	7,200
North America	7,600,000	650 " 2132 "	18,200
South America	6,800,000	650 " 2132 "	22,400
All countries	55,000,000	735 " 2411 "	29,000

We are living in the early part of the first third of a new cycle of geologic processes, or in the early part of a recently-begun geological period. We now also know that in the last third of a period the lands begin to rise and that they continue highest in the first part of each period, and are most often reduced to their lowest elevation during the latter part of the middle third of each cycle when the floods are greatest. It is therefore evident that the mass of the land wash added to the oceans must be greatest during the first half of each period and actually during the time when each flood becomes progressively larger.

These facts were known to Suess as long ago as 1888, when he discussed this matter fully, with the following conclusion: "The oceanic regions are filled up slowly but without intermission, and their waters in consequence are gradually displaced. . . . . *The formation of sediments causes a continuous, eustatic positive movement of the strandline*" (English translation, 2: 540-543, 555). With Suess we agree that the land waste carried into the oceans is the second great factor bringing on the marine floods.

(3) *Volcanic growths on the ocean floors.* Volcanoes have grown at various times and apparently in all of the oceans from the bottoms. Most of them are small affairs when contrasted with the volume of oceanic water (placed by F. W. Clarke at about 300 million cubic miles), and yet Bermuda, one of the smallest ones, has a submarine volume of about 2,500 cubic miles. In the southern Pacific there are great numbers of such masses, and in far greater volume, beneath sea-level; and when one thinks of the Hawaiian submarine ridge on which the islands rest, with a height of 16,000 feet and a length of over 1,600 land miles, the total amount of water so displaced is indeed very large. These volcanic growths probably rise fairly quickly to above sea-level—in less time than half the length of a geologic period. When once grown they remain forever, since there is no erosive power to remove them beyond a few hundreds of feet below the surface of the oceans and the amount dissolved away is negligible. However, in some instances there is more or less of compensation in the way of subsiding bottoms on either side of the volcano. On the other hand, since the Hawaiian volcanoes appear to have risen in early Cretaceous time, their growth probably assisted in displacing as much water as the land wash derived from the various late Jurassic highlands, and both together may have been the cause for most of the Cretaceous flood, one of the greatest of geological history (see Fig. 5).

(4) *The changing sea-level.* In general practice we speak as if there were a mean sea-level. There is, however, no such condition as a per-

fect spheroidal oceanic level, that is, a water surface equidistant throughout each circle of latitude from the center of the earth. Nevertheless, recent researches indicate that the differences of level at different points of the sea-surface do not depart more than 100 or 200 feet from a true spheroid of revolution.

There can not be spread over the entire lithosphere a sheet of water of equal depth, because the earth rotates and is locally heterogeneous in density, is flattened at the poles, and has an uneven surface. Furthermore, the edges of the continents attract the waters upward to them, whereas the mass of the earth attracts the waters downward. When a great mountain range arises, like the Andes, the water level must rise through attraction all along the coast of these mountains, and elsewhere may bring on an emergence; and when these ranges are worn away, then again the general water level must rise somewhat.

(5) *Subtraction of water during glacial climate.* Penck and Daly have demonstrated that when continental glaciers are formed, like those of Pleistocene times, all of their frozen water has primarily come from the oceans, and accordingly the oceanic level must be considerably lowered in the tropical region. The amount of water subtracted depends on the extent and thickness of the glaciers, and whether they form simultaneously in both hemispheres. At one time or another during the Pleistocene, about eight million square miles of the earth's surface was covered by ice, and in many places to a thickness of some thousands of feet. So much water extracted from the oceans, plus that attracted by the continental glaciers, lowered the strand lines in the tropical and warm temperate regions not less than 200 feet and probably not more than 400 feet. This cause therefore makes the emergent times of the cycles all the more pronounced in the warmer parts of the earth. The coral islands are then all emergent.

(6). *Oceanic level during the geologic ages.* The mean oceanic level in the sense of a flooding plane over the continents has also fluctuated considerably throughout the geologic ages, and the times of these inundations since the beginning of the Paleozoic are now commencing to be deciphered. These, however, are the smaller pulsations of the oceanic level, but there appear also to be long-enduring times when the mean of the strand level is either low or high. During the Archeozoic the total of the land areas may have been far greater than at any other time, and although there were times of wide oceanic flooding during the Proterozoic, yet the continents stood in the main well above the mean of the oceanic level. Toward the close of the Proterozoic, however, all of the present continents appear to have been completely emergent, since nowhere is there found a marine record until the beginning of the Paleozoic. This interval, named Lipalian by Walcott, may have had a length of something like 100 million years. In the Paleozoic the mean of the oceanic level was high, but in the Permian it sank and did not rise again widely over the lands until Middle Jurassic time. The fluctuating floods continued to rise well into Cretaceous times, but toward the end of the Mesozoic the waters subsided. During the Cenozoic, and especially after the Miocene, the continents were mostly emergent, the climax coming in the Pleistocene or Glacial Period. Now the oceans are again tending to submerge the lands.

The cause for such long-persisting changes in the oceanic level is not yet known, but they appear to be due in least amount to unloading of the protuberant lands into the oceanic basins and the constant increase of the volume of water through the additions from volcanic action. On the other hand, the greater fluctuations have been explained as due to periodic deepening of the oceanic basins, but as the latter have also become wider through continental fracturing, this twofold volume increase should have made the continents more emergent than they have been. In other words, the oceans seemingly have long had their present mean depth, and the increase in the volume of water has been compensated for by downsinking parts fragmented from the continents. Continental fragmenting works in cooperation with isostasy to maintain the residual continents above the mean of the oceanic level. Finally, as the rising continents are said to be in isostatic relation with the sinking oceanic sectors, and as the newly risen masses are thought to be at first over-elevated and the basins over-deepened, there finally comes about a better adjusted balance in that the lands sink while the basin surfaces rise.

Conclusions. That the land moves up and down, causing the appearance and vanishing of seas, is the widely accepted theory of geologists, but that a submergence or emergence may be due to a change in the hydrosphere without any deformation in the lithosphere is held by few. Dana, as long ago as 1863, said that an emergence of the land may be due to a subsidence of the oceanic areas, and vice versa. He states: "As all parts of the earth, oceanic as well as continental, must have participated in the changes of level, the water-level was ever fluctuating like the land level. . . . . Many of the apparent elevations may have been due to a deepening of the oceanic basin . . . . and some of its apparent subsidences may have been caused by an elevation of its bottom. It is probable that at least 1,000 feet of the height of the continents . . . . has arisen from the increase in depth of the ocean" since the beginning of the Paleozoic.

Suess has given more study than anyone else to the causation of the transgressions of the sea, and in the first two volumes of *Das Antlitz der Erde* concludes that most of these can not be explained by the movements of the lands alone, and some not even by crustal deformation anywhere. He says: "The repeated inundation and emergence of the land . . . . are much too extensive and too uniform to have been caused by movements of the earth's crust." That of the middle Cretaceous especially is recorded in many continents and "marks a general physical change which affected the whole surface of the planet. . . . . But it is a striking fact that in the best known of these primary cycles the positive phase [=apparent subsidence of the land] is of much greater duration than the negative phase [=apparent elevation of the land] which follows it." Suess then asks the question: Are these positive and negative movements eustatic or world-wide? His answer is: "We are acquainted with two kinds of eustatic movement; one, produced by subsidence of the earth's crust, is spasmodic and negative; the other, caused by the growth of marine deposits, is continuous and positive." He concludes: "In all probability the Ocean is subject to an independent movement which in the course of long periods causes an alternation of positive and negative phases at the equator." Such, he says, may be caused by a quickening of the earth's revolving axis and then by a slow reduction of this speeding, due to the friction of the moon. "These great oscillations are not, however, cumulative in time; on the contrary, they are compensatory. The persistent continuance of a continental surface is in the main the result of local subsidences of the earth's crust, which time after time open up fresh abysses for occupation by the sea, and lower the general level of the strand. Every eustatic negative movement of this kind . . . . induces a heightened eustatic positive movement. . . . . The effect of eustatic subsidences and the deposition of sediments is cumulative, and in the course of geologic periods the eustatic negative movements obtain the predominance. In this matter the folding of the mountain chains plays only a secondary part" (English translation, 2:24, 537, 551-555).

We may then conclude that in general it is most often local crustal movements—in one or another of the continents or oceanic bottoms, or both in combination—that bring on the oceanic transgressions and the emergences of the lands. But the local movements of the lithosphere that change the position of the strand-line in respect to the lands are further affected by the accumulation of sediments, the birth of submarine volcanoes, and the accumulation of land ice. At other times the lithosphere appears to be practically immobile and then the new sediments and new submarine volcanoes alone bring about world-wide rising of sea-level that locally inundates more and more of the land. Finally, there may be in addition astronomic causes, changing the earth's axis, and probably others that have to do with alterations in the interior of the earth, which either reduce or enlarge its diameter and so during times of speeding cause the oceanic waters to heap up toward the equator, and then, because of the moon's friction, bring about slow flowage toward the poles.

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