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GEOLOGIC HISTORY OF CENTRAL AMERICA AND THE WEST INDIES DURING CENOZOIC TIME[1]

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(Read before the Paleontological Society January 1, 1918)

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INTRODUCTION

During the past two or three years several papers of unusual importance, in my opinion, have appeared on the geographic distribution of terrestrial organisms. These include "Climate and evolution," [2] by W. D. Matthew; "The development of the natural order Myrtacecæ," [3] "The

[1] Manuscript received by the Secretary of the Society August 22, 1918.
The article herewith presented is based upon a paper by me, entitled "The biologic character and geologic correlation of the sedimentary formations of Panama in relation to the geologic history of Central America and the West Indies," now in page proof, as the closing part of Bulletin 103 of the U. S. National Museum, which bears the general title "Contributions to the geology and paleontology of the Canal Zone, Panama, and geologically related areas in Central America and the West Indies." The two correlation tables contained in the present article have been published in the Journal of the Washington Academy of Sciences, vol. 8, no. 9, May 4, 1918, pp. 272-275.
[2] New York Acad. Sci. Ann., vol. 24, 1915, pp. 171-318.
[3] New South Wales Linn. Soc. Proc., vol. 38, 1913, pp. 529-568.

development and distribution of the natural order Luguminosæ,"[4] and "The geological history of the Australian flowering plants,"[5] by C. E. Andrews; and "Plants, seeds, and currents in the West Indies and Azores," by H. B. Guppy.[6] These three authors agree in their main thesis, namely, that vertebrates and plants have spread from northern areas radially southward over Africa, South America, southeastern Asia, Malaysia, and Australasia. They all deny direct land connection, at least since Paleozoic or early Mesozoic time, between Africa and South America and between South America and Australia, and they question there ever having been any such bridges. Furthermore, they all agree, explicitly or implicitly, in the essential permanence of the continents and of the great oceanic basins. There are other points of agreement, but these are the ones I wish particularly to emphasize in this connection. Although I may not accept every detail of the conclusions of these authors, it is my belief that their main contention is incontrovertible.

All geologic evidence known to me supports the theory of the permanence of continents and oceanic basins, but the validity of this theory does not exclude there having been great differential crustal movements in some areas. As I shall speak of certain earth blocks that, in my opinion, have changed their position with reference to sealevel, I wish to remind you that faults and folds causing great vertical and horizontal displacement of strata now above sealevel are known to all geologists, and that it is reasonable to expect in other areas of disturbance that downthrown blocks or the synclines of folds lie below, while only the upthrown blocks or the anticlines stand above ocean level.

Geographic Relations of the three Americas

The boundaries of the Gulf of Mexico and the Caribbean Sea form a parallelogram; those on the north and south extend along east and west lines, those on the east and west are northwest to southeast, while the basins are separated by east and west structures. There are two landlocked basins, except that between Florida and Trinidad relatively shallow passages between land areas connect with the Atlantic Ocean. The two basins are separated by structures transverse to the continental trend in Yucatan and Cuba, and the Gulf of Mexico is a simple while the Caribbean Sea is a compound basin.

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[4] New South Wales Roy. Soc. Proc., vol. 48, 1914, pp. 333-407.

[5] Amer. Jour. Sci., 4th ser., vol. 42, 1916, pp. 171-232.

[6] Published by Williams and Norgate, London, 1917, pp. 531, 3 maps and a frontispiece.

Twelve major tectonic provinces, with several subordinate provinces, may be discriminated, as follows:

1. Bahamas.
2. Atlantic and Gulf Coastal Plain.
3. Mexican Plateau.
4. Oaxaca-Guerrero.
5. Yucatan.
6. Guatemala-Chiapas.
7. Cuba and northern Haiti.
8. Honduras and its continuation to Jamaica, southern Haiti, Porto Rico, the Virgin Islands, and the outlying island of Saint Croix.
9. Costa Rica-Panama.
10. Andes.
11. Maritime Andes.
12. Caribbean Islands.
    12*a*. Barbadian Ridge.
    12*b*. Main Caribbean Arc.
    12*c*. Aves Ridge.

Of these provinces, (1) the Bahamas, (2) the Atlantic and Gulf Coastal Plain, and (3) the Mexican Plateau will be only mentioned, but the others will be briefly described.

4. Oaxaca-Guerrero: A structural axis extends through Michoacan, Guerrero, and Oaxaca, almost at right angles to the trend of the Mexican Plateau. The northern boundary of this province is the escarpment at the southern margin of the Mexican Plateau; the western and southern boundary is the Pacific Ocean, while the eastern boundary is the Isthmus of Tehuantepec. It is thus set off from the Mexican Plateau and the Yucatan lowland.

5. Yucatan: This province consists of lowlands under 600 meters in height, underlain by only slightly deformed Tertiary strata, except some problematic rocks west of Belize. The Yucatan Peninsula and Campeche Bank are comparable to the Floridian Plateau. They are developed along a structural axis almost at right angles to the continental trend. Campeche Bank projects northward from the shoreline of the peninsula 170 nautical miles to the 100-fathom curve, and has a width of nearly 360 nautical miles along an east and west line. On the east the depth of water between it and Cuba exceeds 1,000 fathoms and the axial trends are not coincident, but the axis of Yucatan Bank and that of the Province of Pinar del Rio, Cuba, curve so that they are nearly parallel, with a trough, Yucatan Channel, between them.

6. Guatemala-Chiapas: This province lies between the Yucatan lowland on the north and Rio Motagua on the south. It is an upland domi-

nated by east and west tectonic lines, and has been called the Guatemala-Chiapas Plateau by Tower.[7]

7. Cuba: This province is coincident with Cuba and its submarine continuation, the Cayman Ridge. At least four subdivisions should be recognized: (1) The Isle of Pines, which is composed of mountains of schists and marbles with piedmont plains and marsh, separated from the main island by water less than ten fathoms deep. (2) Organos Mountains of Pinar del Rio and the accompanying piedmont plains. The 1,000-fathom curve is less than 20 miles off the north shore. (3) Central Cuba, from the east end of Organos Mountain to Cauto River, is mostly a plain broken by some hills of serpentine and granite, and in Santa Clara Province, near Trinidad, mountains reported to be composed of Paleozoic sediments attain an altitude of about 2,000 feet. (4) Sierra Maestra and Cayman Ridge. This subprovince lies between the Cauto Valley and the south shore and is continued westward as the submarine Cayman Ridge, along the axis of which only the Cayman Islands project above water level. The axial trend is nearly east and west between Cabo Cruz, Cuba, and Little Cayman, whence it curves to the southwest and pitches toward the head of the Gulf of Honduras, which is an area of depression. Between the Caymans and the Isle of Pines the depth of water exceeds 1,000 fathoms, while the Bartlett Deep to the south, separating Cuba and Jamaica, exceeds 3,000 fathoms in depth.

7a. Haiti, northern part: The Island of Haiti lies at the convergence of the trend of the axis of the central subprovince of Cuba and the Honduras-Jamaican axis. The dividing line in Haiti is from Port au Prince to Ocoa Bay. The area south of this line belongs to a Jamaican axis, while that to the north belongs to the central Cuban trend. The structural axes of the mountains in the northern and northeastern part of Haiti are from northwest to southeast and are parallel to the axis of elongation of Cuba from the Sierra Maestra to Santa Clara. In Cuba this trend is cut diagonally by the axis of the Sierra Maestra, which is bounded on the south by a tremendous fault-scarp. Previous to this faulting it seems that central Cuba and Haiti formed parts of the same land area. The Island of Haiti might be treated as separate from Cuba and Jamaica, but lying at the intersection of two tectonic trends.

8. Honduras and the Jamaican Ridge: The Honduran Province in Central America is dominated by tectonic lines extending from southwest to northeast, of which Têlusa Mountains are representative. A line from the Gulf of Honduras along Motagua River to a point north of Jalapa,

[7] W. L. Tower: Investigation of evolution in chrysomelid beetles of the genus *Leptinotarsa:* Carnegie Inst. Washington, Pub. No. 48, 1906, p. 50.

thence southwest to the Pacific coast, may be taken as the northern boundary and Rio San Juan and the southern side of Lake Nicaragua as the southern boundary.

From the northeast coast of Honduras and Nicaragua a great submarine plateau continues, with depths of less than 1,000 fathoms, to Jamaica. Above it rises numerous banks and keys and along its course are Thunder Knoll, Rosalind, Seranilla, and Pedro banks between the continental shore and Jamaica.

The principal old tectonic lines of Jamaica trend northwest to southeast. As these are parallel to the shore northwest of Cape Gracias a Dios and to the northeast edge of Mosquito Bank, there are evidently cross-tectonic lines nearly at right angles, to each other in this ridge.

A submarine ridge extends some 45 miles from the east end of Jamaica and overlaps on the south side a ridge which protrudes westward from the west end of Haiti. The two ridges, however, do not connect, but are separated by water over 1,000 fathoms deep. The ridge representing an eastward submarine continuation of Jamaica indicates a third tectonic line in that island. The last mentioned line nearly parallels the Bartlett Deep, which lies to the north. The submarine slopes to the southeast are toward the bottom of the Caribbean basin.

8a. Haiti (southern part), Porto Rico, and the Virgin Islands: The political division of Haiti designated Sud is dominated by east and west trending mountains, which parallel in direction the east and west axis of Jamaica. As the maximum depth between Haiti and Porto Rico is about 318 fathoms, they rise from a common, not greatly submerged, bank. (See statement on preceding page in regard to considering Haiti as a separate province.)

The main mountain mass of Porto Rico, the Sierra Central, the maximum altitude of which is 3,750 feet at El Yunque, trends east and west, paralleling in direction Sud, Haiti. There is coincidence in the direction of elongation of the Jamaican bank, Sud (Haiti), and Porto Rico.

The relative truncation of the west end of Porto Rico, except the protuberant which forms Cabo de San Francisco, is striking and suggests faulting. The declivities both to the north and south of the island are great, over 4,000 fathoms in depth being reached within 40 miles of the north coast, while 2,000 fathoms are attained within a shorter distance from the south coast.

A submarine bank extending from the east end of Porto Rico to Anegada Passage is known as Virgin Bank. The depth of water between the islands rising above this bank is less than 20 fathoms, which is a maximum for the amount of submergence they have recently (geologically speaking) undergone. These islands are detached outliers of Porto Rico.

8*b*. Saint Croix: Although Saint Croix is separated from the Virgin Islands by a depth as great as 2,400 fathoms and is joined to the Saint Christopher chain by a ridge less than 1,000 fathoms deep, it possesses great similarity to members of the Virgin group. The west end is truncate and the submarine slope precipitous; the submarine slope to the north is also steep. There is clear evidence of faulting on the west and north sides. A ridge, largely of igneous rock, stands against the north shore from the west end of the island for some distance to the east. South of the ridge is a sloping, rolling, calcareous plain. The east end has a submarine continuation in a bank less than 50 fathoms deep. The tectonic axis is east and west, the rocks resemble those of the Virgins, and the zeogeography indicates former connection with them. For these reasons it seems probable that this island was formerly a part of the Porto Rican-Virgin Island land-mass and has been sundered from it by diastrophic processes. However, Saint Croix might be accorded separate status as a province, or referred to the Saint Christopher axis; but it appears to me preferable to classify it with the Virgin Islands.

9. Costa Rica-Panama: Between the Nicaragua-Costa Rican boundary and the mouth of Rio Atrato is an S-shaped land area which does not exhibit striking tectonic lines, although some deformation axes are obvious in Panama. The region is largely one of vulcanism, present or past, which, although occurring within limits, does not follow continuous straight axes, but occurs in a curving belt. The topography appears disordered, with volcanic protuberants here and there without perceptible system. The volcanic heaps range from a few hundred to nearly 10,000 feet in altitude.

10. Andes: The south-north trending ranges of the Andes reach the shores of the Caribbean Sea between the gulf of Darien and Venezuela, and send a spur, Cordillera de Merida, northeastward to Porto Cabello, where the main Andean trend is crossed by that of the Maritime Andes. The shore of the Caribbean Sea lies across the northern end of the Andes in a way similar to the manner in which the landward border of the Coastal Plain crosses the southwestern end of the Appalachian Mountains.

The islands of Curaçao, Arube, and Bonaire lie off the Venezuelan coast in the angle between the ends of the main Andes and the Cordillera de Merida.

11. Maritime Andes: The Maritime Andes lie along the Venezuela coast from Caracas eastward. Trinidad and Tobago are outlying islands. On the south side of these mountains is the great valley of the Orinoco.

12. Caribbean Islands: These islands lie along triple arcuate ridges, the Barbadian Ridge, the main Caribbean Arc, and Aves Ridge, the second of which is double at its northern end.

A PROVISIONAL CORRELATION TABLE OF THE TERTIARY FORMATIONS OF THE SOUTH ATLANTIC AND EASTERN GULF COASTAL PLAINS OF THE UNITED STATES

Age of deposits		North Carolina (South of Hatteras axis)	South Carolina (Santee drainage)	South Carolina and Georgia (Savannah drainage)	Georgia (Chattahoochee drainage)	Florida	Alabama	Mississippi	Louisiana
Pliocene		Waccamaw marl	Waccamaw marl	(Not recognized)		Caloosahatchee marl, Nashua marl, Alachua clay, and Bone Valley gravel (largely contemporaneous) / Citronelle formation	Citronelle formation	Citronelle formation	Citronelle formation
Miocene	upper	Duplin marl Unconformity	Duplin marl —Unconformity— Edisto marl	Duplin marl —Unconformity— Marks Head marl		Jacksonville formation / Choctawhatchee marl	Pascagoula clay	Pascagoula clay	Pascagoula clay
	middle			—Unconformity—		—Unconformity—			
	lower			Alum Bluff formation	Alum Bluff formation	Alum Bluff formation: Shoal River marl member; Oak Grove sand member; Chipola marl member	Alum Bluff formation / Hattiesburg clay	Hattiesburg clay	Hattiesburg clay
Oligocene	upper, middle			Chattahoochee formation	Chattahoochee formation —Unconformity—	Tampa formation / Chattahoochee formation	Chattahoochee formation / Catahoula sandstone	Catahoula sandstone	Catahoula sandstone
	lower			Vicksburg formation	Vicksburg formation	Vicksburg group: Marianna limestone (western Florida)	Vicksburg group: Marianna limestone (with Glendon limestone member); Red Bluff clay	Vicksburg group: Byram calc. marl; Marianna limestone (with Glendon limestone and Mint Spring calcareous marl members); Red Bluff clay	Vicksburg limestone
Eocene	upper	Cast e Hayne limestone Trent marl	Cooper marl / Barnwell formation	Barnwell formation (with Twiggs clay member)	Ocala limestone	Ocala limestone	Ocala limestone / Jackson formation	Jackson formation (with Yazoo clay member and Moodys calc. marl member)	Jackson formation
	middle		McBean formation	McBean formation	McBean formation	(Buried)	Claiborne group: Gosport sand; Lisbon formation; Tallahatta buhrstone	Claiborne group: Yegua formation; Lisbon formation; Tallahatta buhrstone	Claiborne group: Yegua formation; St. Maurice formation
	lower		Congaree shales of Sloan Williamsburg formation	(Probably overlapped)	Wilcox formation	(Buried)	Wilcox group: Hatchetigbee formation; Bashi formation; Tuscahoma formation; Nanafalia formation	Wilcox group: Grenada formation; Holly Springs sand; Ackerman formation	Wilcox formation
			Black Mingo formation	(Probably overlapped)	Midway formation	(Buried)	Midway group: Naheola formation; Sucarnochee clay; Clayton limestone	Midway group: Tippah sandstone of Lowe; Porters Creek clay; Clayton limestone absent or replaced by sand	Midway formation

12*a*. Barbadian Ridge: As Barbados is connected undersea with Tobago Island by a ridge less than 1,000 fathoms deep, and as the depth between it and Saint Lucia is less than 1,000 fathoms, there is a closed basin over 1,000 fathoms deep between the Barbadian Ridge and the main Caribbean Arc.

12*b*. Caribbean Arc: The Caribbean Arc is a ridge that extends from north of the Gulf of Paria to Anegada Passage. The islands occurring along it from the Grenadines to Dominica are entirely or predominantly volcanic. Guadeloupe is a compound island; the western half is volcanic; the eastern half, with the outlying Marie Galante, is mostly composed of calcareous sediments. North of Martinique the arc splits; along the inner fork are the volcanic islands Montserrat, the members of the Saint Christopher Chain, and Saba; along the outer fork are Antigua and Barbuda, and the Saint Martin group. The latter islands are largely or predominantly composed of sedimentary rocks resting on an igneous basement of pre-Tertiary or early Tertiary age.

12*c*. Aves Ridge: This ridge takes its name from Aves Island, which stands on a ridge running from the north coast of Cumana to Saba Island at depths slightly less than 1,000 fathoms, while water of greater depth occurs both east and west of it.

Correlation of the Tertiary Formations of the south Atlantic and eastern Gulf Coastal Plain

The accompanying table indicates the present status of the correlation of these formations, and, although it may have to be modified to accord with the results of additional investigations, there is every reason to believe that subsequent changes will be only in matters of minor refinement. However, I wish to say that I believe four paleontologic zones will be discriminated and defined in the Chattahoochee formation, and that the collections on which to base these subdivisions have already been made and in large part described, but I will not take the time to discuss these details. I also confidently expect the Ocala limestone to be subdivided into two or more zones, for the genus *Orthophragmina,* so abundantly represented in the lower part of the formation, appears to be absent in the upper beds.

Correlation of the Tertiary sedimentary Formations of Panama and the West Indies

A summary of these correlations is given on the accompanying table. Only one point appears to need special comment—that is, whether the limestone containing *Orthophragmina* on Haut Chagres and at David, Panama, should be referred to the uppermost Eocene or to the basal Oligocene. The Ocala limestone contains large stellate species of *Orthophragmina,* and I collected a similar species in Saint Bartholomew. Of the Eocene age of these deposits, of the typical Brito formation in Nicaragua, and of certain limestones containing *Orthophragmina* in Cuba there seems to be no reasonable doubt; but, according to Douvillé, the small stellate *Orthophragmina* (subgenus *Asterodiscus*) ranges upward into the lower Oligocene. The association of *Asterodiscus* and small, even non-stellate, species of *Orthophragmina* with species of *Lepidocyclina* that at some localities are found in association with a coral fauna of middle Oligocene affinities has inclined me to the opinion that certain peculiar species of *Orthophragmina* occur in deposits of lower Oligocene age. Doctor Cushman, however, is disposed to regard the beds in which these species of *Orthophragmina* were found as of Eocene age. At present the evidence is not decisive and additional studies are needed.

Paleogeographic Summary

IN GENERAL

As Doctor Stanton has summarized in the preceding paper of this series the Mesozoic history of Central America, Mexico, and the West Indies, and as his conclusions are incorporated in the tabular statement on page — of this paper, I need not repeat anything he has said, but regarding the Paleozoic history I will state a few of the important events.

LATE PALEOZOIC

The great Appalachian revolution occurred in late Paleozoic, Permian time, and resulted in the northern boundary of the Gulf of Mexico—the southern Appalachian, the Ouachita, and Wichita Mountains.

The east and west trend in southern Mexico and in southwestern Chiapas already existed or was developed about this time, while farther to the southeast, as Sapper has shown, Rio Motagua, in Guatemala, divides two chains of this age—one to the north, the other to the south—with spurs of a third chain farther toward the southeast. The nearly north and south trend of the Coxcomb Mountains, in British Honduras, which are composed of sediments apparently of pre-Paleozoic age, indicates that the Yucatan protuberant had been outlined in Paleozoic, perhaps early Paleozoic, time. Granitic debris in Costa Rica and Panama suggests old deformation along east and west lines in those areas. The east and west mountains of Venezuela have an old foundation and certainly date back to the Paleozoic in origin. There is evidence of old

TENTATIVE CORRELATION TABLE FOR THE TERTIARY MARINE SEDIMENTARY FORMATIONS OF PANAMA

American time subdivisions		Panama	Jamaica	Other Antilles	Mexico and Central America	Southeastern United States	European time subdivisions
Pliocene		Toro limestone	Manchioneal formation Kingston formation	Pliocene of Guantanamo, Cuba	Pliocene of Yucatan and Limon, Costa Rica	Waccamaw marl, Nashua marl, and Caloosahatchee marl (nearly contemporaneous)	Sicilian Astian Plaisancian
Miocene	upper					Yorktown formation, Duplin marl, and Choctawhatchee marl (nearly contemporaneous)	Pontian Sarmatian
						St. Marys formation Choptank formation	Tortonian
						Calvert formation; Marks Head marl	
	middle	Gatun formation (spanning middle and lower)		La Cruz marl (Cuba); Upper horizon in Martinique; Upper horizon in Santo Domingo	Gatun formation (Costa Rica); Pacific Coast of Nicaragua; Exposures on Isthmus of Tehuantepec (spanning middle and lower)		Helvetian
	lower		Bowden marl	Marl at Baracoa, Cuba; Lower horizon in Martinique; Zones G, H, and I in Santo Domingo		Alum Bluff formation: Shoal River marl member; Oak Grove sand member; Chipola marl member	Burdigalian
Oligocene	upper	Emperador limestone; Culebra formation: Upper part of Culebra		Anguilla formation (Anguilla) and beds at many localities in Cuba	San Rafael formation (spanning upper and middle)	Chattahoochee formation (spanning upper and middle); Tampa formation	Aquitanian Chattian
	middle	Culebra formation: Lower part of Culebra and limestone at Tonosi		Coral reef at Guantanamo, Cuba; Antigua formation (Antigua); Pepino formation (Porto Rico); Lower horizon in Santo Domingo			Rupelian
	lower	Limestone, with *Orthophragmina*, on Haut Chagres[a] and limestone at David (contemporaneous); Bohio congl.[b]	Montpelier white limestone		Manzanilla, Costa Rica, and deposits with Pecten aff. *P. poulsoni* and large discoid orbitoids, Mexico	Vicksburg group: Byram calcareous marl; Marianna limestone; Red Bluff clay	Lattorfian (Sannoisian)
Eocene	upper		Cambridge formation Richmond formation	St. Bartholomew limestone (St. Bartholomew). Widely distributed in Cuba	Brito formation of Nicaragua (typical Brito); Frio clay Fayette ss.	Jackson formation; Ocala limestone	Ludian (Priabonian) Bartonian
	middle	Eocene of Tonosi			Claiborne group (Near the Texas border)	Claiborne group: Gosport sand; Lisbon formation; Tallahatta buhrstone	Auversian[c] Lutetian
	lower				Wilcox formation (Near the Texas border)	Wilcox group: Hatchetigbee formation; Bashi formation; Tuscahoma formation; Nanafalia formation	Ypresian[c] Sparnacian[c]
					Midway formation (Near the Texas border)	Midway group: Naheola formation; Sucarnochee clay; Clayton limestone	Thanetian[c] Montian[c]

a Reported by H. Douvillé and referred to "Stampien inférieur" = Vicksburgian = Lattorfian. Cushman thinks these deposits should be referred to the upper Eocene and placed opposite the Saint Bartholomew limestone in the table.

b May belong stratigraphically somewhat higher.

c Correlations proposed by E. W. Berry.

deformation in Cuba, rendering it highly probable, if not certain, that the major tectonic trends of Cuba are as old as the Paleozoic. Although no Paleozoic rocks have been identified in Jamaica, the inference appears warranted that Jamaica itself dates back to late Paleozoic, as it has been shown by Sapper that the west end of the tectonic features represented in Mosquito and Rosalind banks and Jamaica already existed in late Paleozoic time. The Cuban and Jamaican trends meet in Haiti and continue through Porto Rico to the Virgin Islands, while Saint Croix, which is closely related in its geologic features to the Virgins, was probably at one time a member of that group and has been separated from them by faulting of comparatively late geologic date. There is no direct evidence of the existence at this time of any of the Caribbean Islands, but certain relations suggest that at least parts of the Caribbean Arc may be old. Saint Croix stands on the western end of a ridge between 600 and 700 fathoms deep, on the eastern end of which is Saint Christopher. This ridge extends northward to the Saint Martin Plateau, eastward to Antigua and Barbuda, and southward from the latter islands through Guadeloupe, Saint Lucia, and the Grenadines to South America. These relations suggest that the eastern perimeter of the Caribbean basin may have been outlined in late Paleozoic time.

From the preceding statement it is evident that the principal tectonic lines of the perimeters of the Gulf of Mexico and Caribbean Sea existed at the close of the Paleozoic. The northern, western, and southern boundaries had been outlined and the major transverse trends had also been formed—the more northern through Oaxaca and Chiapas, including the northward trending Coxcomb Mountains of British Honduras; the more southern through Honduras and Nicaragua. The first may have connected along the axis of the Coxcomb Mountains with Cuba and thence with Haiti; the second probably connected with Jamaica, Haiti, Porto Rico, and the Virgin Islands, and there are vague suggestions that the Caribbean Arc also existed. As the positive and negative areas so early outlined dominated the tectonic development during later geologic time, the subsequent history consists in tracing the modification of these old features.

CENOZOIC

The Cenozoic history may be summarized as follows:

Eocene and Oligocene.—The West Indian Islands, because no old Eocene sediments are known in any of them except Trinidad, which is South American in its affinities, are supposed to have stood above sealevel at that time. In Cuba and Jamaica there are Upper Cretaceous and upper Eocene sediments without the intervention of lower Eocene deposits.

During later Eocene (Ludian) and middle and upper Oligocene (Rupelian and Aquitanian) time there was extensive submergence in the West Indies and interoceanic connection through a number of straits across Central America. There may have been interoceanic connection during lower Oligocene (Lattorfian) time, but this is not established. The maximum submergence was in middle Oligocene (Rupelian) time. Vulcanism was widespread in Central America and the Antilles during Eocene and probably also during earlier Oligocene time. The line of the great Mexican volcanoes had its inception at the close of the Cretaceous, near the beginning of the Tertiary, according to Felix and Lenk.

In Jamaica, Cuba, Saint Bartholomew, and Antigua, the later Eocene age of some of the volcanic rocks is established. There was between the upper Eocene and the middle Oligocene deposition periods great deformation in the Antilles. The folding in the principal mountains of Jamaica, the Sierra Maestra of Cuba, and apparently those of Haiti, Porto Rico, the Virgin Islands, and Saint Croix, appears to have taken place at this time. Diastrophism seems also to have been active in Chiapas, Tabasco, Petén, Guatemala, Nicaragua, Costa Rica, and Panama.

Miocene.—During older Miocene (Burdigalian) time apparently there was in places connection between the Atlantic and Pacific oceans, as is shown by deposits of this age containing fossils of Atlantic affinities on the Pacific coast of Nicaragua and at other localities in Central America, but such connections seemingly were restricted, not of wide extent, as in upper Eocene and Oligocene time.

As no upper Miocene has yet been identified in the West Indies, this is supposed to have been a period of high uplift which terminated the connection between the Atlantic and Pacific oceans. The middle and upper Oligocene and lower Miocene sediments of Mexico, Panama, Cuba, Haiti, Jamaica, Porto Rico, Anguilla, and Antigua, although deformed by tilting and faulting, are not intensely folded, as are the older sediments. According to Hill, "In mid-Tertiary time granitoid intrusions were pushed upward into the sediments of the Great Antilles, the Caribbean, Costa Rican, and Panamic regions." The information I obtained in Antigua and Saint Bartholomew accords with this opinion.

That there was at some place interoceanic connection subsequent to lower Miocene (Burdigalian) time is suggested, if not actually proven, by the presence on Carrizo Creek, Imperial County, California, of a coral fauna of post-Miocene affinities.[8]

[8] T. W. Vaughan: The reef-coral fauna of Carrizo Creek, Imperial County, California, etc., U. S. Geol. Survey Prof. Paper 98, 1917, pp. 355-386, pls. 92-102.

Roy S. Dickerson,[9] in the paper cited below, says regarding my conclusion that the coral fauna of Carrizo Creek is of probably Pliocene age: "His [Vaughan's] conclusions concerning the Pliocene age of these beds rests upon the infirm basis of comparison with a Pliocene coral fauna of Florida," and "All the coral genera except one occur in the Bowden or associated horizons." The last statement is correct, and the first is correct in that I compared the fauna from Carrizo Creek with that from the Pliocene Caloosahatchee marl of Florida; but Doctor Dickerson evidently did not comprehend the entire basis for my opinion. The following genera, now extinct in the Atlantic Ocean, but living in the Indo-Pacific, occur in the Bowden marl and related zones, but are not known from Carrizo Creek or from the Caloosahatchee marl:

Placocyathus	Antillia
Placotrochus	Syzygophyllia
Stylophora	Pavona[10]
Pocillopora	Goniopora

Neither the coral fauna of Carrizo Creek nor that of the Caloosahatchee marl, as at present known, contains any of the coral genera distinctive of the Bowden and related zones. These distinctive genera became extinct in the Atlantic during upper Miocene time, according to present information. It therefore seems to me more probable that the fauna of Carrizo Creek migrated to the head of the Gulf of California after these forms had become extinct than that they were eliminated after migration at an earlier period.

Pliocene and later.—Subsequent to the Miocene there have been many oscillations of the West Indian area, and during perhaps Pliocene time there was profound deformation. Zeogeographic data, in the opinion of several investigators, seem to demand former connection, probably during late Miocene or Pliocene time, from Yucatan across Cuba to Haiti, Porto Rico, and the Virgin Islands; from Honduras to Jamaica; and from Anguilla to South America. It also appears that Saint Croix was once joined to Anguilla and to the eastern end of the Virgin Islands. There are certain geologically late fault-lines which perhaps date from this time, and the severance of the old ridges into the islands we now know may be largely due to movement along them. One of these fault-lines forms the northern boundary of the Bartlett Deep and passes between the east end of Cuba and the west end of Haiti. Another tectonic line which forms the south side of the Bartlett Deep converges toward the former in the Wind-

[9] Ancient Panama canals. California Acad. Sci. Proc., vol. 7, 1917, pp. 197-205 (date printed with title, July 30, 1917; received by me on October 16, 1917).

[10] Added from Miss Maury's Santo Domingan collections.

ward Passage. A downthrown block between these lines has separated Cuba and Haiti and produced the Bartlett Deep. Probably there was also faulting or flexing between Cayman Ridge and the southern shore of Cuba west of Manzanillo Bay, while either faulting or flexing may have separated Cuba and Yucatan. There is evidence of a downthrown fault block between Saint Thomas and Saint Croix, the two sides converging toward Anegada Passage. This will account for the deep of over 2,400 fathoms north of Saint Croix, and the severance of Saint Croix and the Saint Martin Plateau group of islands from the Virgin group.

There are three kinds of evidence that bears on the age of these faults, namely: (1) In eastern Cuba, as the Miocene La Cruz marl is abruptly cut off at the shoreline in the vicinity of the Morro, at the mouth of Santiago Harbor, the faulting must be subsequent to old or middle Miocene; (2) as the sea along fault shores has been able subsequent to the faulting to cut only narrow benches into the fault-planes on the upthrown side, the fault-planes are physiographically young; (3) the biologic evidence, in the opinion of most of those who have recently considered it, demands land connection in late Tertiary time between Cuba, Santo Domingo, Porto Rico, and thence to South America. Miller has recently published an important paper on this subject,[11] and states:

"With the characters of so many [eight] genera known it becomes possible to gain some idea of the Antillean hystricine fauna.[12] The most noticeable feature of these genera, considered as a group, is their similarity to the Santa Cruzian and Entrerian rodents which Ameghino and Scott have described and figured. In no instance has the same genus been found in both the West Indies and Argentina or Patagonia; but the Antillean rodents thus far discovered never show such peculiarities that their remains would appear out of place among those of their extinct southern relatives, while as a whole they would at once be recognized as foreign to the present South American fauna."

On the following page of the same paper he says:

"So far as can be judged from eight[13] very distinct genera, the Antillean hystricine rodents do not present the characters that would be expected in animals derived from South America during any period geologically recent. Neither have they the appearance of an assemblage brought together at different times by migration or chance introduction. On the contrary, they suggest direct descent from such a part of a general South American fauna, probably not less ancient than that of the Miocene, as might have been isolated by a splitting off of the archipelago from the mainland. Of later influence from the continent there is no trace."

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[11] Gerrit S. Miller, Jr.: Bones of mammals from Indian sites in Cuba and Santo Domingo. Smithsonian Misc. Coll., vol. 66, no. 12, 1916, 10 pp., 1 pl.

[12] Op. cit., p. 3.

[13] "Two more were described by Anthony in January, 1917. They bear out my statement about the eight and make it stronger.—G. S. M., Jr."

The mammals furnish more evidence of this kind than I am presenting here, and Barbour and Stejneger, from their study of reptiles, have reached similar conclusions, which accord with the tectonic history of the region, namely, that in late Tertiary, probably Pliocene, time the West Indian Islands as we know them were produced by block-faulting which broke into pieces a far more extensive land area. Dr. W. D. Matthew does not agree with the postulated connections from Cuba to Yucatan, from Jamaica to Honduras, and from Anguilla to South America.[14] The method of distribution of the terrestrial organisms must be left for the consideration of those best versed in such subjects, and I am only warranted in saying that at present there is no known geologic evidence against a late Miocene or early Pliocene connection from Anguilla to South America or from western Cuba and Jamaica to Central America.

Following this geologically late episode of cataclysmic faulting, it appears that in some areas there was minor submergence of the margins of some of the West Indian Islands and parts of Central America—for instance, Panama and Costa Rica.

According to Hill, the volcanoes of the Windward Islands date back at least to the Eocene. He says:

> "After the Miocene, vulcanism became quiescent in the Great Antilles and the Coastal Plain of Texas, but has continued to the present in the four great foci of present activity—southern Mexico, the northern Andes, Central America, and the Windward Islands. In the last two regions mentioned, the greater masses of the present volcanic heights were piled up before the Pliocene, and the present craters are merely secondary and expiring phenomena."

The last important shift in position of strand-line along the Atlantic coast of the United States and around the shore of the Gulf of Mexico and the Caribbean Sea has been by submergence of land areas, but subsequent to this there has been local emergence, often accompanied by minor tilting or warping.

Except vulcanism, the following table presents a succinct summary of the major events considered in the foregoing remarks. My primary intention has been to characterize biologically and to correlate the marine formations of the Canal Zone and the geologically related areas in Central America and the West Indies, and to lay particular stress on the succes-

[14] Miller says in a letter to me: "Matthew's argument seems to me to have two very weak spots in it: He minimizes the variety of structure shown by the W. I. rodents, and he banks altogether too heavily on what we don't know—that is, on the apparent absence of ungulates and other things that ought to be present in a continental fauna. When it is remembered that all but three of these ten genera of rodents and the insectivore *Nesophontes* were unknown five years ago, we ought to be very shy of predicting what the next digging will not turn up. But it seems to me that what you have quoted of mine contains about all the comment I need to make in print.—G. S. M., Jr."

sive periods of emergence and submergence of the land and the crustal deformation, folding and faulting, concomitant with changes of that kind. Comparison of the table showing the correlation of the Tertiary formations of Panama with the tabular summary will reveal that the story told by the two tables is essentially identical, the erosion intervals and the marine formations in the correlation table representing respectively the periods of emergence and the periods of submergence in the tabular summary.

TABULAR SUMMARY OF SOME OF THE IMPORTANT EVENTS IN THE GEOLOGIC HISTORY OF THE WEST INDIES AND CENTRAL AMERICA

Epoch		Events
Recent		Submergence of land areas, probably resulting from deglaciation, except local differential crustal movements, in places producing uplift.
Pleistocene		Emergence of large areas, probably due to withdrawal of water to form the continental ice-sheets; also oscillation of land areas by differential crustal movement.
Pliocene		Local moderate submergence, period of cataclysmic faulting breaking up a large land area and forming the Antilles nearly as they are at present. Probably a narrow interoceanic connection that admitted an Atlantic fauna into the present site of the Gulf of California.
Miocene	Upper	Extensive emergence of the land joining North and South America through Central America; Greater Antilles joined to each other, and possibly to Central America, by bridges from Jamaica to Honduras and from western Cuba to Yucatan, and to South America along the Caribbean arc. All these supposed connections not necessarily contemporaneous.
	Middle	Extensive marginal submergence in some of the West Indies and on the Atlantic side of Central America. No known interoceanic connections.
	Lower	Extensive submergence in the West Indies and around the continental margins; narrow, areally limited interoceanic connections; land emerging in Central America.
Oligocene	Upper	Extensive submergence with interoceanic connections.
	Middle	Maximum areal submergence with extensive interoceanic connections.
	Lower	Extensive submergence in Central America and the southeastern United States; local emergence in the West Indies. Extensive diastrophism and mountain-making by folding.

Epoch		Events
Eocene	Upper	Extensive submergence with interoceanic connections.
	Middle	Apparently interoceanic connection across Central America.
	Lower	Emergence of the Greater Antilles and Central America. No known interoceanic connection.
Cretaceous[3]	Upper	Extensive submergence, but without interoceanic connection.
	Lower	Submergence in southern Mexico and Central America, especially in late Comanche time. Probable emergence in the Greater Antilles. No interoceanic connection.
Jurassic	Upper	Submergence in western Cuba, eastern Mexico, and west Texas, without interoceanic connection, except possibly in late Upper Jurassic time.
	Middle	Submergence in southern Mexico (Oaxaca and Guerrero), with possible interoceanic connection.
	Lower	Submergence in southeastern Mexico (Puebla, Vera Cruz, and Hidalgo, possibly also in Guerrero), with possible interoceanic connection. Non-marine plant-bearing beds in same region and also in Oaxaca. Possibly the latter may be of same age as the supposed Rhætic plant-bearing beds of Honduras and Nicaragua.
Triassic	Upper (Rhætic)	Plant-bearing beds in Honduras and Nicaragua, above mentioned, bespeak land conditions in latest Triassic or earliest Jurassic.
	Upper (Karnic)	Submergence in central Mexico (Zacatecas), with probable interoceanic connection.
	Middle	Probable land conditions throughout Mexico and Central America.
	Lower	Probable land conditions throughout Mexico and Central America.
Late Paleozoic		Formation of the major tectonic axes of Central America and the initial east and west axes of the Greater Antilles.

[3] Mesozoic history of Central America, Mexico, and the West Indies, by T. W. Stanton.