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THE GREAT FAULT TROUGHS OF THE ANTILLES[1]

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INTRODUCTION

The region of the Greater Antilles is characterized by a marked elongation of the principal geographic features in an east-west direction and by extremely high relief (Plate I). The highest point above sea-level, Mount Tina on the island of Haiti, has an elevation of over 3,100 m. while the deepest sounding in the Atlantic Ocean (8,526 m.) was obtained only 320 km. to the northeast.[2] The Antillean mountain ranges are among the most precipitous in the world, but their slopes are, in large part, submerged beneath the surface of the Atlantic Ocean and Caribbean Sea. Off the north coast of St. Croix the descent is 4,348 m. in a distance of 8 km., and for shorter distances the slopes are very much steeper.

The physiography of the Greater Antilles is very complex and as yet little of the region has been studied in detail. The dominant tectonic trend is approximately east and west along arcs convex toward the north, in part following the margins of the great trough-like depressions which are such a striking characteristic of the

[1] Presented in part at the Chicago meeting of the Geological Society of America, December, 1920.

[2] All elevations and soundings have been taken from the maps of the Hydrographic Office of the United States Navy.

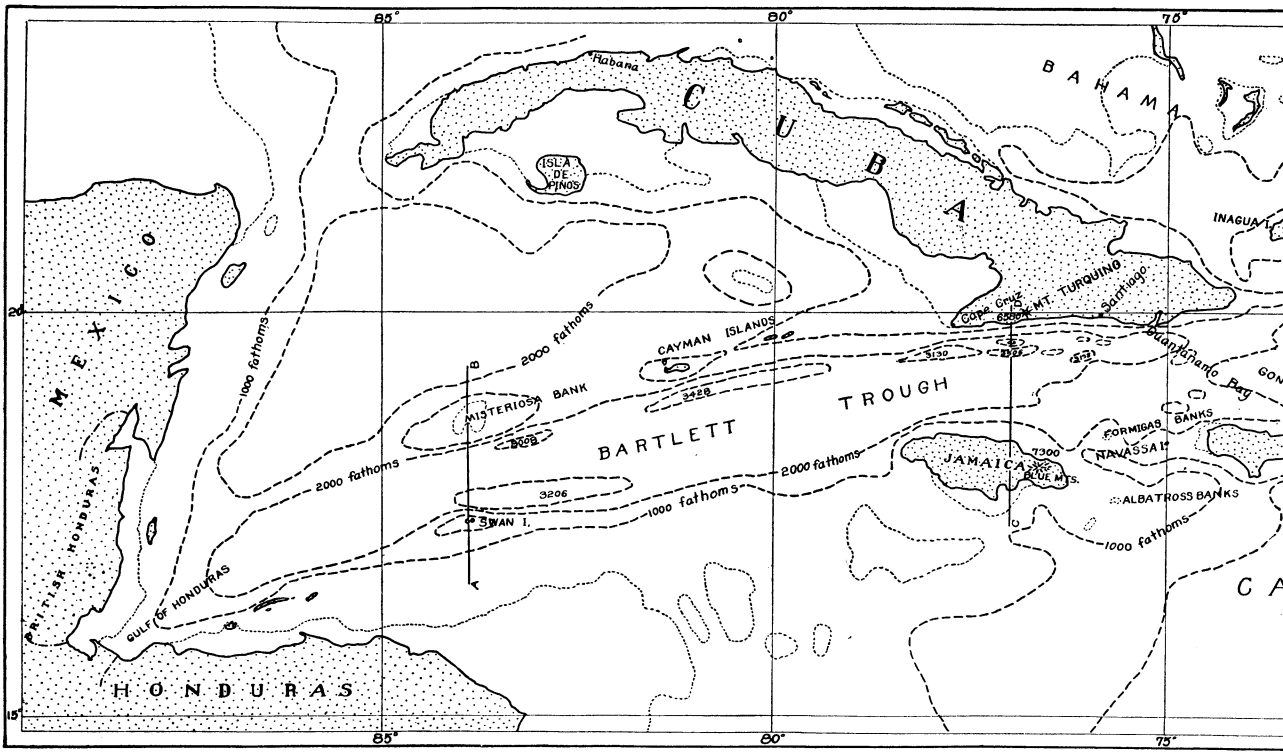
region. These arcs cut directly across the earlier tectonic lines and are everywhere marked by extremely precipitous slopes.

The evidence outlined in the following pages indicates (1) that the east-west arcs delineating the major relief features of the Greater Antilles are zones of normal faulting developed in late geologic time; (2) that this faulting has resulted in the formation of the great troughs of the region; and (3) that the displacements are continuing at the present time.

CRITERIA OF FAULTING

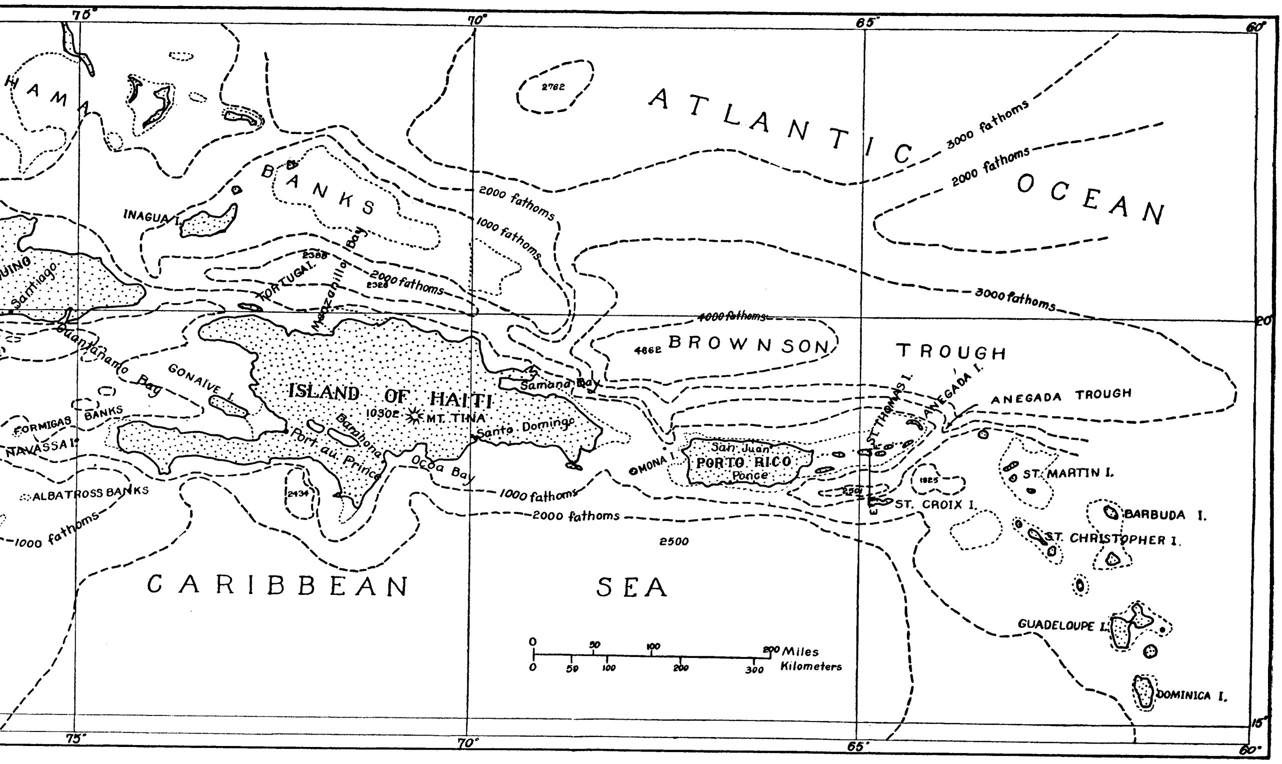
The fault-zone hypothesis rests partly on geologic evidence, but largely, since most of the region is under water, on evidence that is either topographic or seismologic. Topographic evidence of faulting is unusually well preserved because the fault scarps are mostly below sea-level where they have been protected from erosion. The characteristics of these scarps which indicate an origin through faulting are (1) great height; (2) extremely precipitous slopes; (3) abrupt changes in slope at top and bottom; (4) rectilinear course for long distances; and (5) subordinate depressions and elevations (troughs and horsts) near the base of the main scarps.

The last-mentioned features develop within fault zones as a result of the differential displacement of long narrow blocks or wedges formed by the branching and intersection of nearly parallel faults. The formation of these subordinate troughs and horsts is a common accompaniment of normal faulting on a large scale and especially of trough faulting. On land these minor topographic effects of faulting are soon obliterated by erosion and by the accumulation of rock-waste in the troughs; therefore the significance of these criteria in the recognition and interpretation of faulting has been generally overlooked. Because of their short life these topographic features are seldom found on land except in arid regions and where very recent displacements have occurred along old fault zones. Beautiful examples of this type of fault topography on a small scale have developed along the Wasatch fault zone in Utah as a result of post-Pleistocene displacements. Similar topographic effects were produced in California by the faulting that accompanied



MAP OF THE GREATER ANTILLES, SHOWI

Contour interval, 1,000 fathoms (6,000 feet). Areas within



...ER ANTILLES, SHOWING FAULT TROUGHS

...feet). Areas within the dotted lines, less than 100 fathoms.

the Owens Valley earthquake of 1872;[1] and there are many examples along the line of the San Andreas fault zone of California.

Seismologic evidence, when available, is especially valuable in locating active faults which are not exposed to direct observation. Many earthquakes have been recorded in the Greater Antilles and Virgin Islands during the last four centuries, and, while the published catalogues of these earthquakes are far from complete, it seems probable that few, if any, of the very destructive shocks have been omitted. Most of the weak shocks of a district originate in the same localities as the stronger ones, and therefore in this investigation attention has been focused on the destructive earthquakes. In the region of the Greater Antilles the epicenters of destructive earthquakes, instead of being scattered at random, are almost entirely limited to a few well-defined belts, which also possess the topographic characteristics of fault zones.

Most of the earthquakes occurred before seismographs were developed, and, therefore, in determining the location of their epicenters, it has been necessary to rely chiefly on the distribution of intensities and the evidence derived from a study of accompanying sea waves. Fortunately, for present purposes an approximate location of an epicenter is, in most cases, sufficient. The seismologic data are only briefly summarized here as they are discussed in more detail in another paper which will be published shortly in the *Bulletin of the Seismological Society of America.*

DESCRIPTION OF FAULT ZONES AND FAULT TROUGHS

The principal troughs of the Antillean region are: the Bartlett Trough, which lies between Cuba and Jamaica and extends from the Island of Haiti westward into the Gulf of Honduras; the Brownson Trough, lying immediately north of Porto Rico and the Virgin Islands; and the Anegada Trough, which separates Porto Rico and the Virgin Islands Bank from St. Croix and the Lesser Antilles. In addition to these there are some minor troughs and probably one fault zone that is not associated with any trough.

[1] G. K. Gilbert, "Lake Bonneville," *U.S. Geol. Surv. Monograph I* (1890), p. 361.

THE BARTLETT TROUGH[1]

The Bartlett Trough is probably the most striking physiographic feature of the Antillean region (Fig. 1). It is a long, narrow trench stretching from the Gulf of Honduras eastward into Gonaïve Gulf between the two western peninsulas of Haiti, a distance of 15° or 1,570 km. Its width, where widest, between Cuba and Jamaica and near the Cayman Islands is 150 to 160 km. Its deepest sounding, 3,506 fathoms (6,412 m.) was obtained less than 50 km. from the coast of Cuba and is over 8,275 m. below the higher peaks of the Blue Mountains in Jamaica and the Sierra Maestra in southern Cuba. The six deepest places (all over 3,000 fathoms) are close to the inclosing scarps rather than near the center of the trough. The floor of the trough seems to be relatively flat over quite large areas, but in longitudinal profile rises and falls throughout its length. The Bartlett Trough lies between two great fault zones which may be traced longitudinally far beyond the limits of the trough itself. They are here designated the Swan Island–Jamaica–South Haiti fault zone and the Cayman Islands–Sierra Maestra–North Haiti fault zone.

Swan Island–Jamaica–South Haiti Fault Zone.—This fault zone may be traced westward from its juncture with the northern escarpment of the Caribbean Basin in the vicinity of Ocoa Bay, Santo Domingo, across Haiti, and along the southern side of the great Bartlett Trough. On the Island of Haiti it is marked by a trough-shaped valley 15 to 20 km. in width, which extends from Barahona on Neyba Bay to Port-au-Prince, a distance of about 150 km. Throughout its length this depression is confined between the precipitous fronts of two lofty mountain ranges. The floor of the trough comprises the plain of the Cul de Sac in the west, the plains of Neyba in the east, and the lake region lying between. Two of the lakes contain salt water, and W. F. Jones states that they are both below sea-level, but at different elevations.[2] A very slight subsidence of the land would com-

[1] A brief description of this trough was given in a previous paper, "Jamaica Earthquakes and the Bartlett Trough," *Bull. Seis. Soc. of Amer.*, Vol. X (1920), pp. 84–88.

[2] W. F. Jones, "A Geological Reconnaissance in Haiti, A Contribution to Antillean Geology," *Jour. Geol.*, Vol. XXVI (1918), p. 730.

pletely submerge the floor of the trough and separate the Tiburon Peninsula from the rest of Haiti.

The depression has been described and figured by Jones as a normally faulted block, buried under Quaternary deposits which have been removed at one place exposing highly tilted Oligocene-Miocene sediments. Limestones of Eocene–Early Oliogcene age are exposed along the flanks of the inclosing ranges while late Tertiary intrusives form the core of the mountains on the south. Another "large fault is indicated well up on the south range of Haiti, a well-marked depression extending east and west along the course of this fault."[1]

Along the north side of the salt lakes Jones found basalt-flows, which he thinks came from fissure eruptions; and he states that between the Cul-de-Sac depression and Ville Bonheur (Saut d' Eau) there is a well-defined crater from which extend basalt-flows, so recent in origin that they have not been appreciably modified by erosion.[2] In the Province of Azua, Santo Domingo, there are rocks of igneous origin, which C. W. Cooke states are not older than Pleistocene.[3]

During historic times the fault trough of southern Haiti has been the locus of more earthquakes of high intensity than any similar area in the Greater Antilles. The high seismicity of this depression is noted by Scherer in his excellent article on "Great Earthquakes in the Island of Haiti"[4] from which most of the data on Haitian earthquakes given in this paper have been abstracted.

The cities of Azua and Santo Domingo, located on alluvial ground a short distance north of the fault zone and near its juncture with the Caribbean escarpment, have been damaged repeatedly by earthquakes. They suffered from severe shocks in 1673, 1684, and 1691, Azua being entirely destroyed in 1691. On October 18, 1751, an earthquake threw down all houses in Azua and a sea-wave overwhelmed the town. It was rebuilt farther inland.

[1] *Ibid.*, p. 751. [2] *Ibid.*, pp. 750–51.

[3] C. W. Cooke, "Geological Reconnaissance in Santo Domingo," *Bull. Geol. Soc. Amer.*, Vol. XXXI (1920), p. 218.

[4] Rev. J. Scherer, "Great Earthquakes in the Island of Haiti," *Bull. Seis. Soc. Amer.*, Vol. II (1912), pp. 161–80.

Other towns near the coast were severely damaged, Santo Domingo City losing many of its finest buildings. The earthquake of 1751 and several other shocks, assigned by Scherer to the central valley of Haiti, are here correlated with the southern fault trough because of high intensities near the coast and the phenomena of the sea-wave. The earthquake of May 11, 1910, cracked walls in Azua and Santo Domingo City. Scherer states that "the strongest part of the earthquake occurred in the Bay of Ocoa where the sea-wall was broken."[1]

The fault trough apparently continues westward into the Gulf of Gonaïve, for there is a marked depression between Gonaïve Island and the straight north coast of the Tiburon Peninsula. The earthquake of November 9, 1701, threw down masonry houses on the plains near the western end of the trough, and the road along the north shore of the Tiburon Peninsula from Léogâne to Petit Goâve sank into the sea. The severe earthquakes of November 21 and 22, 1751, destroyed the recently founded town of Port-au-Prince and overthrew buildings on the plain of the Cul de Sac. Lyell states that "part of the coast 20 leagues in length sank down and has ever since formed a bay of the sea,"[2] but the writer has found nothing which would confirm this assertion.

The earthquake of June 3, 1770, was one of the strongest shocks recorded on the Island of Haiti, the area of greatest destruction extending from Croix de Boquets through the plain of the Cul de Sac to Port-au-Prince and along the north coast of the Tiburon Peninsula as far as Miragoâne. Southey states that "the sea rose a league and a half up into the island"[3] but does not mention where this occurred. Scherer states that at Grand Goâve the foot of the mountain of La Saline was partly submerged and at Arcahaie north of Port-au-Prince, a wave was also recorded.[4]

The earthquake on the night of April 8, 1860, originated a little farther west than the disturbances previously described, the inten-

[1] Rev. J. Scherer, *op. cit.*, p. 172.

[2] Sir Charles Lyell, *Principles of Geology*, Vol. I, p. 440, London, 1830.

[3] Thomas Southey, *Chronological History of the West Indies*, Vol. II, p. 407, London, 1827.

[4] Rev. J. Scherer, *op. cit.*, p. 178.

sity being greatest from Petit Goâve to Anse à Veau, but towns as far east as Port-au-Prince had houses thrown down or badly damaged. In the vicinity of Anse à Veau the sea withdrew and then broke with a crash on the shore.

Soundings indicate that the fault trough of southern Haiti continues westward as a topographic feature at least as far as the end of the Tiburon Peninsula; and, while it cannot be traced farther, the trend of the entire depression is in alignment with the southern scarp of the Bartlett Trough north of Jamaica. Evidence that the north coast of Jamaica is determined by a fault zone has been given elsewhere.[1] Briefly summarized, it is as follows:

1. The coast is an almost straight line from Port Maria to Montego Bay, a distance of nearly 113 km., where it is offset about 8 km. to the south and then continues westward to Pedro Point. The east-west line between Pedro Point and Montego Bay is continued eastward by the valley of Montego River which runs parallel to the coast for 16 km.

2. The land rises steeply from the sea to the plateau surface which has an elevation of 300 to 400 m. Wave erosion could not have produced these bluffs in the relatively short time that it has been active, and there is no broad, wave-cut terrace either above or below sea-level. The steep slopes continue below the sea and depths of 1,000 to 2,251 fathoms (1,829 to 4,117 m.) are attained within less than 15 km. of the shore.

3. There is a sudden change in slope both at the top and bottom of the escarpment.

4. The Tertiary beds terminate abruptly along the coast and in places the uplift has exposed the older underlying rocks.

5. The occurrence in modern times of several severe earthquakes with their epicenters a short distance off the coast indicates that there is here a zone of instability along which adjustments are still going on. The earthquake of 1692—one of the great catastrophes of history—and the destructive earthquake of 1907 both originated off the north coast of Jamaica and both were accompanied by sea-waves.

[1] Stephen Taber, "Jamaica Earthquakes and the Bartlett Trough," *Bull. Seis. Soc. Amer.*, Vol. X (1920), pp. 55–89.

Passing westward from Jamaica, soundings show that the steep southern escarpment of the Bartlett Trough continues toward Swan Island, and everywhere with abrupt changes in slope at top and bottom. Swan Island has the topographic characteristics of a horst which has remained standing within the zone of subsidence (see Fig. 1).

Great Swan Island is only 2.5 km. in length and about 20 m. in height; Little Swan Island is scarcely more than a reef. The submarine slopes in the vicinity of the islands are precipitous: on the south a sounding of 1,053 fathoms (1,926 m.) was obtained

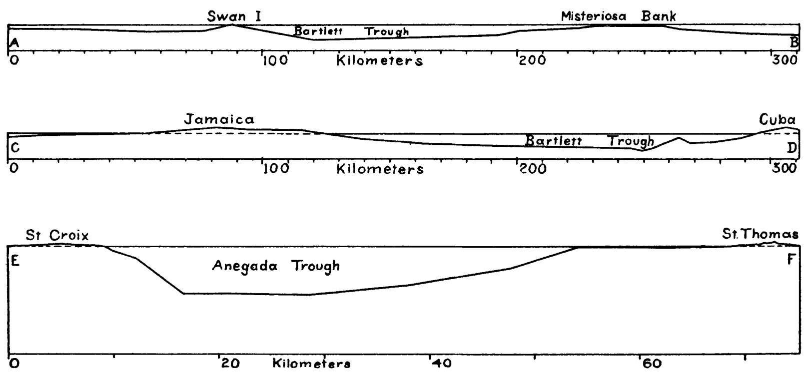


FIG. 1.—Profiles of the Bartlett and Anegada Troughs. Vertical and horizontal scales the same. Additional soundings would show the scarps to have steeper rather than gentler slopes.

within 10 km., the descent continuing until a depth of 2,136 m. is reached 16 km. from the island, after which the sea-bottom rises rapidly to the edge of the submerged Honduras-Jamaica Plateau; toward the north, a depth of 3,010 fathoms (5,505 m.) is attained within 32 km. of the island, thus giving an average slope of about one in six.

The latter sounding was obtained in a long, narrow depression lying at the foot of the scarp. The 3,000-fathom contour surrounding the depression (see map, Plate I) extends eastward from Swan Island along the base of the scarp for 200 km. or more. It has an average depth, below the floor of the Bartlett Trough in this vicinity, of over 1,000 m., the deepest sounding recorded being

3,206 fathoms (5,858 m.). The general form of this depression, in so far as it has been revealed by soundings, and its alignment with the fault trough of southern Haiti, together with the presence of other depressions of unknown shape nearer Jamaica, suggest that there has been more or less trough faulting all along the arc from Ocoa Bay to Swan Island.

Swan Island is built of limestone, mostly Pleistocene or Recent in age. A specimen from the higher part of the island consists chiefly of the coral, *Orbicella cavernosa* (Linn.). The particular form present in the specimen now lives in those waters and has not been found in deposits older than Pleistocene. In places the rock is a loosely cemented, coarse, calcareous sandstone. Pebbles and bowlders of hard limestone, containing terrigenous material, are abundant along the beaches. A specimen, showing well-defined, closely spaced bedding-planes and made up largely of *Globigerina* with amorphous silica filling the cavities, contained flakes of muscovite one millimeter in diameter and subangular quartz grains. Another specimen stained with ferric oxide, contained about 1.5 per cent Al_2O_3 as well as some quartz.[1] The land mass from which these terrigenous materials were derived must have been close at hand, but it has entirely disappeared.

It has not been possible to obtain seismologic data for Swan Island extending back over a long period of time, but during the summer of 1920 two shocks were felt.[2] On July 11 at 10:40 A.M. a distinct rumbling was heard, and this was immediately followed by a pronounced shock, apparently vertical, lasting five seconds. On August 18 at 6:04 P.M. a rather violent earthquake of approximately fifteen seconds' duration was experienced. The motion was reported as vertical and similar in character to that of the earthquake of July 11. No unusual sea conditions were noticed. Tools were dislodged in the engine-room and shop of the

[1] A set of rock specimens was procured from Swan Island through the courtesy of George S. Davis, General Manager of the Radio Telegraph Department of the United Fruit Company. The writer is also indebted to him for his kindness in furnishing seismologic data for Swan Island. The specimen of coral was identified by Dr. T. W. Vaughan, and the *Globigerina* by Dr. Jos. A. Cushman and Dr. Vaughan.

[2] These earthquakes were observed and reported by George H. Rogers, Chief Operator of the Swan Island Radio Station.

Radio Station, some falling from racks to the floor, but no damage resulted. The descriptions of these two earthquakes and the fact that they were not recorded on the seisomographs at Panama, Port-au-Prince, or Vieques indicate that they were local, probably originating close to Swan Island.

An earthquake at $11^h\ 01^m\ 46^s$ G.M.T. on January 1, 1910, was of sufficient intensity to throw two men out of bed. Instrumental records indicate an origin about 35 miles south of Swan Island but this determination is not regarded as very accurate.[1]

The submerged scarp bounding the Bartlett Trough on the south continues beyond Swan Island in a southwesterly direction and is especially well defined north of the Bay Islands (Utilla, Ruatan, and Bonacca) where it has a height of about 4,000 m. The Bay Islands are probably the eastern continuation of the Sierra de Omoa of Honduras[2] and they are also in alignment with Swan Island. Basalt-flows on the Island of Utilla and in the Sierra de Omoa at Chameleconcito near Puerto Cortez are believed by Powers to be Recent, perhaps Pleistocene in age;[3] and their presence is indicative of profound faulting such as has permitted the effusion of basalts in the fault trough of Southern Haiti.

Topographic evidence suggests that the separation of Jamaica and Haiti has resulted from faulting along a branch of the Swan Island–Jamaica–South Haiti fault zone, extending from a point near the north coast of Jamaica eastward along the south coast of Haiti until it joins the northern escarpment of the Caribbean Basin. The Tiburon Peninsula of Haiti continues westward beyond Cape Dame Marie as a submarine ridge for 150 km., passing through Navassa Island and Formigas Bank; a parallel ridge extends eastward from Morant Point, Jamaica, through Albatross Bank for a distance of over 100 km.; between the two lies a narrow channel having a nearly uniform depth of 2,000 m. Immediately south of the Tiburon Peninsula there are very steep slopes, especially near Vache Island and near Jacmel where soundings of over

[1] These data were supplied by Professor Harry Fielding Reid.

[2] Karl Sapper, "Über Gebirgsbau und Boden des südlichen Mittelamerika," *Petermann's Mitteil.*, Bd. 32, Heft 151 (1906), p. 17.

[3] Sidney Powers, "Notes on the Geology of Eastern Guatemala and Northwestern Honduras," *Jour. Geol.*, Vol. XXVI (1918), p. 514.

3,932 m. have been obtained within 20 km. of the coast. There is no evidence of important seismic activity along this branch zone east of Jamaica, and therefore, if the channel be due to faulting, as seems probably, a condition of at least temporary stability has been attained.

The Cayman Islands–Sierra Maestra–North Haiti Fault Zone.—This fault zone extends along the north side of the Bartlett Trough, crosses the Island of Haiti between Manzanillo Bay and Samana Bay, and, in the vicinity of Mona Passage, joins the fault zone which forms the south side of the Brownson Trough.

The Sierra Maestra range, after closely following the straight east-west coast of southern Cuba, continues westward as a submarine ridge, which, bearing slightly toward the south, reappears above the surface in the Cayman Islands and almost reaches the surface in the Misteriosa Bank. It culminates in the Pico del Turquino which rises abruptly from the sea to an altitude of 2,000 m. The precipitous southern slope of the range is continued below sea-level to depths of over 6,000 m., forming one of the most magnificent fault scarps known. At the base of this scarp, which forms the north side of the great Bartlett Trough, there is a narrow subordinate trough or series of elongated depressions containing four of the deepest soundings obtained in these waters; and it is interesting to note that these soundings are located opposite points where the top of the scarp is relatively high. The four soundings are: 5,501 m. immediately southeast of Misteriosa Bank; 6,269 m., 32 km. south of the Cayman Islands; 5,724 m., 35 km. south of Cape Cruz; and 6,412 m., 50 km. south of Turquina Peak. In passing south from Turquina Peak there is a precipitous descent to something more than 2,286 m. below sea-level, and then an ascent to 1,582 m. below sea-level before the descent to 6,412 m. is made (see profile, Fig. 1). Farther east there are other submerged peaks or ridges near the base of the scarp.

Vaughan has referred to the precipitous profiles along the south shore of Cuba as indicative of faulting and states that this interpretation is supported by the geologic structure.[1] The La Cruz marl

[1] T. W. Vaughan, "Some Littoral and Sublittoral Physiographic Features of the Virgin and Northern Leeward Islands and Their Bearing on the Coral Reef Problem," *Jour. Wash. Acad. Sci.*, Vol. VI (1916), p. 56.

(Miocene) is abruptly cut off by faulting at the shore line near the mouth of Santiago Harbor.[1]

Seismologic data are not available for the Cayman Islands, and because of sparse population little is known about the effects of earthquakes along the Sierra Maestra scarp except at Santiago de Cuba. This city, founded in 1514, has been repeatedly damaged by earthquakes.[2] Strong earthquakes were recorded at Santiago in 1578, 1675, and 1677. Kimball states that the city was destroyed by the shock of 1675,[3] but the writer has not been able to verify this statement. The earthquake of February 11, 1678, known in Cuban tradition as the *great earthquake*, caused enormous destruction in Santiago; and exactly one year later the cathedral was destroyed by another shock. The severe earthquake of 1755 was accompanied by a sea-wave which almost completely inundated the town. The strongest earthquake recorded at Santiago, according to Salterain, occurred June 11, 1766, and it was followed by a large number of aftershocks. Many buildings were completely destroyed and others were badly damaged. Between 1777 and 1852 eighteen important earthquakes are listed by Salterain, the earthquake of August 20, 1852, and its aftershocks being especially severe.

In contrast with the Sierra Maestra region the north and central parts of Cuba have been virtually free from seismic disturbances. A severe earthquake followed by aftershocks originated in the Sierra de los Organos of western Cuba in 1880, but, before that time and since, earthquakes have been almost unknown in that section.

Passing eastward from the Bartlett Trough the fault zone is marked by a depression which obliquely crosses the Windward Passage and extends between Tortuga Island and the coast of Haiti. The depression enters Haiti through Manzanillo Bay, and,

[1] T. W. Vaughan, "Geological History of Central America and the West Indies during Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 626.

[2] Most of the facts concerning Cuban earthquakes given in this paper have been abstracted from "Ligera Reseña de los Temblores de Tierra Occuridos en la Isla de Cuba" by P. Salterain, *Boletin de la Comisión del Mapa Geólogico de España*, Vol. X, pp. 371–85, Madrid, 1883.

[3] R. B. Kimball, *Cuba and the Cubans*, p. 20, New York, 1850.

as a land valley, crosses the island to Samana Bay, a distance of 240 km. This great valley was named the Véga Real by Columbus in 1494, but now the name is usually limited to the eastern portion. It is very similar topographically to the great valley of southern Haiti. The floor of the valley, less than 25 km. in width, consists of a series of broad plains lying between the Sierra de Monte Christi on the north and the Grande Hilera on the south. The valley is drained by two rivers, the Yaqui del Norte and the Yuma, flowing in opposite directions.

The geologic structure of the valley has not been studied in detail. Cooke,[1] who has recently visited the region, states that the south front of the Cordillera Sententrional (Sierra de Monte Christi) is a fault scarp which brings up Eocene and Cretaceous rocks high above upper Miocene. The displacement is therefore in the same direction as along the Sierra Maestra fault. Cooke found several faults of slight displacement along the Gurabo River near the southern side of the Véga Real and states that these are probably normal, with uplift on the north. There are other faults of much greater magnitude near the southern side of the Véga Real and in the adjacent part of the Cordillera Central, but no data are now available concerning them. Cooke believes that faulting has been an important factor in shaping some of the boundaries of the Véga Real, but he does not regard the valley as a simple down-dropped fault block.

The high seismicity of the great northern valley of Haiti was recognized by Scherer, who states that the first great earthquake mentioned in histories of Haiti occurred here in 1564. It resulted in the destruction of Conception de la Véga and Santiago de los Caballeros, two cities in the Véga Real about 30 km. apart. In 1783 the principal church at Santiago was partly thrown down by an earthquake and several buildings were destroyed.

The earthquake of May 7, 1842, was one of the most severe recorded on the island. Destruction was greatest at Cap Haitien, a city of ten thousand inhabitants, which lost half of its population. The intensity was almost equally as high at Môle St. Nicolas,

[1] Dr. C. W. Cooke kindly furnished information concerning the geologic structure of the Véga Real in letters dated January 26, and October 5, 1920.

Port de Paix, Fort Liberté and Santiago de los Caballeros, all of which were destroyed with the loss of several thousands of lives. At Cap Haitien waves dashed against buildings along the quay; at Port de Paix the sea withdrew 60 m. and, upon returning, buried the city under 4 or 5 m. of water. The bed of the Yaqui River is said to have been suddenly elevated, driving its waters both up and down stream. The shock was severe at Santiago de Cuba and was felt throughout the length of the Sierra Maestra. The distribution of intensities and the phenomena of the sea-wave indicate that the earthquake was caused by a vertical displacement along a fault passing between Tortuga Island and St. Nicholas Peninsula.

The earthquake of December 29, 1897, seems to have originated in the central part of the Yaqui Valley, the intensity being greatest between Guyaubin and Santiago and at Altamira. At Guyaubin and Santiago great cracks were formed and subsidence of the ground was reported.

Scherer correlates the disastrous earthquake of September 23, 1887, with the great northern valley, but the writer thinks that it was caused by a vertical displacement along a fault near the east end of the Bartlett Trough, a short distance south or southwest of Môle St. Nicolas. The destruction was greatest at Môle St. Nicolas, nearly all of the houses being thrown down. Buildings were also damaged or destroyed at Cap Haitien, Port de Paix, Gonaïves, and other places. A sea-wave followed the earthquake and was reported from points along the shores of Gonaïve Gulf as far as Anse d'Hainault on the end of the Tiburon Peninsula; at Jérémie on the north coast of the Tiburon Peninsula the sea withdrew 20 m. and returned with a rush. Along the north coast of the St. Nicholas Peninsula, however, the wave seems to have been of no importance. The shape of the St. Nicholas Peninsula suggests that both its north and its south coasts may have been determined by faulting.

Three other Haitian earthquakes of moderately high intensity cannot be correlated with either of the great fault valleys. One originated in the eastern part of the island in 1882 and damaged the churches at Seybo and Higuey; another, which occurred October 6, 1911, was of highest intensity in the central part of the

island and probably originated on the south flank of the Grande Hilera or in the central valley of Haiti. This valley, according to Jones, was formed by folding and erosion rather than by faulting.[1] The earthquake of April 23, 1916, which damaged buildings at Boya, Guerra, and Bayaguana, seems to have originated near latitude 18° 45′ N., longitude 69° 45′ W.

The separation of Cuba and Haiti has been attributed by Vaughan to the downthrow of a block between two faults; one forming the north side of the Bartlett Deep, the other forming the south side and converging toward the former in the Windward Passage.[2] The evidence summarized in the present paper indicates that the separation of the two islands is to be correlated with the formation of the series of depressions, including the Végа Real, which mark the Cayman Islands–Sierra Maestra–North Haiti fault zone, and which have probably originated through differential displacement of relatively narrow blocks or wedges within that zone.

A narrow trough, 3,058 to 4,353 m. in depth, separates the Island of Haiti from the Bahama Banks. It extends eastward, in a great arc convex toward the north, from a point north of the Windward Passage and enters the Brownson Trough northeast of the Samana Peninsula. The topographic characteristics of this trough and its parallelism to the two Bartlett Trough fault zones suggest that it has originated through faulting; but no geologic evidence of faulting is known and little seismologic evidence is available except for the extreme eastern end where it joins the Brownson Deep (see page 106).

THE BROWNSON TROUGH

The Brownson Trough, containing the deepest sounding made in the Atlantic Ocean, parallels the Porto Rico–Virgin Islands ridge on the north. Its shape is not known in detail for as yet few soundings have been made in these waters. The 4,000–fathom contour surrounds a narrow area, about 320 km. long in an east-west direction; and the 3,000-fathom contour which is approxi-

[1] W. F. Jones, *op. cit.*, *Jour. Geol.*, Vol. XXVI (1918), pp. 735–36 and Plate V.

[2] T. W. Vaughan, "Geologic History of Central America and the West Indies During Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), pp. 625–26.

mately concentric extends nearly three times as far. The trough is deepest near its western end.

On the south the trough is bounded by a great scarp that rises steeply to the plateau-like ridge on which Porto Rico and the Virgin Islands stand, the average slope being about one in thirteen. The rectilinear north coast of Porto Rico and the steep submarine scarp descending from it are indicative of faulting. This coast is bordered, near the west end of the island, by a long line of high cliffs which evidently represent a fault scarp, for the youthful topography of the plateau back of the cliffs and the gorge-like valley of Guajataca River near its mouth testify to a recent elevation of the land, whereas a long period of time would be required for the sea to cut such cliffs in gently dipping rock strata. A wave-cut bench at the foot of the cliffs marks the latest uplift of the land, amounting to several meters; and a similar sea-terrace bordering Desecheo Island proves that this recent elevation extended at least that far westward.[1] The abrupt change in the slope near the 100-fathom contour about 8 km. north of the sea-cliffs and the occurrence of earthquakes at points lower down along the slope indicate the presence of a zone of faulting, and suggest that the descent into the trough is not accomplished by a single fault scarp.

The fault zone along the south side of the Brownson Trough is possibly the eastward extension of the Cayman Islands–Sierra Maestra–North Haiti fault zone, but if so, there is a sharp flexure in the trend of the zone immediately north of Mona Passage, and the downthrow changes to the opposite side. The topography of this critical region, in so far as it has been revealed by soundings, suggests that the ends of the two zones overlap and intersect; and this may explain the origin of the peculiar submarine valley, which, heading in Aguadilla Bay, extends northwestward into the Brownson Trough. This valley was described and figured in a previous paper.[2] At Aguadilla the coast has been slowly sinking during the last half-century, while at Mayagüez, 23 km. farther south as well

[1] Harry Fielding Reid and Stephen Taber, "The Porto Rico Earthquakes of October–November, 1918," *Bull. Seis. Soc. Amer.*, Vol. IX (1919), p. 120.

[2] *Ibid.*, pp. 118–21 and Plates 13 and 14.

as along the north coast the land has been rising. The seismicity of the region immediately north of Mona Passage is high.

Many earthquakes have been recorded in Porto Rico and the Virgin Islands.[1] Most of them have had a low intensity and have been reported from only one or two places, so that it is impossible to determine accurately their epicenters, but it is usually possible to locate, approximately at least, the epicenters of the stronger shocks. If consideration is limited to earthquakes which have had a probable maximum epicentral intensity of above VI in the Rossi-Forel scale, it is found that, with very few exceptions, they have originated along the steep slopes descending into the Brownson or the Anegada troughs.

The earthquake of April 16, 1844, which damaged buildings at Isabela on the north coast of Porto Rico, probably had its origin a short distance north or possibly northwest of the island. The shock of November 28, 1846, was most strongly felt in the northwestern part of Porto Rico where some buildings were injured, the distribution of the intensity indicating an origin off the northwest coast. The earthquake of October 11, 1915, which was felt over most of Porto Rico and as far west as Puerto Plata, Santo Domingo, probably originated a short distance north of Mona Passage.

The destructive earthquake of October 11, 1918, with its accompanying sea-wave, and the strong aftershocks of October 18 and 24 and November 12, as well as a host of weaker shocks felt during 1918–19, all originated a few kilometers west of Point Borinquen on the northwest coast of Porto Rico.

Other earthquakes have originated at points farther east along the southern scarp of the Brownson Trough. On the night of December 8, 1875, an earthquake, which probably had its epicenter a short distance north of the coast, damaged buildings in Arecibo. The earthquake of September 27, 1906, having an epicentral

[1] A catalogue of earthquakes felt in Porto Rico and the Virgin Islands from 1772 to 1918 was given in "The Porto Rico Earthquake of 1918 with Descriptions of Earlier Earthquakes. Report of the Earthquake Investigation Commission," by Harry Fielding Reid and Stephen Taber, *Document No. 269*, U.S. House of Representatives, 66th Congress, 1st Sess. (1919), pp. 53–66.

intensity close to IX R.-F., originated about 50 km. north of the coast and opposite the middle of the island; and the shock on September 5, 1908, with slightly lower intensity seems to have had its origin in approximately the same locality. On July 7, 1869, two light shocks were felt on board the ship *Esther and Sophie* when about 20 km. north of Culebra Island. The earthquake of February 17, 1909, felt over the greater part of Porto Rico and the Virgin Islands, originated along the steep submarine slopes north of Culebra and St. Thomas. On October 29, 1886, an earthquake was felt on board the British brigantine *Wilhelmina* while over the steep scarp 75 km. north of Anegada Island.

The north side of the Brownson Trough is entirely under water few soundings have been made in its vicinity, and it is so far from the land that earthquakes originating along its slopes could cause little or no damage; therefore evidence of faulting is not abundant. A broad ridge rising 3,200 to 5,600 m. above the floor of the trough separates it from the North Atlantic Basin. The trough-like depression separating Haiti from the Bahama Banks apparently joins the north slope of the Brownson Trough at a slight angle, in much the same way that the Cayman Islands–Sierra Maestra–North Haiti fault zone joins the fault zone on the south side of the Brownson Trough.

On February 19, 1883, the bark *Siddartha* experienced a sharp earthquake, lasting 25 seconds, while over the north side of the Brownson Trough in lat. 20° 04′ N., long. 67° 41′ W. The bark trembled as if dragging over a hard bottom although the depth here is more than 6,000 m.

On November 29, 1916, and on July 13 and 26, 1917, severe earthquakes originated in the vicinity of lat. 19° 30′ N., long. 68° 30′ W. The last of these shocks was felt over most of Haiti and Porto Rico and probably had an intensity of IX R.-F. near the epicenter. It was followed by a series of aftershocks lasting several days. These earthquakes of 1916 and 1917 should be correlated, perhaps, with the trough that separates Haiti from the Bahama Banks for they originated in the area where it joins the Brownson Trough (see page 103).

THE ANEGADA TROUGH

The Anegada Trough, separating Porto Rico and the Virgin Islands group from St. Croix and the Lesser Antilles is the deepest of the many passages connecting the Caribbean Sea with the Atlantic Ocean. A description of this trough accompanied by a map and transverse profile was given in a previous paper.[1]

It is deepest midway between St. Croix and Vieques where a sounding of 2,501 fathoms (4,574 m.) was obtained; here it extends nearly east and west for 100 km. Between St. Croix and the islands of St. Thomas and St. John the depth is over 2,000 fathoms. Farther east the trough rises until the depth is a little over 1,000 fathoms and there it bifurcates. One branch seems to extend northeast and join the Brownson Trough about 60 km. northeast of Anegada Island, where the depth is over 3,000 fathoms; the other extends eastward in the direction of St. Martin but is not well defined. In its deeper parts the trough is about 40 km. in width between the tops of the inclosing scarps, which show abrupt changes in slope at both top and bottom. The floor of the trough is relatively flat.

The south side of the trough near St. Croix and westward therefrom is bounded by a tremendous fault scarp (see profile Fig. 1). Near Harms Bluff at the northwest corner of St. Croix the scarp descends 4,348 m. in 8 km., an average slope of 30°. For a distance of 4.4 km. the slope averages over 37°, and for shorter distances it is much steeper. Vaughan states that the faulting has taken place so recently that the sea has barely cut a niche into the fault plain.[2] The northern scarp of the trough does not touch the coast of any of the islands; it lies 15 km. south of St. Thomas and 6 or 7 km. from Vieques. It is not so precipitous as the opposing scarp, the average slope being about 12°, though in places it is much steeper.

[1] Harry Fielding Reid, and Stephen Taber, "The Virgin Islands Earthquake of 1867–1868," *Bull. Seis. Soc. Amer.*, Vol. X (1920), pp. 20–25

[2] T. W. Vaughan, "Some Features of the Virgin Islands of the United States," *Asso. Amer. Geog. Ann.*, Vol. IX (1920), pp. 78–82.

Several severe earthquakes have originated in the Anegada Trough and many light shocks are recorded by the seismographs on the Island of Vieques. A severe earthquake was felt in Antigua, St. Christopher, and Tortola July 11, 1785. Since the shock was strongly felt on all three islands its epicenter was probably between them; and the report that cracks were formed in the ground in Tortola suggests an origin in the vicinity of that island.

A severe shock was felt in St. Thomas, April 20, 1824. The precise location of the epicenter cannot be determined from the data available but is not far from St. Thomas, probably in the Anegada Trough, though possibly on the opposite side of the island along the southern scarp of the Brownson Trough. The strong shock reported from St. Thomas September 19, 1853, and the two felt on May 12, 1865, appear also to have originated near that island.

The great earthquakes of November 18, 1867, originated along the northern scarp of the trough 15 to 20 km. south of St. Thomas. There were two strong shocks separated by an interval of about 10 minutes, both being followed by sea-waves. Aftershocks continued for several months, the strongest occurring December 1 and 12, 1867; January 5 and March 17, 1868, and September 17, 1869. The shock on March 17, 1868, was accompanied by a small sea-wave and seems to have had its epicenter a little farther west than the others, though all originated along the same scarp.

On July 24, 1913, a severe earthquake was felt in the Virgin Islands and throughout Porto Rico except along the west coast. The epicenter was apparently in the Anegada Trough near latitude 18° 30′ N., longitude 64° W.

THE NORTHERN ESCARPMENT OF THE CARIBBEAN BASIN

The Caribbean Basin is bounded on the north by an escarpment that descends steeply from Porto Rico and Haiti to a depth of 4,572 m. within 90 km. of the islands. This is the only important scarp in the region that does not form one side of a relatively narrow trench. It gives the Porto Rico–Virgin Islands ridge, extending eastward from Haiti, the topographic characteristics of a great horst.

Near Ponce on the south coast of Porto Rico, Berkey has traced an east-west fault which he thinks is of very late Tertiary age.[1] It brings the older rocks of the pre-Tertiary into contact with the younger series forming the present coastal margin. This fault may be one of a series by which the descent to the floor of the Caribbean Basin is accomplished. There is, however, no topographic evidence of recent displacements along it; and the Seismic history of the region indicates that, if the Caribbean scarp be due to faulting, it is now relatively stable. The epicenter of no earthquake can be definitely assigned to this scarp, although some of the shocks reported only from the south coasts of Porto Rico and Haiti may have originated there. Certainly no disastrous earthquakes and comparatively few light shocks have occurred there in several centuries.

On August 4 and 13, 1908, moderately strong shocks were felt at Ponce and neighboring points. The intensity was about VI R.-F., and some buildings were slightly damaged. The origin was probably not far from Ponce.

Earthquakes of low intensity have originated at many places in Porto Rico, but in contrast with the north coast none has had an intensity of more than VI or VII. A shock on August 30, 1865, which slightly damaged churches at Manatí and Ponce, probably had its origin near the center of the island. On October 23, 1860, an earthquake with intensity of VI–VII caused some damage at Mayagüez on the west coast, and the epicenter was probably not far away. Several light shocks have originated in the eastern part of Porto Rico near Cidra, the strongest, on October 22, 1901, having an intensity of about VI.

RELATION OF FAULT ZONES TO EARLIER TECTONIC TRENDS

The fault zones described in this paper collectively form a great fault system which extends from the eastern end of the Brownson Trough westward to the Gulf of Honduras, a distance of 2,500 km. The two fault zones inclosing the Bartlett Trough are apparently in alignment with the Matogua Valley and the

[1] C. P. Berkey, "Geological Reconnoissance of Porto Rico," *Ann. N.Y. Acad. Sci.*, Vol. XXVI (1915), p. 40.

Polochie–Lake Izabal Valley in Guatemala, but Powers who has recently visited the region states that he believes these valleys are due to erosion dependent on folding.[1] Sapper,[2] in mapping the tectonic lines of Central America attributes the east-west ranges of Guatemala to folding, and this view has been adopted by other geologists. If the Antillean fault zones continue westward beyond the Gulf of Honduras their curvature is reversed, for in Central America the mountain ranges extend in approximately parallel arcs convex toward the south.

The Central American ranges, as they approach the Gulf of Honduras, curve gradually toward the northeast, and therefore meet at an angle the north coast of Honduras which extends east and west. Powers states that this coast is evidently a fault-zone area.[3] Vaughan correlates the tectonic lines of Honduras with the submarine ridge or plateau connecting the Honduras Peninsula with Jamaica,[4] but this feature is abruptly terminated by the fault scarp north of Jamaica. The tectonic lines of Central America, according to Sapper, are of several different ages; some having been formed in the Paleozoic, others as late as the Tertiary. Possibly some of these lines continue into the West Indies with curvature convex toward the south while others turn gradually southward and become convex toward the north. Faulting in Central America may have followed along the old structural lines due to folding. The location of Guatemala in a belt of high seismicity that may be traced from the Greater Antilles through Central America and Mexico into California, together with the precipitous topography of the region suggest that the great Antillean fault system may extend into Central America, and, gradually curving toward the north, continue into California. These questions cannot be decided, however, until more field data are available.

The Sierra de los Organos, which form the backbone of western Cuba, have a northwest-southeast trend and may be genetically

[1] Sidney Powers, written communication dated September 10, 1920.

[2] Karl Sapper, *op. cit.*

[3] Sidney Powers, written communication dated September 10, 1920.

[4] T. W. Vaughan, "Geologic History of Central America and the West Indies during Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 618.

related to the tectonic lines of Central America and southeastern Mexico.

Another group of tectonic lines, prominent in the Greater Antilles, trends northwest and southeast. The principal mountains of Jamaica, composed of intensely folded Cretaceous rocks trend about N. 70° W. parallel to the northeast coast; the Grand Hilera or Sierra Cibao extend across the Island of Haiti in a northwest-southeast direction from a point near Cape Engano to Môle St. Nicolas, and the axis of elongation of Cuba from the Windward Passage almost to Habana also follows this trend. Vaughan infers that a fault runs northeast from Cape Cruz but the evidence is meager.[1]

Another old structural direction, which seems to have no relation to the present topography, is indicated by the north-south strike of the crystalline rocks exposed on the Isla de Pinos lying south of western Cuba.[2]

The Antillean fault zones cut across the earlier trend lines which seem to be due chiefly to folding, and, because of their recency as well as the magnitude of the displacements, they dominate the present topography. Transverse faulting seems to be rare, and it has had little or no effect on the topography. The irregular coast lines at the east and west ends of the various islands are in marked contrast to the rectilinearity of many of the coast lines that run east and west.

Berkey has suggested that Porto Rico is a large fault block uplifted along the southern margin and tilted toward the north with breaks at each end. In support of this hypothesis he mentions the unsymmetrical position of the main drainage divide, which is nearer the south coast; the comparatively abrupt termination of the island at both ends; and the absence of the younger limestone margin from these coasts although it is fairly continuous along the north coast and about half of the south coast.[3]

[1] T. W. Vaughan, "Fossil Corals from Central America, Cuba, and Porto Rico, with an Account of the American Tertiary, Pleistocene, and Recent Coral Reefs," *U.S. Nat. Mus. Bull. 103* (1919), pp. 288–89.

[2] C. W. Hayes, T. W. Vaughan, and A. C. Spencer, "Report on a Geological Reconnaissance of Cuba," Washington, 1901.

[3] C. P. Berkey, *op. cit.*, pp. 40–41.

In opposition to this view it may be urged that the east and west ends of Porto Rico are rather irregular; that there is neither topographic nor seismologic evidence of faulting; and that the absence of Tertiary limestones from the ends of the island may be due to submergence. The numerous reefs, projecting rocks, and small islands extending eastward from Porto Rico as far as Anegada are proof of subsidence at this end of the island; and at the other end the water is relatively shallow between Porto Rico and Haiti, averaging less than 450 m., while Mona and Desecheo islands rise above the surface. Semmes attributes the present position of the drainage divide to greater rainfall on the north side of the island.[1]

ORIGIN OF THE ANTILLEAN TROUGHS

The great troughs of the Antilles are bounded by fault zones, and are characterized by great depth, by precipitous inclosing scarps which show abrupt changes in slope at top and bottom, and by relatively flat floors that, instead of being graded like river valleys, rise and fall throughout their length. Many of the deepest places are close to the inclosing scarps instead of near the centers of the troughs, and occasional horst-like elevations are also found within the fault zones. The troughs are parallel rather than convergent and in places are roughly arranged *en echelon*.

All of the evidence is in accord with the conclusion that the troughs have been formed through faulting. Moreover, they must be attributed to subsidence of long narrow blocks rather than elevation of the areas on each side; for the rock strata exposed in the marginal scarps standing above sea-level were laid down in relatively shallow water, and portions of the larger islands have remained continuously above sea-level since pre-Tertiary time, while the faulting is more recent. The subordinate depressions at the base of the main scarps are also indicative of normal faulting, and there is an absence of lateral pressure effects such as would be expected to accompany thrust faulting.

Vaughan is of the opinion that the faulting took place in late Tertiary, probably Pliocene time, and he cites three kinds of evi-

[1] D. R. Semmes, "The Geology of the San Juan District, Porto Rico," *Scientific Survey of Porto Rico and the Virgin Islands, N.Y. Acad. Sci.*, Vol. I, Part I (1919), p. 38.

dence, namely: (1) The faulting along the south coast of Cuba is subsequent to old or middle Miocene, as the Miocene La Cruz marl is abruptly cut off at the shore; (2) the sea has had time to cut only narrow benches into the fault scarps that form shore lines; and (3) the biological evidence demands land connection in late Tertiary time between Cuba, Santo Domingo, Porto Rico, and thence to South America.[1]

The faulting may date from the Pliocene, as suggested by Vaughan but the frequent occurrence of earthquakes along the fault zones proves that the displacements are still continuing; and the sea-waves, which have accompanied nearly all of the great earthquakes with the exception of those originating in the Haitian land valleys, indicate that these latest displacements have also been vertical. Another evidence of recent displacements is furnished by the character of the material on the sea-floor along the fault zones. Off the northwest coast of Porto Rico broken coral is found at a depth of 1,864 m. and the bottom is "rocky" at 3,221 m.[2]

The Antillean fault system, whether it continues into Central America or not, forms one of the major structural features of the earth; and the displacements now going on are similar to those which have occurred in the past. The earthquakes are not limited to the immediate vicinity of land areas and hence cannot be attributed to adjustments resulting from changes in surface-loading due to erosion. That the faulting extends to profound depths is shown by the persistence of the fault zones, by the great height of the scarps, and by the extrusion of lava from some of the fault fractures.

The total volume of lava that has reached the surface along the Antillean fault zones is insignificent as compared with the size of the troughs; consequently there can be in this instance no causal relation between volcanic activity and the foundering of the narrow blocks, such as has been suggested for the Christiania Fiord in southern Norway, the "rift valley" of eastern Africa and similar troughs elsewhere.

[1] T. W. Vaughan, "Geologic History of Central America and the West Indies during Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 626.

[2] United States Coast and Geodetic Survey Chart 901.

Fault phenomena of the type exhibited in the Antilles testify to a state of tension rather than compression in the earth's crust. This tension is difficult to explain. It may be due to warping, for there is some evidence that the formation of the troughs has been accompanied and perhaps, in part, preceded by an upswelling or arching of the region together with more or less subsidence of the border portions. The uplift has culminated in the Island of Haiti, and the Bartlett Trough has developed along the axis of uplift, the surface being in most places higher near the borders of the trench than farther back. Sea-terraces, marking intermittent elevations have been observed along many coasts of the Antilles; in Cuba they extend entirely around the east end of the island but attain their finest development along the south coast between Cape Maisi and Guatanamo.[1] On the opposite side of the trough near Montego Bay, Jamaica, they are also well developed, Hill having observed six distinct benches.[2]

While the evidence is extremely meager it is at least in accord with what is known concerning the structural relations of fault troughs in the other parts of the earth. Most of these troughs appear to have been formed as a result of the upswelling of broad arches and plateaus of the downwarping of basin-like areas under the influence of forces that probably have acted vertically.

[1] R. T. Hill, *Cuba and Porto Rico with the Other Islands of the West Indids*, p. 44, New York, 1899.

[2] R. T. Hill, "The Geology and Physiography of Jamaica: Study of a Type of Antillean Development," *Bull. Mus. Comp. Zoöl. Harvard College*, XXXIV, Geol. Ser. 4 (1899), p. 31.