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JAMAICA EARTHQUAKES AND THE BARTLETT TROUGH

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INTRODUCTION

The island of Jamaica lies between the parallels 17° 42′ and 18° 32′ north and the meridians 76° 11′ and 78° 23′ west. Its extreme length in an east-west direction is 232 kilometers and its greatest width north and south is 79 kilometers; the total area being 10,900 square kilometers. Within this relatively small area many earthquakes have been felt since the discovery and settlement of the island over four centuries ago. Although most of the earthquakes have been of low intensity, several have resulted in destruction of property, and the earthquake of 1692 must be classed among the great earthquakes of history. The earthquake of 1907 was extremely destructive but did not equal that of 1692 in intensity. It is impossible to fix the origin of the large number of shocks that have caused no appreciable damage, for in most cases the only information preserved is the date and time of their occurrence. However, fairly good descriptions of the more destructive earthquakes are available, which make it possoble to fix their origins approximately at least; and it is a general rule that most of the weak shocks of a district originate in the same localities as the stronger ones.

THE EARTHQUAKE OF 1687

The first earthquake of which we have knowledge occurred on Sunday, February 19, 1687, at about 8 a.m. Sir Hans Sloane states that it "was generally felt all over the island at the same time, or near it; some houses therein being cracked and very near ruined, others being uncovered of their tiles; very few escaped some injury. The ships in the harbour at Port-Royal felt it; . . . a gentleman . . . saw the ground rise like the sea in a wave, as the earthquake passed along . . . "[1] Prior to this time, however, many severe earthquakes

[1] "A letter from Hans Sloane, M. D. and S. R. S., with several Accounts of the Earthquakes in Peru, Oct. 20, 1687; and at Jamaica, Feb. 19, 1687-88; and June 7, 1692." *Philosophical Transactions of the Royal Society of London, Abridged,* **3**, 625, 1809.

must have been felt, for the Spaniards had learned that precautionary measures were desirable in the construction of buildings. The English, who took Jamaica from the Spaniards in 1655, do not seem to have learned this lesson, for many of their houses were of brick. Sloane states: "The inhabitants of Jamaica expect an earthquake every year. Some are of the opinion that they follow the great rains. . . . The Spaniards who inhabited this island, and those neighboring, built their houses very low; and they consisted only of ground-rooms, their walls being made of posts, which were as much buried under-ground as they stood above, purposely to avoid the danger which attended another manner of building, from earthquakes. And I have seen in the mountains afar off bare spots, the effects of earthquakes throwing down part of the hills, which continued bare and steep."[2]

THE EARTHQUAKE OF 1692

Descriptions.—The Jamaica earthquake of June 7, 1692, was one of the most appalling in its effects of any recorded in history; others may have had a higher intensity of shock, but few have been accompanied by phenomena more terrifying. The sudden submergence beneath the sea of the greater part of Port Royal, then the most prosperous and important English city of the New World, was a catastrophe so unusual as to appeal powerfully to the imagination. The descriptions of this earthquake found in textbooks are derived from several contemporary accounts, mostly written by eyewitnesses, which were collected and published by Sir Hans Sloane.[3] These narratives, although they contain a few exaggerations and descriptions of phenomena that are obviously impossible, seem to be unusually accurate for that time; but, unfortunately, they contain few references to the effects of the earthquake outside of Port Royal.

Some of the more significant statements contained in the accounts collected by Sloane are quoted below.

"On Tuesday the 7th of June, about 40 min. past 11 in the forenoon, it being then a very hot and fine day, scarcely a cloud to be seen in the sky, or a breath of air to be felt, happened that great shake, so fatal to this place, and to the whole island, which for its violence and strange effects, may perhaps be compared with the greatest that ever yet happened in the world, and may as well deserve the memory of future ages.

[2] *Op. cit.*, p. 625.

[3] *Op. cit.*, pp. 625–632.

"It began with a small trembling, so as to make people think there was an earthquake, which thoughts were immediately confirmed by a second shake something stronger, accompanied all the while with a hollow rumbling noise, almost like that of thunder, which made them begin to run out of their houses. But alas! this was but short warning for them to provide for their safety; for immediately succeeded the third shock, which in less than a minute's time shook the very foundation of Port-Royal so that at least two parts in three of the houses, and the ground whereon they stood, and most part of those who inhabited them, all sunk at once quite under water: and on the place which was left, and is now standing, shook down and shattered the houses in so violent a manner, that at our landing, it looked like a heap of rubbish, scarcely one house in ten left standing, and those so cracked and shattered, that but few of them were fit, or thought safe to live in. All those trees which were next the water, towards the harbour-side where there were excellent wharfs, close to which ships of 700 tons might lie and deliver their lading, where were the best store-houses and conveniences for merchants, where were brave stately buildings, where the chief men of the place lived, and which were in all respects the principal parts of Port-Royal, now lie in 4, 6, or 8 fathoms water. That part which is now standing, is part of the end of that neck of land which runs into the sea, and makes this harbour, and is now a perfect island; the whole neck of land from the part of Port-Royal now standing, to the pallisadoes, or the other end of Port-Royal toward the land, which is above a quarter of a mile, being quite discontinued and lost in the earthquake; and is now also, with all the houses, quite under water. This part of Port-Royal which is now standing, is said to stand upon a rock; . . . several houses now standng were shuffled and moved some yards from their places. One whole street is said to be twice as broad now as before the earthquake . . . Indeed it is melancholy now to see the chimneys and tops of some houses, and the masts of ships appear above water; and when one first cames ashore, to see so many heaps of ruins; to see so many houses shattered, some half fallen down, the rest desolated and without inhabitants; to see where houses have been swallowed up, some appearing half above ground, and of others the chimneys only . . .

"And though Port-Royal was so great a sufferer by the earthquake, yet it left more houses standing there, than in all the island

besides, all over which it is said to rage more furiously than at Port-Royal; for it was so violent in other places, that people could not keep their legs, but were thrown on the ground, where they lay on their faces with their arms and legs spread out, to prevent being tumbled and thrown about by the almost incredible motion of the earth, like that of a great sea. It scarcely left a planter's house or sugar-work standing all over the island: I think it left not a house standing at Passage-Fort, and but one in all Liganee,[4] and none in St. Jago [Spanish Town], except a few low houses, built by the wary Spaniards. . . . In several places in the country the earth gaped prodigiously; on the north side, the planters' houses, with the greatest part of their plantations, were swallowed, houses, people, trees, all up in one gape; instead of which, appeared for some time after a great pool or lake of water, covering above 1000 acres which is since dried up, and now is nothing but a loose sand, or gravel. . . In Clarendon precinct the earth gaped, and spouted up with a prodigious force great quantities of water into the air . . . One may see where the tops of great mountains have fallen, sweeping down all the trees, and everything in their way, and making a path quite from top to bottom; and other places which seem to be peeled and bare a mile together; which vast pieces of mountains, with all the trees thereon, falling together in a huddled and confused manner, stopped up most of the rivers for about 24 hours; which afterwards having found new passages, brought down into the sea, and this harbor, several hundred thousand tons of timber . . . Some are of opinion that the mountains are sunk a little, and are not so high as they were: others think the whole island is sunk something by the earthquake. . . . Two gentlemen happened at the time of the earthquake to be in Liganee, by the sea-side; where at the time of the great shake the sea retired from the land in such sort, that for 2 or 300 yards the bottom of the sea appeared dry, whereon they saw lie several fish, some of which the gentleman who was with him ran and took up, and a minute or two after, the sea returned again, and overflowed great part of the shore. At Yall-house the sea is said to have retired above a mile. It is thought there were lost in all parts of the island 2000 people . . ." The aftershocks continued for several months, "sometimes two or three in an hour's time, accompanied with frightful noises, both from under the

[4] This probably includes the Plains of Liguanea on which Kingston now stands. The district of Liguanea is now known as St. Andrews.

earth, and from the continual falling and breaking of the mountains."

Another witness at Port Royal states: "I lost all my people and goods, my wife and two men, Mrs. B. and her daughter. One white maid escaped, who gave me an account, that her mistress was in her closet, two pairs of stairs high, and she was sent into the garret, where was Mrs. B. and her daughter when she felt the earthquake, and bid her take up her child and run down; but turning about, met the water at the top of the garret stairs; for the house sunk down right, and is now near 30 feet under water. My son and I went that morning to Liguania; the earthquake took us in the mid-way between that and Port-Royal, where we were near being overwhelmed by a swift rolling sea, 6 feet above the surface, without any wind; but being forced back to Liguania, I found all the houses even with the ground. The earth continues to shake 5 or 6 times in 24 hours, and often trembling. Great part of the mountains fell down, and fall daily."

Another account states: "Great part of Port-Royal is sunk; so that where the wharfs were, is now some fathoms of water: all the street where the church stood is overflowed, that the water stands as high as the upper rooms of those which are standing. . . . At the north about 1000 acres of land sunk, and thirteen people with it; all our houses thrown down all over the island, that we were forced to live in huts. The two great mountains at the entering into Sixteen Mile Walk fell and met, and stopped the river, so that it was dry from that place to the Ferry for a whole day; and vast quantities of fish taken up, which was greatly to the relief of the distressed. At Yellows a great mountain split, and fell into the level land, and covered several settlements, and destroyed 19 white people. One of the persons, whose name was Hopkins, had his plantation removed half a mile from the place where it formerly stood."

The Gentleman's Magazine of London for May 1750, pp. 212-215, contains an account of the earthquake of 1692 in which are included two letters from the minister of Port Royal. In a letter dated June 22, 1692, after describing his experiences during the earthquake, he states: "When I came to my lodging, I found all things in the order I had left them. I then went to my balcony to view the street in which our house stood, and saw never a house down there, nor the ground so much as crack'd." Later he was persuaded to go aboard a ship anchored in the harbor. He writes: "I found the sea had swallowed

up the wharf, with all the goodly brick houses upon it, most of them as fine as those in Cheapside, and two entire streets beyond that. From the tops of some houses which lay level with the water, I got first into a canoe, and then into a long boat, which put me aboard a ship . . ."

In an account of the earthquake given by Southey the following statement is found: "the harbour was agitated as in a storm—the ships parted their cables. The Swan frigate lay by the wharf, and was forced over the tops of the sunken houses, and saved some hundreds of the inhabitants. The fort and about 200 houses escaped; but part of the neck of land, about a quarter of a mile in length, was entirely submersed, with all the houses, which stood very thick upon it."[5]

The Assembly of Jamaica in 1693 passed "an Act for the better securing of Port-Royal" which begins as follows: "Whereas the Town of *Port-Royal* is a Town of very considerable Trade, and of great Strength to resist the Enemy in Time of War, by Reason of their Majesties Fortifications, and a great Number of Houses, through the Mercy of God, left standing thereon; and whereas by the late dreadful Earthquake, the Land on the Back-Sea-Side is settled lower than it was, by Reason whereof the Sea hath more Power to gain upon it . . ."[6]

Lyell in the 5th edition of his "Principles of Geology" states: "I am informed by an eyewitness that eighty-eight years after the convulsion of 1692, the houses of Port Royal were still visible at the bottom of the sea." And in a footnote he adds: "Admiral Sir Charles Hamilton frequently saw the submerged houses of Port-Royal in the year 1780, in that part of the harbour which lies between the town and the usual anchorage of men-of-war,"[7]

This is confirmed by Edwards who says that "to this hour the ruins of that devoted town, though buried for upwards of a century beneath the waves, are visible in clear weather from the boats which sail over them."[8]

Charlevoix has given a brief description of the experiences of

[5] Southey, Thomas, "Chronological History of the West Indies," **2,** 162. London 1827. As authority for the quotation, Southey gives "Browne's History of Jamaica," p. 7.

[6] "Acts of Assembly Passed in the Island of Jamaica from 1681 to 1738, Inclusive," p. 60. London, 1738.

[7] Lyell, Charles, "Principles of Geology," 5th ed., **3,** 255. London, 1837.

[8] Edwards, Bryan, "The History Civil and Commercial of the British Colonies in the West Indies," **1,** 235. London, 1801.

some French buccaneers, who were plundering the north coast of Jamaica at the time of the earthquake; and this supplements the meager references to the effects of the earthquake in that part of the island contained in the accounts collected by Sloane. Daviot, who was in command of the plundering expedition, landed 135 men at St. Ann's. Before they could re-embark their vessel was driven off shore by a sudden gale of wind. In encounters with the English they had lost 20 men and had taken about 40 prisoners. When the earthquake occurred they were on the bank of a small river, not far from its mouth. The description by Charlevoix is as follows:

"Les Flibustiers . . . se trouvoient alors assés près de la Mer sur le bord d'une petite Riviere, où il y avoit plusieurs Canots . . . Dès qu'ils sentirent la terre trembler sous leurs pieds, ils s'embarquerent tous dans les Canots, mais les ayant tourner à force de les charger, ou par la précipitation avec laquelle ils y entrerent, ils furent encore bien heureux de pouvoir regagner le rivage; ils voulurent alors se sauver plus avant dans les terres, & ils se mirent à courir de toutes leurs forces; mais la Mer, qui dans ce moment venoit de franchir ses bornes avec un mugissement affreux, couroit encore plus vîte, & les eut bien-tôt atteints. Plusieurs furent engloutis dans les vagues, il y en eut qui tomberent dans des abîmes, qui s'ouvrirent sus leurs pas; tous les autres s'aviserent de grimper au haut des arbres, & quelques-uns de ces arbres ayant ensuite été renversés par la violence du tremblement, ils eurent l'adresse de s'attacher aux plus hautes branches, où ils se soûtinrent dans la chute des arbres. Il en étoit resté un bon nombre dans les Canots; ils furent emportés bienloin au large par le reflux de la Mer, laquelle étant venuë ensuite à monter avec une rapidité surprenante, il leur fallut faire des efforts incroyables avec leurs rames, pour n'être point brisés contre la Côte. Mais ils tinrent bon, & quoique la Mer baissât & montât encore six fois en cinq heures, ils ne voulurent point quitter l'abri, qu'ils trouvoient sur ses ondes contre ses fureurs & les secousses de la terre.

"Enfin vers les cinq heures du soir le tremblement cessa, les Flibustiers se rassemblerent & ne se trouverent plus que 80 avec 60 fusils & leurs Prisonniers, dont aucun n'avoit songé a se sauver, & dont fort peu avoient peri."[9]

[9] Charlevoix, P. Pierre-François-Xavier de, "Histoire de L'Isle Espagnole ou de S. Domingue. Escrite particulierement sur des Memoires Manuscrits du P. Jean-Baptiste le Pers,. Jesuite, Missionnaire à Saint Domingue, & sur les Pieces Originales, que se conservent au Dépôt de la Marine," **2**, 244–245. Paris, 1730.

Discussion of the Evidence.—The descriptions given above enable us to form a fair idea of what occurred during the earthquake. Several witnesses mention that the intensity of shock was greater in other parts of the island than at Port Royal, and this view is confirmed by a critical analysis of the evidence. At Port Royal the fort and 200 houses escaped destruction and many of the houses that were partly or wholly submerged remained standing. In other parts of the island men were unable to stand and were thrown to the ground; trees were overturned near St. Ann's and the French buccaneers lost 35 out of 115 men from the earthquake and sea wave, although it was broad daylight and they were in the open, away from all buildings.

The destruction at Port Royal was due in large part to the "swallowing up" or submergence of certain portions of the town which were built on a sand spit; and this submergence evidently resulted from a slumping and flowing of loose water-soaked material, such as occurred again at the time of the earthquake in 1907. Port Royal was built partly on a limestone reef and partly on the sand spit connecting this reef with the mainland. According to De la Beche, Port Royal was an island in the middle of the 17th century, the connection being completed prior to 1692. After the submergence of part of the spit at the time of the great earthquake, sand was again gradually deposited until the connection was restored in the first quarter of the 19th century.[10] The spit stood only a few feet above sea level and the sand was saturated with water nearly to the surface. The settling of the land was chiefly on the "back-sea-side" or harbor side of the spit, where the wharfs were located, with quite deep water close to shore.

Because of the references to subsidence in the accounts collected by Sloane and because houses were submerged without being thrown down, Lyell was "inclined to believe that there were various and unequal subdsidences of the land at Port Royal, independent of any sliding and undermining of the sands."[11] Elsewhere he stated that if "some of the houses in Port Royal subsided, together with the ground they stood upon . . . we are not to suppose that this was the only spot . . ."[12]

Edwards reached a different conclusion. He states that, "it is not

[10] De la Beche, Henry T., "The Geological Observer," p. 493. London, 1851.
[11] Lyell, Charles, "Principles of Geology," 5th ed., **2**, 263. London, 1837.
[12] Lyell, Charles, "Principles of Geology," 1st ed., **2**, 264. London, 1832.

generally known that the town was built chiefly on a bank of sand adhering to a rock in the sea, and that a very slight concussion, aided by the weight of the buildings, would have probably accomplished its destruction. I am inclined therefore to suspect that the description of the shock is much exaggerated."[13]

De la Beche, who also opposed the idea that there was any general subsidence of land in Jamaica, states that "the part of the town which disappeared was built upon sands accumulated against and around a rock, which, though shaken by the earthquake, retained its place as respects the level of the adjoining sea . . . no mention being made, amid all the details extant, of any permanent change in the relative level of the sea and the part of the town preserved."[14] In a footnote he adds: "Heavy brick houses were built on the sand, and it is stated (Philosophical Transactions, 1694, that 'the ground gave way as far as the houses stood and no further.' . . . Long (History of Jamaica) says, 'The weight of so many large brick houses was justly imagined to contribute, in a great measure, to their downfall, for the land gave way as far as the houses erected on this foundation stood, and no further.' Dr. Miller, of Jamaica, was informed that it was a tradition at Port Royal, prior to 1815, among the descendants of the early settlers, that the great damage was produced by the slipping of the sand during the earthquake."[15]

The submergence of many buildings at Port Royal without their walls being thrown down can not be regarded as evidence proving a depression of the land and disproving the hypothesis that the occurrence was due to a landslip. Many landslides were caused by the earthquake, and in one instance a whole plantation was said to have been moved without disturbing the crops. During the California earthquake of 1906 an area of land, 0.2 kilometers across, slipped downward and at the same time was displaced horizontally several feet without disturbing the trees on it except near the borders of the slide. At the time of the earthquake in 1907 some buildings at Port Royal sank several feet, others were tilted, and palm trees were partly submerged without being overthrown.

The statement that, during the earthquake of 1692, houses were moved several yards and one whole street was broadened to twice its

[13] Edwards, Bryan, *Op. cit.*, **1**, 230–231.

[14] *Op. cit.*, pp. 492–493.

[15] *Op. cit.*, pp. 493–494.

former width, indicates that the depression of the surface was accompanied by a considerable horizontal displacement, such as always occurs in landslips.

The earthquake was accompanied or followed in some places by a great sea wave. In the various accounts of the catastrophe at Port Royal it is difficult to distinguish between the effects of the submergence and those that may have been due to a wave from the sea. However, the ground on which the town was built was only a very few feet above sea level, so that a large wave would have inundated the entire town, and there is nothing to indicate that this occurred. The disturbance of the waters in the harbor of Port Royal, which caused ships to part their cables, probably resulted from the slumping of the sand into deep water. A similar though less destructive disturbance of the waters of the bay occurred again at the time of the earthquake in 1907 (see page 79). The two gentlemen, who, in Liguanea, saw the sea retire and then overflow the shore, do not seem to have been frightened nor do they record any damage resulting from the wave. The report that at Yallhouse the sea retired over a mile is obviously a gross exaggeration. The swift rolling sea encountered by the gentleman and his son as they were going from Liguanea to Port Royal may have resulted from the submergence of part of the sand spit, though the description suggests that it was probably a true wave. It was, however, only six feet in height and may have been generated by the landslips along the harbor side of the sand spit.

The best account of the sea wave is given by Charlevoix. According to his circumstantial description the wave came in, near St. Ann's on the north coast, very soon after the earthquake began, and before the shocks had entirely ceased. No preliminary withdrawal of the sea is mentioned; if a withdrawal occurred along this part of the coast it may not have been very noticeable where the French buccaneers were located, on the small river a short distance above its mouth. The wave must have been quite high, for the men were frightened and tried to save themselves by flight and by climbing trees. Several were engulfed in the waves. The men in the canoes were carried out by the retreat of the sea, which again rose so rapidly that it was with difficulty they avoided being dashed against the shore. The sea rose and fell yet six more times in five hours. This oscillation in sea level was possibly due to the reflection of the waves back and forth between

the coast of Jamaica and Cuba, but if so the eight waves must have broken on the Jamaican coast in less than five hours, since the calculated time for a wave to travel from one coast to the other is about nineteen minutes. However, under such conditions of excitement it is unlikely that an accurate count was kept of the number of waves or the time of their arrival. It is also possible that some of the strong after-shocks immediately following the initial disturbance were likewise accompanied by sea waves.

Location of the Origin.—It has been generally assumed, because of the catastrophe at Port Royal, that the origin of the earthquake was on the south side of the island; Hall[16] placing it, together with the origin of the earthquake of 1907, about ten miles (sixteen kilometers) south of Bull Bay and the mouth of the Hope River. The evidence summarized above, however, does not support this assumption.

The fact that the earthquake was accompanied by a great wave proves that the origin was under the ocean and indicates that the disturbance was caused by a sudden vertical displacement of the bottom of the ocean. The height of a wave decreases as it spreads out from the origin and the time interval between the arrival of the earthquake vibrations and the arrival of the sea wave increases rapidly with the distance. The sea wave was very high on the north coast of Jamaica, while on the south coast, which was more densely populated, the wave seems to have been smaller and to have produced little impression on most observers. On the north coast the wave came in soon after the earthquake began; on the south coast the time interval is unknown as it cannot be inferred from the accounts now available. It would have taken the wave over thirty minutes to travel from an origin near Kingston to St. Ann's. Moreover, the intensity of the shock was apparently greater on the north coast, and several observers state that it was less near Port Royal than in other parts of Jamaica. The origin was probably a short distance off the north coast of the island, the evidence now available being insufficient to locate it more definitely.

THE EARTHQUAKE OF SEPTEMBER 3, 1771.

On September 3, 1771, a very severe earthquake was recorded at Port Royal and Kingston. According to Hall it was strong enough

[16] Hall, Maxwell, "The Historic Epicentre," Jamaica Weather Report, No. 422, p. 6, September, 1913.

to throw down a few houses.[17] Nothing has been found describing its effects in other parts of the island.

THE GREAT SEA WAVE OF OCTOBER 3, 1780.

In 1780 a great sea wave devastated the western coast of Jamaica and swept away the town of Savanna la Mar. This wave has been attributed to a submarine earthquake by Lyell[18] and others, but the fact of its occurrence on the day of a great hurricane suggests that it may have been caused by the wind. One of the best accounts of the disaster is given by Southey. It is as follows:

"Upon the 3rd of October, the inhabitants of Savannah-la-Mar were gazing with astonishment at the sea swelling as it never had before: on a sudden, bursting through all bounds, and surmounting all obstacles, it overwhelmed the town, and swept everything away so completely on its retreat, as not to leave the smallest vestige of man, beast, or habitation behind. About 300 persons perished in this dreadful irruption. The sea flowed half a mile beyond its usual limits; and so sudden and unavoidable was the destruction, although it took place at noon-day, that of the inhabitants of one gentleman's house, consisting of ten Whites and forty Negroes, not a soul escaped. Where the sea did not reach, the destruction was nearly as effectual by the succeeding earthquake and hurricane . . .

"The gale began from the S.E. at one p.m., at four it veered to the south, and became a perfect tempest, which lasted in full force till near eight; it then abated . . . At ten there was a smart shock of an earthquake, and the waters subsided. All the vessels in the bay were dashed to pieces, or driven on shore. The earthquake lifted the Princess Royal, Captain Ruthwin, from her beam-ends, and fixed her upright in a firm bed, where she afterwards served as a house for the inhabitants."[19]

Beckford gives a very detailed description of the hurricane, which wrecked the house in which he was living. During the morning and until 4 p.m. the wind blew from the north and east; it became severe between 2 and 3 in the afternoon, but was most violent after 4 o'clock,

[17] Hall, Maxwell, "Third Report on Earthquakes in Jamaica," Jamaica Weather Report, No. 337, p. 12, 1907.

[18] Lyell, Charles, "Principles of Geology," 1st ed., **2**, 232–233. London, 1832.

[19] Southey, Thomas, "Chronological History of the West Indies," **2**, 472–473. London, 1827. The authority given by Southey is the "Annual Register," 1781, pp. 35, 292.

when it changed into the south.[20] He has very little to say about the earthquake and sea wave, but in his concluding remarks he states: "The sudden swelling of the sea we may reasonably attribute to the heavings of the earthquake to which likewise the general ruin of our houses may be in some measure attributed."[21]

Savanna la Mar, being on the southwest side of the island, is protected from northerly winds, and according to both accounts the wind did not shift to the south until 4 p.m., or about four hours after the wave reached the coast. Since the wave cannot be attributed to the wind it was possibly caused by a displacement of the sea bottom at some point west of Jamaica. Savanna la Mar is peculiarly susceptible to damage by a wave from the sea, for the coast is very low and flat and the form of the coast line would tend to accentuate the height of the wave. A wave from the west would decrease greatly in size before it reached Kingston Bay which has a narrow entrance protected by reefs and shallow water: therefore a wave might do much damage at Savanna la Mar and yet be scarcely noticeable at Kingston. The earthquake, which should have been felt before the arrival of the sea wave, unless the origin was too far off, is not referred to in either account. The earthquake mentioned as occurring later in the day could not have had any connection with the sea wave.

The information that has been preserved concerning the earthquake and sea wave is far from satisfactory, due to the fact that the hurricane occurring on the same day was extremely destructive throughout Jamaica, while the earthquake seems to have caused little or no damage and the effects of the wave were of importance only on the west coast which had few settlements.

THE EARTHQUAKE OF NOVEMBER 11, 1812.

A severe earthquake occurred on Wednesday, November 11, 1812, at about 5:50 a.m. There were three strong shocks in rapid succession, accompanied by a rumbling noise, the disturbance lasting over thirty seconds. It was felt throughout the island, especially near the eastern end, and many houses and plantations suffered severely.[22] Hall states that: "Great damage was done to the houses in Kingston. At Annotto Bay the anchorage ground sank; the 'Experiment' lost her anchor

[20] Beckford, William, "A Descriptive Account of the Island of Jamaica," **1**, 91–94. London, 1790.

[21] *Op. cit.*, **1**, 114.

[22] Southey, Thomas, *Op. cit.*, **3**, 518–519.

and 90 fathoms of cable which were swallowed up. There had been a slight shock previously at 2:30 a.m. that morning. (*Jam. Mag.* 1812, p. 364). . . the anchor and cable of the 'Experiment' ran out with such force that unless a certain bulk-head (to which the end of the cable was attached) had given way the ship would probably have foundered."[23] In one of his earlier reports Hall placed the origin of this earthquake southeast of Kingston,[24] but later he located it about eight miles (thirteen kilometers) northeast of Annotto Bay.[25]

It is impossible with the data now available definitely to locate the origin of this earthquake but it seems not improbable that the origin was on the north side of the island and not far from Annotto Bay. The loss of the anchor and cable of the "Experiment" was probably due to a submarine landslide; it could scarcely be explained by faulting or the formation of "a large chasm" as suggested by Hall. There is no mention, in the reports, of a sea wave having followed the earthquake at Annotto Bay or other points along the coast.

THE EARTHQUAKE OF AUGUST 12, 1881.

At 5:20 a.m. on August 12, 1881, a well marked shock was felt in Jamaica, and according to the report, six hours afterward the water rose eighteen inches in Kingston harbor. It is stated that the earthquake consisted of two shocks: "The first was nearly vertical and lasted about one second; after an interval of about three seconds there were several horizontal oscillations which made the houses swing to and fro: and this series lasted about four seconds."[26] The wave recorded in Kingston harbor may have been caused by an earthquake, but it could hardly have been caused by the earthquake reported at 5:20 a. m., for the time interval is too great.

THE EARTHQUAKE OF JANUARY 14, 1907

Description.—The earthquake of January 14, 1907, was closely

[23] Hall, Maxwell, "The Annotto Bay Epicentre," Jamaica Weather Report, No. 422, p. 5, September, 1913.

[24] Hall, Maxwell, "Fourth Report on Earthquakes in Jamaica. On the periods of the Shocks from the Principal Jamaica Earthquake Centres." Jamaica Weather Report, No. 365, p. 3, 1909.

[25] Hall, Maxwell, "The Annotto Bay Epicentre," Jamaica Weather Report, No. 422, p. 5, September, 1913.

[26] Hall, Maxwell, "Third Report on Earthquakes in Jamaica. The Great Earthquake of January 14, 1907, and the After-Shocks," Jamaica Weather Report, No. 337, pp. 8 and 13 1907.

similar in its effects to the great disturbance of 1692, except that the intensity seems to have been somewhat lower. Detailed descriptions of the earthquake have been published by Brown,[27] Cornish,[28] Hall,[29] and Fuller.[30] It began about 3:31 p.m., local Jamaica time, and lasted at least 30 seconds, perhaps longer, with two or more maxima of intensity during this period. According to observers, who were interviewed by Fuller, "the first vibrations seemed to come from below, the action somewhat resembling in effect the feeling one might experience if the floor on which one was standing was subjected to a hard blow from underneath."[31] Hall quotes Mr. J. C. Ford as saying that the vertical movement seemed "to be considerable, say 6 or 8 inches."[32] Davison states: "All observers agree that the movement was chiefly vertical. It is said that objects jumped from the ground . . ."[33] The majority of observers, especially at Kingston, believed that the principal horizontal motion was nearly east and west; and in support of this view it is stated that most of the fallen walls and pillars in Kingston were thrown towards the east or west. A short distance north of Kingston, however, and also in the Hope River Valley, five miles east of the city, the motion is said to have been in a north and south line.[34] For other parts of the island the evidence is more or less conflicting. The earthquake was followed, on the north coast at least, by a wave from the sea, but it caused comparatively little damage.

Location of the Origin.—The great destruction of property at Kingston has led most people to assume that the origin was in the vicinity of that city. Fuller concluded that the earthquake was "due to a displacement along an east-west fracture probably not over three miles in depth at a point three or four miles south of the city, the

[27] Brown, Charles W., "The Jamaica Earthquake," *Popular Science Monthly*, **70**, 385–403, 1907.

[28] Cornish, Vaughan, "The Jamaica Earthquake (1907)," *The Geographical Journal*, **31**, No. 3, pp. 245–276, 1908.

[29] Hall, Maxwell, "The Great Earthquake of January 14th, 1907; and the After-Shocks," Jamaica Weather Report, No. 337, 25 pp., 1907; and "Further Notes on the Great Earthquake, 1907, Jan. 14," Jamaica Weather Report, No. 365, pp. 20–23, 1909.

[30] Fuller, M. L., "Notes on the Jamaica Earthquake," *Journal of Geology*, **15**, 696–721, 1907.

[31] *Op. cit.*, pp. 701–702.

[32] Jamaica Weather Report, No. 337. p. 2.

[33] Davison, Charles, "The Kingston Earthquake," *Nature*, **75**, 296, 1907.

[34] Brown, C. W., *Op. cit.*, p. 394.

greatest movement being at a point about four or five miles southeast of the city of Kingston."[35]

Brown found the apparent intensity greatest in the eastern part of Kingston, but the presence of easterly-dipping cracks in the walls of buildings, he thought, pointed "to a locus of disturbance much to the west of that city."[36] He concluded "that the eastern end of the Liguanea plain was the nearest area to the real epicenter that by nature of material would give the greatest amplitude to the destructive epifocal waves." And because "the line of intensity of the earthquake destruction apparently extended to a greater distance northward than to the east or west," he inferred, "that the locus of the disturbance originated in a line of north-south faulting."[37]

Cornish, basing his conclusions partly on the supposed direction of motion during after-shocks, decided that there were two foci; one lying under the ocean, south of west from Kingston, and the other at a point in the interior slightly east of north from Kingston.[38]

Hall indicated three circular epicenters for this earthquake on the map accompanyng his report; the largest being located a few kilometers south of the Palisadoes near the east end of Kingston Bay, the second near the north coast between Enfield and Buff Bay, and the smallest southeast of Bull Head Mountain near the center of the island.[39] In a later paper, however, after describing the effects of the earthquake on the submarine cables south of Bull Bay, he states, that the area of highest intensity should be extended much further to the south, and that, instead of circular epicenters as previously indicated, there was a narrow band or line of greatest intensity which extended from Enfield, near the north coast, through Bull Bay to a point beyond the southern margin of the map, a distance of over forty miles.[40] In subsequent papers Hall attributes the earthquake to the "Historic Epicentre," situated about ten miles (sixteen kilometers) south of Bull Bay and the mouth of the Hope River, but he states that there are three other epicenters located along the narrow band of maximum intensity which extended nearly north and south.[41]

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[35] *Op. cit.*, p. 720.

[36] *Op. cit.*, p. 395.

[37] *Op. cit.*, pp. 395–396.

[38] *Op. cit.*, pp. 259–265.

[39] Jamaica Weather Report, No. 337, p. 11.

[40] Jamaica Weather Report, No. 365, p. 21.

[41] Hall, Maxwell, "The Historic Epicentre," Jamaica Weather Report, No. 422, p. 6, September, 1913.

Spencer suggested that the earthquake might be due to a gigantic submarine landslide originating near the head of the deep embayment a short distance southeast of Kingston.[42]

Davison thought the origin was close to Kingston and suggested that the earthquake was due to a subsidence on the south side of Jamaica accompanied by a slipping towards the Caribbean Sea.[43]

Each of the writers cited above has located the origin (or origins) of the earthquake in a different position, no two being in agreement. This is partly explained by the fact that they worked independently, and published their results within a few months after the catastrophe occurred, so that they did not have access to the data compiled by one another. The different investigations were largely limited to Kingston and vicinity and no one seems to have examined all parts of the island. The evidence published is supplementary rather than contradictory; and with the knowledge obtained from detailed investigations of other earthquakes in the Antilles it is possible to interpret most of the phenomena observed, and reconcile some of the discrepancies contained in the earlier papers.

A study of all the facts now available has led the present writer to the conclusion (1) that the earthquake was due to a sudden displacement along a fault located a few kilometers off the north coast of Jamaica in the vicinity of Buff Bay and Annotto Bay; and (2) that the displacement had an important vertical component. The evidence on which this conclusion is founded is discussed below.

1. For the Jamaica earthquake of 1907 the usual method of locating an epicenter, by mapping the distribution of intensity and drawing isoseismals, has not proved very satisfactory, because most of the region affected is under water, and on the island the apparent intensity was largely controlled by the character of the underlying rocks and soils, being much higher on the narrow coastal plains and in alluvium-filled valleys than on the rock and residual soil found over most of the island.

Brown states that "at Buff and Annotto Bays on the north shore, the destruction was but little less than at Kingston."[44] On his isoseismal map[45] the highest intensity shown is 9.5 in the eastern part

[42] Spencer, J. W., "The Jamaica Earthquake," *Science,* **25,** 966–967, 1917.

[43] Davison, Charles, *Op. cit.,* p. 296.

[44] *Op. cit.,* p. 396.

[45] *Op. cit.,* p. 386.

of Kingston, and the next highest is 8.5 at Buff Bay, while in the Blue Mountains between these towns the intensity is given as 5.

Hall assigns an intensity of VI, the maximum in the scale adopted by him, to Buff Bay, Enfield, Kingston, Port Royal and several intermediate points.[46] He quotes a witness to the effect that at Buff Bay, where there were many stone buildings, "Every stone and brick building is either a complete wreck or will have to be pulled down."[47]

Cornish states that "the damage at Buff Bay was severe" and he estimates "the force at Buff Bay as about equal to that at Constant Spring [ten kilometers north of Kingston], somewhat less than at Gordon Town [thirteen kilometers northeast of Kingston] and considerably less than in the eastern half of Kingston."[48]

According to these investigators, therefore, there was little or no difference in the apparent intensity at Kingston and at Buff Bay, Annotto Bay, Enfield and other points on or near the north coast; while in the mountains between Kingston and the north coast it was lower. The property loss was much greater at Kingston than elsewhere; but Kingston, with a population of 60,000, was the only large town on the island, and its houses were chiefly of brick, while in most of the other places frame buildings were the rule. The use of poor lime mortar in construction is believed to explain the collapse of many of the brick buildings in Kingston; the power station of the street railway company near the center of the city, which was built of brick and cement but without partitions or internal supports, was not thrown down, and other well constructed brick buildings likewise escaped.[49] Kingston is built on a gently sloping alluvial fan consisting of loosely consolidated gravel, sand and clay. Branner, who visited Kingston in the spring of 1907, states, "that it is a matter of common information that the serious damage done by that earthquake was confined to the low ground, apparently of incoherent materials, and near the water."[50] The greater destruction at Kingston than at points on the north coast must be attributed to the size of the town, the low resistance of the

[46] Hall, Maxwell, Jamaica Weather Report, No. 337, pp. 10–11, 1907.

[47] *Idem*, p. 5.

[48] Cornish, Vaughan, *Op. cit.*, p. 255.

[49] Nicholson, Sir Charles, "The Jamaica Earthquake (1907): Discussion of the paper by Vaughan Cornish," *Geographical Journal*, **31**, 272, 1908.

[50] Branner, J. C., "Impressions Regarding the Relations of Surface Geology to Intensity in the Mendoza, Valparaiso, Kingston, and San Francisco Earthquakes," *Bulletin of the Seismological Society of America*, **1**, 43, 1911.

brick buildings and the character of the ground on which the town is located, rather than to its closer proximity to the origin. The towns on the north coast are built chiefly on rock and residual soil, which explains why the destruction there was not greater.

The "sinking of the ground" at Port Royal and at other points along the shores of the bay seems to have been a repetition, though on a smaller scale, of the phenomenon which occurred in 1692; but this recent sinking, certainly, had no especial geologic significance, nor did it indicate extremely high intensity. Cornish estimated that "the damage to the town of Port Royal was about the same as that in the less damaged parts of Kingston."[51] Branner states: "The sinking of the ground at Port Royal was, in my opinion, similar to the slumping of banks in alluvial grounds along streams of which we had so many illustrations in California at the time of the San Francisco earthquake in 1906."[52] Fuller offered a similar explanation.[53]

There was no general depression of the land nor deepening of the harbor. Soundings made by Mr. Charlton Thompson, the harbor master, show a subsidence of over twenty-four feet in places along the east edge of the Palisadoes, but he states that "the soundings further from the shore and through the center line of the harbor are practically unaltered."[54] The tilting of buildings and twisting of rails, well shown in one of Brown's[55] illustrations, are indicative of the slumping of unconsolidated material rather than a depression of the land.

In passing east or west from either Kingston on the south coast or Buff Bay and Annotto Bay on the north coast, the intensity decreased. According to the map published by Cornish, the intensity at points on the north coast was in most cases a little higher than at points on the south coast having the same longitude, if Kingston and vicinity be excepted; and this is what we would expect if the origin was near the north coast. The shock was strongly felt toward the north at Santiago and Guatanamo in Cuba, and also in the southern peninsula of Haiti, but it does not seem to have been felt as far west as Grand Cayman.

The evidence now available concerning the distribution of in-

[51] Cornish, Vaughan, *Op. cit.*, p. 255.
[52] Branner, J. C., *Op. cit.*, p. 43.
[53] Fuller, M. L., *Op. cit.*, p. 711.
[54] Quoted by Maxwell Hall, Jamaica Weather Report, No. 337, p. 3, 1907.
[55] Brown, C. W., *Op. cit.*, fig. 16, p. 399.

tensity at the time of the earthquake, while not conclusive, is at least in accord with the theory that the earthquake originated near the north coast of Jamaica.

2. The direction of motion, during an earthquake caused by faulting, is of little value in locating the origin, because, near the fault at least, the principal transverse vibrations have their direction determined by the direction of the displacement along the fault. Moreover in the absence of suitable instruments, properly mounted, it is difficult to determine the principal direction of motion. Personal impressions are practically worthless; and the motion of framed structures, such as buildings, is to a large extent controlled by their framing. It is probable that the surface geology also has some effect. As previously noted, the direction of motion, as determined by observers during the earthquake of January 14th, varied within short distances.

The arguments advanced by Cornish and by Hall for two or more foci are based chiefly on the direction of motion at different places during the earthquake of January 14th, and also at the time of the after-shocks. They made use of the pendulum records of after-shocks obtained by Mr. J. F. Brennan[56] in Kingston. Most of these records show a maximum motion in one or the other of two directions that are approximately at right angles, a fact which suggests that the framing of the building and its orientation may have influenced the movement of the pendulum. No evidence has been found by the present writer that would warrant the assumption that the Jamaica earthquake had more than one epicentral area; and certainly, until more is known concerning the character of earthquake motion in megaseismic areas, other methods than the direction of motion should be used in locating the origin.

3. In the region of high intensity the earthquake was accompanied by a loud roaring sound. Such sounds are usually attributed to earth tremors of small amplitude and short period which radiate, as do the larger vibrations, outward from the origin in all directions. In the regions of lower intensity the sounds heard were due chiefly to the movement of buildings and other structures. Hall, who located the principal epicenter a short distance southeast of Kingston, states, "that the sound at any place seems to come from a direction more or less opposite to the epicentre. Thus in January 14th, 1907, the sound at

[56] The after-shocks recorded by Mr. Brennan are listed by Cornish, *Op. cit.*, pp. 259–260; and by Hall, Jamaica Weather Report, No. 337, pp. 22–23.

Blue Mountain Valley was from the NE; at Annotto Bay the same: at Cinnamon Hill from the N: and at Kempshot from NW, and at Kingston the after-shocks that night were from the NW and at Buff Bay on the 15th from the sea, or N. Again, on January 2nd, 1908, we have the sound at Cinnamon Hill and Kings Valley from the NW, and at Chapelton from the E."[57] The observations quoted by Hall are in accord and indicate that the origin was north of the island rather than south of it; but it is so difficult, without instruments, to determine the direction from which the sounds come that this method of locating the epicenter is not dependable.

4. Brown located the origin to the west of Kingston on the assumption that the "cracks in buildings, which at Kingston dip some 50 degrees east, are always perpendicular to the path of the emergence of earthquake waves."[58] The "angle of emergence," as indicated by cracks in buildings, was first used by Mallet[59] in determining the depth of the focus, but Milne[60] and others have pointed out the objections to this method and it is no longer in use.

5. The rupturing of the submarine cables at points to the south and southeast of Bull Bay led Fuller[61] and Hall[62] to regard this as the region of greatest disturbance.

The cable of the Direct West India Cable Company was damaged for a distance of about fifteen miles south and east of Bull Bay. Hall quotes Mr. Sullivan, superintendent of the company, as stating that it was "pulled, crushed, torn and twisted; in some places the cable was deeply buried and could hardly be lifted; but some sections, nearly a mile long, were, however, in as good condition as when laid."[63]

With reference to the cable of the West India and Panama Telegraph Company, Hall quotes Captain Morrell of the cable ship "Henry Holmes," who "wrote that the first break on the Jamaica-to-Colon cable occurred 4 miles or so south of Bull Bay; and that on testing again, another break was found 20 or 25 miles south of Bull Bay. On attempting to raise the cable south of the first break, it was

[57] Hall, Maxwell, Jamaica Weather Report, No. 365, p. 23.

[58] Brown, C. W., *Op. cit.*, p. 395.

[59] Mallet, Robert, "The Neapolitan Earthquake," Reports to the British Association, **1**, 10–95, 1862.

[60] Milne, John, "Seismology," p. 195, London, 1898.

[61] Fuller, M. L., *Op. cit.*, p. 712.

[62] Hall, Maxwell, Jamaica Weather Report, No. 365, p. 21.

[63] Hall, Maxwell, Jamaica Weather Report, No. 365, p. 20.

found deeply buried in mud and parted at a strain of five tons. Proceeding to the place of the second break, the two ends of the cable were found fully one mile apart, the cable having been dragged from west to east.

"Captain Morrell wrote:—'There is no doubt, that these two ends coincide, as they fitted together exactly. The cable at the position of the break was excellent, and it was evidently broken by a tremendous strain as the wires at the break were broken clean, and there were no signs of erosion at all. I am certain by the lay of the cable, and the distance the ends were apart from one another, there must have been a landslide from the direction of the shallow water to deeper water. Further south of this great break the cable was again deeply buried and had to be abandoned."[64]

Hall concluded that the shifting of the cable and the separation of the ruptured ends "could only have been produced by a great chasm opening in the bed of the sea to the east of the great break."[65] With this conclusion the present writer can not agree. In view of the steep slopes in the vicinity of the ruptured cables (south and east of California Bank the gradient is 1 in 2 or 1 in 3 and in places steeper), the burying of parts of the cable and the appearance of the injured portions, it seems certain that the damage, as explained by Captain Morrell, resulted from landslides. The relatively small displacements that occur along faults at any one time would seldom if ever be sufficient to break a cable resting on the bottom of the ocean. A horizontal displacement would be more likely to rupture cables than a vertical displacement, but the cable of the Commercial Pacific Cable Company terminating at San Francisco was not ruptured by the horizontal displacement which caused the California earthquake of 1906.[66] Moreover the absence of a great sea wave radiating from this area proves that there was no important vertical displacement of the sea bottom.

6. The large sea waves that sometimes accompany earthquakes are caused by a sudden vertical displacement of the sea bottom; they are absent when the origin is entirely on land or where the displacement is horizontal, as in the California earthquake of 1906, or where

[64] Hall, Maxwell, Jamaica Weather Report, No. 365, p. 20.

[65] *Op. cit.*, p. 21.

[66] Written communication from Mr. Geo. Clapperton, Traffic Manager of the Commercial Pacific Cable Company.

it does not reach the surface. Waves on the surface of the ocean travel slowly as compared with earthquake vibrations, and therefore the time interval between the arrival of the earthquake shock and the arrival of the sea wave increases rapidly with the distance from the origin. Perhaps the strongest evidence that the origin of the earthquake of January 14th was off the north coast of Jamaica is furnished by the fact that a large sea wave came in along this coast soon after the earthquake, while along the south coast this wave, if it reached that far, was so small that it does not seem to have been noticed.

Cornish states that the wave was observed at Port Antonio, Hope Bay, Orange Bay, Buff Bay, Annotto Bay, Sheerness Bay, Port Maria, Ocho Rios and St. Ann's Bay, all of which are on the north coast. At all of these places the water first withdrew from the shore and then returned in waves.[67]

Hall quotes an observer at Annotto Bay who states: "Immediately after the shock the sea receded about 80 to 100 yards, going down below its usual level from 10 to 12 feet, and then the wave which was of thick mud came back 6 to 8 feet higher than the usual level of the sea, and then again receded slightly. The wave passed over the lower portion of Annotto May, lifting small houses into the streets; but on the higher land it came up 25 to 30 feet. The former level of the sea has not been changed in any way that is discernible."[68] Mr. C. H. Roe, another observer quoted by Hall, states that at Annotto Bay "The sea receded about 200 ft., falling 20 ft. below its usual level; and came back about the same distance on land, rising 20 ft. above its usual level. The recession occurred fully 3 minutes after the shock: and the sea came back with a rush."[69] According to another observer at this place "the sea dislodged from their pillars about six small houses near the sea front, and moved them further inland."[70] At Buff Bay "the sea withdrew some distance from the land."[71]

With reference to the wave at Port Maria, Hall quotes Mr. Ernest H. Kerr: "I did not have the opportunity of seeing the action of the sea myself but my wharfinger told me next day that the first thing they noticed before the earthquake was that the sea had receded a con-

[67] Cornish, Vaughan, *Op. cit.*, p. 256.

[68] Hall, Maxwell, Jamaica Weather Report, No. 337, p. 6.

[69] *Idem*, p. 6.

[70] Hall, Maxwell, *Idem*, p. 6.

[71] *Idem*, p. 5.

siderable way out. They showed me the place on my pier to which it receded, at least 84 feet from the usual tide mark. This, according to the wharfinger, happened 3 or 4 minutes before the shock; . . . According to his idea, the sea took a good quarter of an hour to return to its normal limit."[72]

Mr. Roe estimated that the sea fell twenty feet. The statement that the sea receded before the earthquake was felt must be erroneous, for it is contradictory to the evidence from all neighboring points, and there is no conceivable way by which the sea wave could have reached the coast before the earthquake. If the origin was close to the shore the water may have receded soon after the earthquake began and while the vibrations still continued.

"Ocho Rios, near St. Anne's Bay, on the north shore," according to Brown, "also had its harbor emptied for about seventy-five yards, after which a small incoming wave was followed by gradually lessening oscillations."[73]

At Port Antonio the wave, according to Cornish,[74] was quite small, but Fuller[75] states that it was sufficient to move small buildings situated near the beach.

Mr. Henry Hunt is authority for the statement, quoted by several writers, that there was a wave on the south coast of Jamaica. At the time of the earthquake he was sailing his sloop about two miles southeast of Port Royal. Hall quotes him as stating that "the wind was changeable, sky cloudy, and general appearance of atmosphere such as to cause some anxiety. He and his boat's crew saw to the S. coming in a direction of S.S.W., a sort of half misty cloud over the surface of the water, resembling steam issuing in spray, or a sort of boiling appearance; they felt the boat rock and toss soon after as if she were bumping on the ground. In a few seconds they saw a huge wave strike Gun Cay and completely cover it from view, and almost simultaneously the Point was struck by the wave and obscured from view; a few seconds later a huge cloud of dust was seen to rise from the town, and a black cloud from the coal wharf, as when a shell ricochets over the water; and he and his boat's crew observed the same phenomenon when it struck Kingston."[76]

[72] *Idem*, p. 6.

[73] Brown, C. W., *Op. cit.*, pp. 401–402.

[74] Cornish, Vaughan, *Op. cit.*, p. 256.

[75] Fuller, M. L., *Op. cit.*, p. 719.

[76] Hall, Maxwell, Jamaica Weather Report, No. 337, p. 4.

The statement by Mr. Hunt does not prove that there was a true seismic sea wave on the south coast. He and his crew felt the normal vibrations of the earthquake, which are propagated through water as well as solids; and the disturbance that they saw on the water was possibly due to these vibrations, for the large seismic sea waves are not noticeable at sea. Moreover, the south coast of Jamaica near Port Royal is bordered by a shelf from eight to eleven kilometers broad, and submerged to a depth of only sixteen to eighteen fathoms (twenty-nine to thirty-three meters); so that it would take a wave, originating in the area where the cables were ruptured, about ten minutes to cross this shelf, while the earthquake vibrations would travel the distance in two or three seconds. The "sinking of the ground," or slumping of sand along the shore in the vicinity of Port Royal, would cause a small wave which might be observed during or immediately after the earthquake, but not before. If any seismic sea waves reached shore in the vicinity of Port Royal they were small, for the sand spit on which the town stands is barely above sea level and a large wave would have swept completely over it causing much damage. No such wave was reported by the people at Port Royal. The phenomena described by Mr. Hunt may have been partly meteorological in origin.

The small waves observed in Kingston harbor during the earthquake or immediately afterwards may have been seiches started by the shaking of the land, but it is more probable that they were caused by the slumping of alluvium around the shores of the bay, and especially along the Palisadoes, into deeper water. The harbor has a narrow entrance which is well protected from the sea, so these waves must have originated within. At the eastern end of the harbor, near Rock Fort, "the sea retreated for a hundred feet and then advanced inward upon the shore about sixty feet in a low wave a couple of feet high."[77] Fuller states that these waves though small were "powerful enough to throw one vessel up into the mud alongside the dock, while another, the Royal Mail Steamer 'Arno,' barely escaped wrecking by being thrown against the wharf."[78]

7. The earthquake was recorded on the seismograph of the U. S. Weather Bureau in Washington, which is only fifteen minutes west of

[77] Brown, C. W., *Op. cit.*, p. 401.

[78] Fuller, M. L., *Op. cit.*, p. 719.

the meridian of Kingston. Marvin[79] published a short note on this record in which he represents the preliminary tremors as beginning at $3^h\ 38^m\ 23^s$ p.m. 60th meridian standard time, on the north-south component, with nothing at this time on the east-west component, although they both had the same proper periods (20^s) and the static magnifying powers are 25 for the north-south component and 20 for the east-west component.

Reid,[80] after examining photographic copies of the Washington seismograms reached a different conclusion. He writes as follows: "I believe the first movement recorded on the north-south component at $3^h\ 38^m\ 23^s$ is not a record of this earthquake. It shows a slight earth inclination towards the north with little jars not resolvable into vibrations; it only lasts one minute, after which this component shows nothing until $3^h\ 42^m\ 50^s$. Up to this time the east-west component shows absolutely nothing. At $3^h\ 42^m\ 50^s$ both components begin distinct vibrations; the north-south component being stronger until $3^h\ 46^m\ 38^s$, when the east-west component becomes stronger and shows amplitudes two or three times as large as the north-south component.

"If we follow Marvin's interpretation of the record and take P at $3^h\ 38^m\ 23^s$ and S at $3^h\ 42^m\ 50^s$, then S-P becomes $4^m\ 27^s$, which corresponds to a distance of 25.2° from Washington (latitude 38.9°N.) and places the origin in latitude 13.7°N., or some three hundred miles south of Kingston. But this is an impossible epicenter.

"If, however, we consider that P begins at $3^h\ 42^m\ 50^s$ and S at $3^h\ 46^m\ 38^s$, we get S-P = $3^m\ 48^s$, corresponding to a distance of 20.7°; which would place the origin in latitude 18.2° N."

Reid's interpretation of the Washington seismograms, therefore, places the origin on a parallel running about three kilometers south of Buff Bay. Other evidence indicates that the origin was under the ocean and possibly ten or twenty kilometers north of Buff Bay. This is as close a check as could be expected when we consider that only one seismographic record was used and that an error of one second in the recorded time of arrival of the vibrations would correspond to a difference of about ten kilometers in the distance of the origin.

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[79] Marvin, C. F., "The Kingston Earthquake," *Monthly Weather Review*, **35**, 5–6, January, 1907.

[80] Personal communication from Professor Harry Fielding Reid, dated February 24, 1920. The writer is also indebted to Professor Reid for criticism and suggestions in the preparation of this paper.

8. Accurate time was practically unknown on the island and therefore the time at which the shock was felt at different points can not be used in locating the origin. The local time observations can be used however as a rough check on the interpretation of the Washington seismograms.

Hall cites three determinations of the time of the earthquake:

"*Mr. J. A. Soulette, Kingston.*—Mr. Soulette had a large pendulum clock which he used as a regulator in his business as watchmaker; and in October 1906 he took the error and rate by means of a sextant and artificial horizon. He made the time to be 3 hours 33 minutes.

"*Mr. Maxwell Hall, Chapelton.*—Mrs. Hall happened to look at her watch just as the tremors commenced before the great undulations. The watch was subsequently compared with a mean-time chronometer, and the chronometer was taken to the Kempshot Observatory, and its error taken in the usual manner. The time thus deduced was 3 hours 29½ minutes.

"*Mr. J. S. Brownhill, Negril Point Light-house.*—Mr. Brownhill has a mean-time chronometer and a sextant, and he obtains time by altitudes of the sun above the sea-horizon. He made the time to be 3 hours 32 minutes.

"By adding 5 hours 7 minutes we get the Greenwich mean time of the shock for each place."[81]

Assuming that the origin was twenty kilometers north of Buff Bay and that the velocity of propagation was 7.2 kilometers per second, then the time of the beginning of the shock at the origin, as determined by the Kingston observation, was $3^h\ 32^m\ 53^s$; by the Chapelton observation $3^h\ 29^m\ 19^s$, and by the Point Negril Light-house observation $3^h\ 31^m\ 33^s$. These determinations of the time do not agree very closely. Their mean, however, is $3^h\ 31^m\ 15^s$ Kingston mean time, or $3^h\ 38^m\ 15^s$ 60th meridian standard time.

The time as determined from the Washington seismograms by Reid is as follows:

"Taking the *P* at $3^h\ 42^m\ 50^s$ and the distance at 20.7° [origin about three kilometers south of Buff Bay] we find for the time at the origin (according to the B. A. or Zoppritz tables) $3^h\ 38^m\ 0^s$; or by transmission curve of the Porto Rico earthquake of October 11, 1918, $3^h\ 38^m\ 14^s$."

If the origin is assumed to be twenty kilometers north of Buff

[81] Hall, Maxwell, Jamaica Weather Report, No. 337, p. 2.

Bay, making the distance 20.5°, the time would be about three seconds later, or $3^h\ 38^m\ 11^s$, while the time would have to be about 4.5 minutes earlier on the assumption that the Washington record begins at $3^h\ 38^m\ 23^s$. The best estimates of time made in Jamaica, therefore, agree quite closely with the time as calculated from the Washington record by Reid; and $3^h\ 38^m\ 11^s$ is probably as accurate an estimate of the time the earthquake began as can be obtained. This time is also in accord with the time calculated by Reid from the records at several other stations which are listed below.

Tacubaya	$3^h\ 37^m\ 28^s$
Ponta Delgada	$3^h\ 38^m\ 12^s$
Hamburg	$3^h\ 38^m\ 22^s$
Göttingen	$3^h\ 38^m\ 11^s$
Jena	$3^h\ 38^m\ 01^s$

9. Great earthquakes are followed by many after-shocks, most of which originate in the same epicentral area as the initial disturbance, and therefore they may be used in determining its location. The earthquake of January 14, 1907, was followed by a large number of after-shocks. Hall has published a list of those that were recorded.[82] According to this list the majority of the shocks were felt at Kingston while comparatively few were reported from most of the smaller towns. In most cases only one or two towns are listed as having felt the shocks although they must have been felt over a considerable area. This merely shows the greater activity at Kingston in rcording the after-shocks.

Both Cornish and Hall attempted to locate the origin or origins of the after-shocks by using the direction of the principal horizontal motion as indicated by the pendulum records obtained by Mr. Brennan in Kingston. They reached somewhat different conclusions, for one assumed that the principal motion was caused by normal vibrations while the other attributed it to transverse vibrations. As previously explained (p. 74) this method is open to serious objections and therefore is of doubtful value.

Unfortunately no systematic effort seems to have been made to determine the relative intensity of the shocks at the different places where they were felt. The facts that have been recorded, however, indicate that at least some of the after-shocks probably originated near the north coast of the island. Thus Cornish states that: "The after-

[82] Hall, Maxwell, Jamaica Weather Report, No. 337, pp. 16–18 and 22–23.

shock of March 23 was felt more severely at Buff Bay than at Kingston. Several of the early after-shocks . . . were felt as strongly at other places as at Kingston, e. g., the shock of Tuesday, the 15 about mid-day, which brought down a cracked wall at Port Antonio. . . ."[83]

An examination of all the methods used by previous investigators in attempting to locate the epicenter, and of several methods not hitherto used in connection with this particular earthquake, has developed no evidence which would prove that the earthquake had more than a single epicenter. All the established facts are in accord with the hypothesis that the origin was off the north coast of the island, and nothing has been adduced that would indicate a probable origin elsewhere. The earthquake was evidently tectonic in origin and due to a sudden displacement along a fault. The up-and-down vibrations during the early part of the earthquake, reported by several observers, would indicate that the displacement at the origin had an important vertical component, and this is confirmed by the great sea wave which immediately followed the earth vibrations along the eastern part of the north coast.

THE EARTHQUAKES OF AUGUST 3 AND OCTOBER 14, 1914.

On August 3, 1914, at about 6:25 a.m., Kingston mean time, an earthquake was felt all over Jamaica, the intensity being highest near the eastern end of the island. Hall states that "the maximum disturbance was on the Blue Mountain range and not far from the Peak. The shock on or near the Blue Mountain range was sufficient to crack massive mason-work walls and to produce landslides, the largest being probably near the source of the Wild Cane River; and in the town of Morant Bay and the villages of Fellowship and Yallahs great damage was done to the churches and other buildings of mason-work. In Kingston . . . the walls of many houses were cracked, and old walls were thrown down; but the new buildings of reinforced concrete are said to have stood the shock very well."[84]

Hall thinks that six different epicenters, located at various points between the Blue Mountains in the east and North Negril Point at the west end of the island, were all active at the time of this earthquake. This opinion is based on his periodicity theory and the direction of motion at different points. The distribution of intensity, how-

[83] Cornish, Vaughan, *Op. cit.*, p. 265.

[84] Hall, Maxwell, "The Earthquake of August 3rd, 1914, 6:25 a. m.," Jamaica Weather Report, No. 433, p. 7, August, 1914.

ever, indicates a single origin somewhere near the eastern end of the island. No sea wave was reported and no evidence has been recorded that would definitely indicate a submarine origin.

Another strong shock occurred on October 14th, at 2:18 a.m., but no damage seems to have resulted. The distribution of intensity suggests that the origin was near the eastern end of the island and possibly in the same place as the origin of the earthquake of August 3d. Hall, however, thinks that three different epicenters were active.[85]

THE GEOLOGY AND PHYSIOGRAPHY OF JAMAICA AND THE BARTLETT TROUGH

Jamaica is the exposed portion of a broad submarine ridge or plateau which extends in a northeasterly direction from the Central American coast near Cape Gracias á Dios toward Haiti. Between Jamaica and the mainland there is an almost continuous series of banks and shoals. (See Plate IV.)

The topography of the island is extremely rugged. The Blue Mountains in the eastern part of the island attain a height of 2243 meters (7,360 feet) above sea level and trend about N. 70° W. parallel to the northeast coast. The Clarendon Mountains, near the center of the island, and the Jerusalem Mountain, a little to the southeast, are lower, but, according to Hill, they have the same general trend. Hill, who has made a detailed study of the geology and physiography of Jamaica, states that these ridges are composed for the most part of intensely folded conglomerates, tuffs and limestones of Cretaceous age together with some igneous intrusives. The mountains are surrounded by a dissected plateau 300 to 600 meters (1000 to 2000 feet) in height, consisting of Tertiary limestones which lie uncomformably on the older rocks and have not been greatly disturbed. The underlying Cretaceous rocks are exposed at many places in the large central valleys where the plateau limestone has been removed by erosion.[86]

The north coast of Jamaica between Montego and Port Maria is an almost straight east-west line for a distance of nearly 113 kilometers (70 miles), the land rising abruptly to the edge of the plateau, which here has a height of 300 to 400 meters (1000 to 1300 feet).

[85] Hall, Maxwell, "The Earthquakes of October 14th, 1914," Jamaica Weather Report, No. 435, pp. 5–6, October, 1914.

[86] Hill, R. T., "The Geology and Physical Geography of Jamaica: Study of a Type of Antillean Development," *Bulletin of the Museum of Comparative Zoology*, Harvard College, **34**, Geological Series, **4**, 256 pp. Cambridge, 1899.

On Hill's topographic map the 1000-foot contour is in places less than one half mile from the sea and the average distance is between two and three miles. The streams that drain northward are short and flow in rather narrow valleys, the divide being nearer the north coast in spite of the fact that there is heavier rainfall on that side of the island.

From Montego Bay westward as far as Pedro Point, thirty-one kilometers, the coast is likewise straight, and parallel to the coast between Montego and Port Maria, but it is offset about eight kilometers (five miles) to the south. The east-west line between Pedro Point and Montego Bay if continued eastward follows up the valley of the Montego River, which runs nearly parallel to the coast for about sixteen kilometers (ten miles). Hill states that Cretaceous rocks are exposed in the bluffs along the western half of the north coast below the plateau limestone and above the narrow coastal benches.[87] A narrow strip of Pleistocene or Recent alluvium is usually found along the north coast, but in places even this is absent. The steep slopes continue below sea level, and depths of 1000 to 2251 fathoms (1829 to 4117 meters) are attained within less than fifteen kilometers (ten miles) of the shore. The 100-fathom contour is, in most places, less than 1.6 kilometers (one mile) from the coast.

The south coast is irregular in outline, there are large areas of Pliocene, Pleistocene and Recent alluvium on this side of the island, and the water off shore is relatively shallow, the 100-fathom line being in places over twenty-seven kilometers (seventeen miles) from the shore.

Hill found no evidence of volcanic activity in Jamaica, or elsewhere in the Greater Antilles, subsequent to the great eruptive activity of Cretaceous time.[88] The earthquakes of this region, therefore, are not of volcanic origin. Sawkins[89] has figured several faults in his sections illustrating the geological structure of the parishes of Jamaica, and Brown[90] refers to some transverse faults, but Hill does not mention this subject. New displacements have not been observed along any of the faults in Jamaica after earthquakes and there is no reason for believing that any of them are now active.

[87] Hill, R. T., *Op. cit.*, p. 21.
[88] *Op. cit.*, p. 192.
[89] Sawkins, J. G., "Reports on the Geology of Jamaica," London, 1869.
[90] Brown, C. W., *Op. cit.*, p. 389.

Between Jamaica and Cuba lies the great Bartlett Trough, which is one of the most striking physiographic features of the Antillean region. It is a long narrow trench extending from the Gulf of Honduras eastward as far as Gonaive Gulf between the two western peninsulas of Haiti, a distance of fifteen degrees or 1570 kilometers. It has a depth of over 3000 fathoms (5486 meters) at several places between Jamaica and Cuba; the deepest sounding being 3506 fathoms (6412 meters). The width of the trough, near the Cayman Islands where it is widest, is about 1.5 degrees (160 kilometers).

The origin of this great depression has not been generally understood in the past. Spencer[91] attributed its formation to stream erosion when the region stood above sea level. This view was opposed by Hill, who states that the elevation of the region after the Bowden (Lower Miocene) subsidence "was not sufficient to establish a united Antillean continent with great rivers which have since been submerged as alleged by J. W. Spencer."[92] Hill thinks that the folding which occurred in Mid-Tertiary time and resulted in the development of the east-west ridges found near the Caribbean coasts of South America and Central America "may have been instrumental in producing the wonderful Bartlett Trough and its related depths adjacent to Cuba and Haiti."[93] M. de Ballore, who also postulates folding as an explanation of Antillean topography, locates an anticlinal axis along the line of Cuba, Haiti and Porto Rico, and a parallel syncline in the Bartlett Trough between Cuba and Jamaica.[94]

Vaughan thinks that the West Indian Islands were formed in late Tertiary, probably Pliocene time, by block faulting. He states: "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 Windward Passage. A downthrow block between these lines has separated Cuba and Haiti and produced the Bartlett Deep."[95]

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[91] Spencer, J. W., "Reconstruction of the Antillean Continent," *Bulletin of the Geological Society of America,* **6,** 103–140, 1895.

[92] Hill, R. T., *Op. cit.,* p. 216.

[93] *Op. cit.,* p. 212.

[94] Ballore, F. de Montessus de, "Tremblements de Terre," fig. 63, p. 374. Paris, 1906.

[95] Vaughan, T. W., "Geological History of Central America and the West Indies during Cenozoic Time," *Bulletin of the Geological Society of America,* **29,** 625–626, 1918.

In the opinion of the present writer the Bartlett Trough is to be regarded as a great rift valley—one of the greatest now known—and the precipitous sides of the trough as fault scarps. The evidence on which this hypothesis is based is outlined below.[96]

The great depth of the trench indicates a diastrophic origin, and the slopes into it are so precipitous at most places that they can not be explained otherwise than as fault scarps. The deeper portion of the trough is over 8,275 meters below the higher peaks of the Sierra Maestra in southern Cuba and of the Blue Mountains in Jamaica. The six deepest places located by soundings (all over 3000 fathoms or 5486 meters) are situated close to the foot of the inclosing scarps rather than near the center of the trench. The marginal scarps run in straight lines, or rather in flat arcs, for long distances; and there are usually abrupt changes in slope both at the top and at the bottom of the escarpments.

The floor of the trough is relatively flat over quite large areas, and, instead of being graded like a river valley, it rises and falls throughout its length.

The rectilinear north coast of Jamaica and the steep slopes both above and below sea level suggest that this shore line has been determined by faulting; but in addition the Tertiary beds are cut off abruptly along the north coast, and in places the uplift has exposed the older underlying rocks. Wave erosion could not have produced these results 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 occurrence of several great earthquakes in modern times with their origins located a short distance off the north coast of Jamaica indicates there is here a zone of instability along which adjustments are still going on.

The precipitous escarpment on the opposite side of the trough rises two thousand meters above the sea to form the southern front of the Sierra Maestra. Vaughan states that in the vicinity of the Morro at the entrance to Santiago Harbor the Miocene La Cruz marl is abruptly cut off at the shore line, thus proving that the faulting is subsequent to old or middle Miocene.[97] This southern coast of Cuba

[96] The physiographic evidence has been obtained chiefly from the maps of this region published by the Hydrographic Office of the United States Navy, particularly Charts Nos. 347, 373, 394, 948, and 1290.

[97] Vaughan, T. W., *Op. cit.*, p. 626.

coincides with a zone of high seismic activity—a fact that is all the more noticeable since the northern and central portions of Cuba have been relatively free from earthquakes during the last four centuries.[98] The great earthquakes that have occurred along this coast seem to be similar in their characteristics to those that have originated off the coast of Jamaica.

The minor details in the topography of the trough, in so far as they are revealed by soundings, the offset in the north coast of Jamaica at Montego Bay, and other evidence relating to the distribution of faulting in Haiti, all indicate that the depression was not formed by the subsidence of a single block between two marginal faults, but rather that there has been unequal subsidence of long narrow blocks formed by a series of nearly parallel faults, which in places branch and come together again. Swan Island, north of Honduras, and other similar elevations near the coast of Cuba which do not reach above sea level apparently represent horsts that have remained standing within the zone of subsidence; while some of the deeper portions of the trough are found where similar blocks have sunk lower than their neighbors.

Near the eastern end of the Bartlett Trough, as it rises toward the island of Haiti, it seemingly splits into several subordinate troughs, two of which continue across that island as marked physiographic and geologic features; and along these fault valleys the seismic activity is likewise high. The great rift valley between Jamaica and Cuba is not the only feature of this kind to be found in the Antillean region; it forms part of a long belt of trough faulting that extends from the vicinity of the Virgin Islands westward into the Gulf of Honduras and possibly farther, a distance of at least twenty-five degrees of longitude (about 2500 kilometers). Throughout the length of this belt earthquakes are of frequent occurrence, and nearly all of them are to be attributed to displacements along faults that are closely related to the great troughs of the region.

SUMMARY AND CONCLUSIONS

1. Many earthquakes have been felt in Jamaica during the last four centuries; most of them having been of relatively low intensity. It is today impossible to locate, even approximately, the origins of the

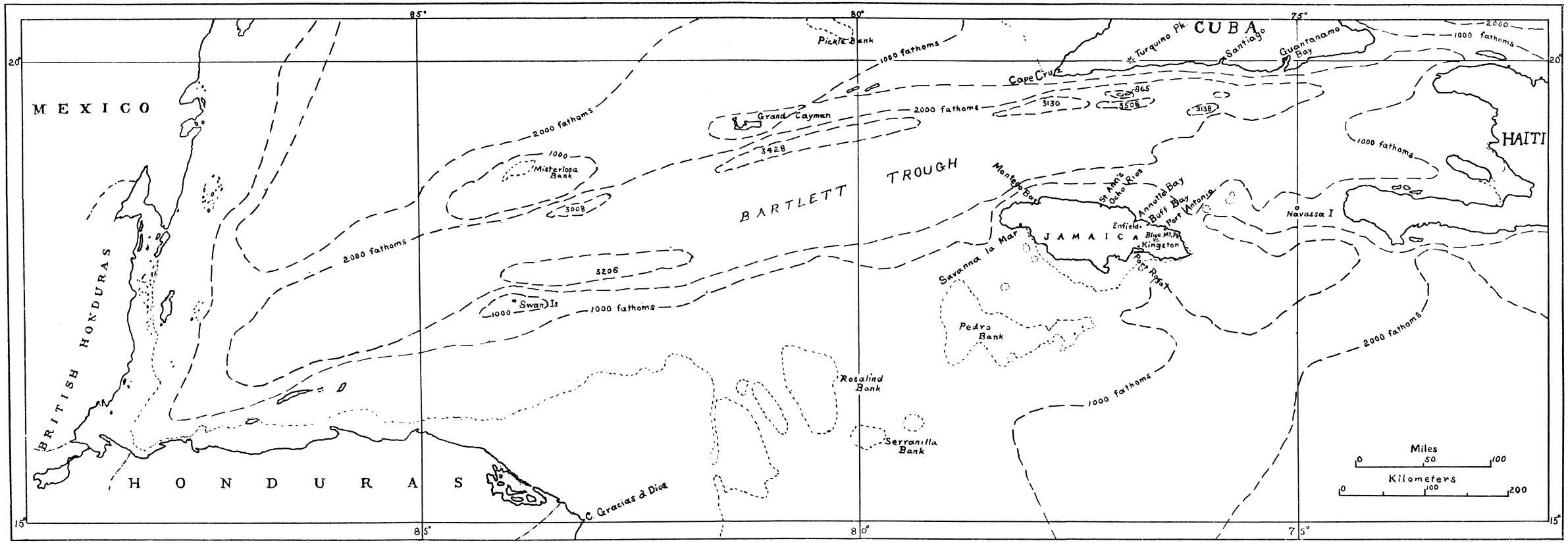
[98] Salterain, P., "Ligera Reseña de los Temblores de Tierra Ocurridos en la Isla de Cuba," *Boletín de la Comisión del Mapa Geológico de España,* **10,** 371–385, Madrid, 1883.

minor shocks, but the two greatest earthquakes, and probably other destructive shocks, have originated off the north coast of Jamaica. In view of the fact that during this period no great earthquakes have originated elsewhere in the immediate vicinity of the island it is highly probable that a large proportion of the minor shocks have also had their origins near the north coast.

2. The vertical vibrations reported by observers and the accompanying sea waves indicate that each of the great earthquakes has been caused by a sudden vertical displacement. The sea wave which destroyed Savanna la Mar in 1780 and some of the other unusual waves noticed along the Jamaican coast have possibly been caused by vertical displacements along the faults forming the steep escarpments to the west and northwest of the island.

3. The geologic and physiographic evidence supports the theory that Cuba and Jamaica are separated by a great rift valley cutting directly across the earlier tectonic lines of the region, which run northwest-southeast and northeast-southwest. The steep north coast of Jamaica is determined by a fault scarp most of which is below sea level, the exposed portion being more or less dissected and cut back by erosion.

4. The formation of the fault trough, as suggested by Vaughan, may date from the Pliocene, but equilibrium has not yet been attained and the displacements which have formed the trough are still continuing.



MAP OF JAMAICA AND THE BARTLETT TROUGH.

Contour interval 1,000 fathoms (6,000 feet). Areas within the dotted lines less than 100 fathoms.