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THE SEISMIC BELT IN THE GREATER ANTILLES

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Introduction

Between North and South America is a region within which the principal geographic features are elongated in an east-west direction, transverse to the trend of the great cordilleras of both continents. It comprises the Caribbean Sea with portions of the land areas immediately adjacent on the north, south and west. It is a region of very high relief, and near the margins of the Caribbean Basin the slopes, especially where submerged, are extremely precipitous. Earthquakes are common. These features, characteristic of the marginal areas as a whole, are most strikingly developed in a belt extending through the Greater Antilles and marking the northern perimeter of the Caribbean Basin. The present paper is a study of seismic activity in this belt.

The seismic records of the Antilles cover a longer period of time than those of any other portion of the western hemisphere, and the high earthquake frequency is apparent from even a casual study. The earthquake catalogues, prepared for the individual islands or for the entire region, are far from complete, though it is improbable that many earthquakes having an intensity of X (Rossi-Forel scale) and occurring within the last four centuries have been overlooked. Many weak shocks are not recorded even today, and, in the catalogues, the ratio of weak shocks to strong shocks tends to increase with the settlement of the islands and the improvement of facilities for communication.

The earliest earthquake mentioned in histories of the Greater Antilles is said to have occurred in 1502. Herrera states that the City of Santo Domingo, founded by Bartholomew Columbus in 1496 on the east side of the Ozama River, was thrown down by an earthquake in 1502, and was then moved by Nicolàs Ovando to the present site on the west side of the river.[1]

[1] "Nicolàs de Ovando, siendo Governador de la Española Año de 1502 la mudò adonde aora està, de la otra parte del Rio al Levante, con ocasion de que la Ciudad se caiò por un gran Terremoto."—"Descripcion de las Indias Ocidentales," by Antonio de Herrera. Chap. VI, p. 6. Madrid, 1730.

Charlevoix attributes the destruction of Santo Domingo in 1502 to the hurricane which occurred in the latter part of June and resulted in the sinking of several vessels belonging to the Spanish fleet.[2] Elsewhere, however, in describing the site of the city he refers to the frequent occurrence of earthquakes near the mouth of the Ozama River.[3] Earthquakes and hurricanes, the two great scourges of the West Indies, are frequently confused by the inhabitants even to this day.

The earthquake catalogues of Alexis Perrey and A. Poey begin with the year 1530. According to Scherer, the first destructive earthquake recorded for the island of Haiti occurred in 1564, but severe shocks had probably been experienced previously by the Spaniards, for, in the construction of buildings at Concepcion de la Vega, destroyed in 1564, an effort seems to have been made to ward against such a catastrophe by embedding iron bars in the brick-work.[4]

Imperfect as they are, the records prove that for the four and a quarter centuries since the region became known to Europeans the seismicity has been high; prior to that time history is a blank, but geologic and physiographic evidence indicate that the high seismicity probably extends back through a very long period.

Previous investigators have made little attempt to correlate Antillean earthquakes with the local geology. In making a detailed study, however, some knowledge of the physiography and tectonic geology is essential.

Physiography and Geology

The Greater Antilles and Virgin Islands are frequently described as a partly submerged mountain system which extends westward through the Virgin Islands and Porto Rico into the island of Haiti where it splits into two branches, one extending through Jamaica toward Central America and the other through southern Cuba, the Cayman Islands and Misteriosa Bank. But the topography of the region is much more complex than this description would indicate. While as yet little detailed field work has been done, the principal topographic features may be readily recognized.

[2] Charlevoix, P. Pierre-François-Xavier de, "Historie de L'Isle Espagnole ou de S. Domingue," **1**, 217. Paris, 1730.

[3] *Op. cit.*, **1**, 225.

[4] Scherer, Rev. J., "Great Earthquakes in the Island of Haiti," *Bulletin Seismological Society of America*, **2**, 163, 1912.

The major relief features are the great trough-like depressions which form the lower flanks of the principal mountain ranges. The dominant tectonic trend is approximately east and west along arcs convex toward the north, in part following the margins of the great submarine troughs. These arcs cut directly across the earlier tectonic lines, due chiefly to folding, which run about N. 70°W. in all of the larger islands. In another paper I have presented evidence, partly geologic but largely physiographic or seismologic, which 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.[5]

The minor relief features of the region are due chiefly to differential displacements within the great fault zones and along the more or less parallel accessory faults, and to erosion of the areas exposed above sea level. Folding and transverse faulting have been, apparently, of much less importance in determining topography.

The most persistent of the fault zones have been designated the Swan Island-Jamaica-South Haiti fault zone and the Cayman Islands-Sierra Maestra-North Haiti fault zone. They are parallel for a distance of nearly 2000 kilometers and are only 100 to 150 kilometers apart. The former has been traced from the vicinity of Neiba Bay westward through the great southern valley of Haiti, a well-defined fault trough, along the north coast of the Tiburon Peninsula and thence along the south side of the Bartlett Trough past the north coast of Jamaica, Swan Island and the Bay Islands into the Gulf of Honduras. Topographic evidence suggests that a branch of this fault zone may extend from a point near the north coast of Jamaica eastward along the south coast of Haiti, thus separating the two islands. According to this hypothesis the Southern Range of Haiti extending along the Tiburon Peninsula would be a horst lying between the two branches of a fault system.

The Cayman Islands-Sierra Maestra-North Haiti fault zone extends along the north side of the Bartlett Trough, past the Cayman Islands and the south coast of Cuba; it then crosses the Island of Haiti following the Cibao Valley from Manzanillo Bay to Samaná Bay, and

[5] Taber, Stephen, "The Great Fault Troughs of the Antilles," *Journal of Geology,* **30,** 89–114, 1922.

possibly continues into the submarine valley that heads in Aguadilla Bay on the west coast of Porto Rico. The north coast of the St. Nicholas Peninsula is determined by this fault zone, and its south coast seems to be marked by a closely related fault. Faulting has also probably formed the submarine trough, which, separating Haiti from the Bahama Banks, extends in a long arc parallel to the Cayman Islands-Sierra Maestra-North Haiti fault zone; but the evidence for this is not so conclusive. The Cordillera Septentrional, lying between the Cibao Valley and the trough north of Haiti, is analogous to the south range. As a physiographic feature it extends eastward through the Samaná Peninsula and westward through Tortuga Island, the Sierra Maestra of Cuba, the Cayman Islands and the Misteriosa Bank.

The two major fault zones outlined above are both characterized by many narrow trough-like depressions which are known to be due, in part at least, to trough faulting. The long and relatively narrow strip between the two fault zones is depressed in its western and central parts to form the great Bartlett Trough having a maximum depth of 3,506 fathoms (6,412 meters), while the eastern end is elevated to form the Cordillera Central on the island of Haiti, culminating in Monte Culo de Maco and Loma Tina, the highest peaks in the Antilles, reputed to be over 3,100 meters above sea level.

The Cordillera Central with its subsidiary ranges is not a simple horst; the rocks, which include the oldest on the island, are complexly folded and faulted. Within this region lies the central valley of Haiti, known in Santo Domingo as the Valley of San Juan. This valley is not quite parellel to the great northern and southern valleys, nor is it such a persistent feature, and, while partly outlined by faults, it does not appear to be due primarily to faulting.

A third major fault zone follows the northern scarp of the Porto Rico-Virgin Islands ridge which rises precipitously from the Brownson Trough, 8,526 meters in depth. Analogy suggests that the opposite side of the Brownson Trough is likewise determined by faulting, but the only evidence supporting this hypothesis is derived from the topography and a few earthquakes that have been recorded.

The Porto Rico-Virgin Islands ridge has the topographic characteristics of a great horst, the south side of which coincides with the northern escarpment of the Caribbean Basin. The steepness of this scarp is suggestive of faulting and there is geologic evidence of a late Tertiary fault approximately paralleling the south coast of Porto Rico. The low seismicity of the district, however, indicates the absence of

active faults, and there is no topographic evidence of recent displacement.

A zone of faulting separates the Virgin Islands group from St. Croix and the Lesser Antilles, and has resulted in the formation of the Anegada Trough. In passing eastward this trough apparently forks; one branch, which is not very well defined, continuing eastward, while the other extends northeast to join the Brownson Trough northeast of Anegada Island at the end of the Porto Rico-Virgin Islands ridge.

In view of the great differences in elevation shown on some east-west profiles and the influence of longitudinal faults in determining the present topography of the region, it is surprising to find so little evidence of transverse faulting. A north-south fault with well defined scarp has been recently observed in the southwestern part of the Province of Azua, Dominican Republic. The scarp forms the east side of Loma El Número.[6] This fault is intersected by an east-west fault which marks the mountain front north of Azua. Detailed field work will doubtless result in the discovery of other transverse faults, but they can not compare in persistence or in their influence on the topography with those running east and west.

In few regions is faulting such a dominant factor in determining the topography. In spite of this fact there are no active volcanoes in the belt through the Greater Antilles. The pre-Tertiary formations on some of the islands are built up largely of volcanic materials, and in a few localities basaltic lava-flows of Pleistocene or post-Pleistocene age have been found. The widespread occurrence of volcanic tuffs and similar rocks in the basal complex all along the arc of the Greater Antilles suggests that crustal movements along east-west lines may have been initiated in pre-Tertiary time. In contrast with the northern perimeter of the Caribbean Basin its eastern boundary is marked by an arc of active or recently active volcanoes. In the Antillean belt the igneous material is largely included in the basal complex of more or less metamorphosed rock, probably Cretaceous or older in age, most of which is found in the higher and central portions of the islands. At lower elevations late-Tertiary limestones and shales, which have not been so greatly disturbed, are the prevailing rocks.

[6] "A Geological Reconnaissance of the Dominican Republic," by T. W. Vaughan, Wythe Cooke, D. D. Condit, C. P. Ross, W. P. Woodring, and F. C. Calkins. pp 79 and 226. Washington, 1921.

Seismic Geography of the Greater Antilles

The most noticeable characteristic of the Antillean earthquakes is the way in which their epicenters are so largely confined to the major fault zones described above. It is of course impossible to fix the origin of most of the weak shocks for very few of them have even been recorded, but the great majority of the weak tectonic earthquakes in any region originate in the same localities as the stronger ones. In locating the epicenters of the stronger earthquakes it is necessary to rely chiefly on the distribution of intensities and the evidence from accompanying sea-waves since seismographic records are available for only a few recent shocks. The descriptions of early earthquakes seldom permit precise determination of epicenters, but fortunately an approximate location is sufficient for the purposes of this investigation.

The epicenters of earthquakes referred to in the present paper and in my paper on "The Great Fault Troughs of the Antilles" are all indicated on the accompanying map (Plate 7). Most of the locations are only approximate. The epicenters of a few earthquakes of relatively low intensity are included for localities, such as Swan Island, where the record covers a very brief period; and the entire absence of epicenters from certain other localities, as between the Cayman Islands and Santiago de Cuba, is probably due to lack of information rather than to low seismicity. The map is therefore inaccurate in places in picturing the relative seismicity of different regions; nevertheless, it does bring out very clearly the localization of epicenters along arcs that coincide with the major fault zones of the region. It differs in several respects from the map of Montessus de Ballore, who apparently locates all epicenters on the islands and most of them so that they coincide with the larger towns.[7]

Earthquakes of Porto Rico and the Virgin Islands.

A recent catalogue[8] of earthquakes felt in Porto Rico and the Virgin Islands from 1772 to 1918 contains about 275 earthquakes, all after-shocks being omitted except four very strong ones following the earthquake of 1867 and three following the earthquake of 1918. When

[7] Ballore, F. de Montessus de, "Tremblements de Terre," fig. 64, p. 377. Paris, 1906.

[8] Reid, Harry Fielding and Taber, Stephen, "The Porto Rico Earthquake of 1918 with Descriptions of Earlier Earthquakes. Report of the Earthquake Investigation Commission," Document No. 269, U. S. House of Representatives, 66th Congress, 1st Sess. (1919), pp. 53-66.

earthquakes recur from time to time along an active fault or system of faults it is often impossible to decide whether some strong shocks should be classed as after-shocks of earlier disturbances or as independent shocks. Thirty-six of the shocks listed had probable epicentral intensities of above VI R.-F., and of these thirty-one seem to have had their origins either along the steep slopes that descend into the Brownson Trough or those descending into the Anegada Trough. These shocks are listed in the paper on Antillean fault troughs. The shocks known to have originated within the island of Porto Rico are all of low or moderate intensity.

The most destructive shocks recorded occurred during the series of 1867–1868 and in 1918. The great earthquakes of November 18, 1867, had their epicenters along the north scarp of the Anegada Trough fifteen to twenty kilometers south of St. Thomas. Two strong shocks occurred separated by an interval of ten to fifteen minutes. They were characterized by vertical vibrations of the ground and both were followed by sea-waves which were propagated in all directions with the trough in front of the crest. After-shocks were numerous, and on March 17, 1868, there was another strong shock followed by a small wave noticeable along the coasts of Viequez and Porto Rico. The sea-wave together with the distribution of intensities indicate that this shock also originated along the northern scarp of the Anegada Trough, but farther west near the southeast coast of Porto Rico.

The earthquake of October 11, 1918, originated about fifteen kilometers west of the northwest corner of Porto Rico, where the fault zone along the south side of the Brownson Trough seems to intersect the Cayman Islands-Sierra Maestra-North Haiti fault zone. It was characterized by vertical vibrations of the ground and was followed by a sea-wave which advanced with the trough in front of the crest. The after-shocks on October 24th and November 12th, which had epicentral intensities of VIII or IX, were not accompanied by sea-waves and were characterized, according to observers, by horizontal oscillations that were in marked contrast to the vertical vibrations of the initial disturbance.

Although many severe earthquakes have originated near the north coast of Porto Rico during the four centuries since it became known to Europeans, there is no record of a severe shock having its origin along the south coast. In fact no earthquake can be definitely assigned to the northern escarpment of the Caribbean Basin from St. Croix to the eastern end of the island of Haiti, though it is possible that some

of the light shocks reported only from the south coast of Porto Rico may have originated there. In 1908 two moderate shocks had their origins somewhere near Ponce, but their maximum intensity was not above VI, R.-F.

Light shocks have occurred at a number of places in the interior of the island but none is known to have caused damage. They probably originate along small local faults, some of which seem to have been active recently since their physiographic manifestations have not been obliterated.[9]

Earthquakes in the Island of Haiti.

M. de Ballore recognizes two unstable regions on the island of Haiti, one in the north, the other in the south, but does not discuss the evidence.[10] The Rev. J. Scherer, in his excellent summary of destructive earthquakes in the islands, groups them by regions, and refers all shocks to either the northern, the southern or the central depression.[11]

Scherer correlates five great earthquakes with the northern valley, which, as we have seen, is a physiographic manifestation of the Cayman Islands-Sierra Maestra-North Haiti fault zone. The shock of May 7, 1842, was the most destructive, though the intensity may have been no higher than during the earthquake of 1564. The region was more densely settled in 1842 and therefore more information is available for that disturbance. The distribution of intensities and the phenomena of the accompanying sea-wave indicate that the earthquake of 1842 resulted from a vertical displacement along a fault passing between Tortuga Island and the St. Nicholas Peninsula. The displacement may have continued eastward into the island, for it is stated that the bed of the Yaqui River was suddenly heaved up driving its waters both up and down the stream. Along the coast the ocean first withdrew and then returned causing much destruction.

Sea-waves are not reported as accompanying the destructive earthquakes of 1564, 1783 or 1897, and there is no other evidence of a submarine origin for these shocks. The statement that the earthquake of 1897 was accompanied by the formation of cracks and subsidence of the ground suggests that the disturbance may have been caused by a vertical displacement, but the phenomena described might be due

[9] Mitchell, G. J., "Geology of the Ponce District," *Scientific Survey of Porto Rico and the Virgin Islands,* N. Y. Acad. Sci., **1**, part 3, 266, 1922.

[10] Ballore, F. de Montessus de, *Op. cit.,* p. 378.

[11] Scherer, Rev. J., *Op. cit.,* p. 161.

merely to slumping of loose superficial material. The breaking of a submarine cable east of Puerto Plata was probably caused by a submarine land-slide. For the other shocks mentioned no evidence is available that would even suggest the nature of the displacement.

The earthquake of September 23, 1887, included by Scherer in his list of earthquakes originating in the northern valley, evidently had its epicenter to the southward of Môle St. Nicolas, for the accompanying sea-wave was practically limited to the shores of the Windward Passage and Gulf of Gonaïve, being of no importance along the north coast of Haiti. The distribution of intensities is not inconsistent with this interpretation. At all points for which data are available the sea first receded from the land and then advanced.

The great southern valley of Haiti has had a higher seismicity during historic times than any other part of the island. Earthquakes have originated along the course of this trough sometimes in one part of it, sometimes in another. The shocks have been very destructive because several of the principal cities of Haiti and of Santo Domingo, such as Port-au-Prince, Azua and Santo Domingo have been built on deep alluvial soils either in the valley or close to the fault zone which passes through it.

The cities of Santo Domingo and Azua were damaged by severe earthquakes in 1673, 1684 and 1691. Azua, which was a flourishing city, is said to have been entirely destroyed by the earthquake of 1691. It is impossible with the meager data now available definitely to locate the origins of these shocks, but the close proximity of Azua and Santo Domingo City to the great southern fault trough with its high seismicity makes it not improbable that the Swan Island-Jamaica-South Haiti fault zone was the locus of the disturbances. The old site of Azua was not more than ten or fifteen kilometers north of the fault zone. Ballore,[12] in referring to the destruction of Port-au-Prince on June 12, 1692, confuses this town with Port Royal which was destroyed by the Jamaica earthquake of that date.

The earthquake of November 9, 1701, had its origin near the western end of the trough, possibly in the strait between Gonaïve Island and the north coast of the Tiburon Peninsula. Port-au-Prince was not yet founded, but at Léogâne there was some destruction and in the plain of the Cul de Sac several masonry houses were thrown down, while the road leading along the shore from Léogâne to Petit Goâve sank into the sea.

[12] Ballore, F. de Montessus de, *Op. cit.*, pp. 273 and 278.

On October 18, 1751, at about 3 p.m. a severe earthquake occurred near the eastern end of the trough. Azua, which had been rebuilt since 1691, had all of its houses thrown down, and this time was overwhelmed by a great sea-wave—a fact which proves that the shock was due to a vertical displacement along a submerged fault running a short distance south of the coast. The situation of Azua at the head of a bay was such as to increase the destructiveness of the wave. The town was rebuilt farther inland. Santo Domingo City lost many of its finest buildings and other towns near the south coast were severely damaged. The displacement along the fault possibly extended westward into the island. The violent shocks reported at Croix de Bouquets and Port-au-Prince at 2 p.m. of the same day may represent a separate though closely related earthquake, but in those days time was not very accurately kept, and any shock sufficiently severe to destroy Azua must have been strongly felt in the western part of the valley.

The earthquake of October 18, 1751, was followed by strong after-shocks and about a month later, on November 21st and 22nd, severe earthquakes, originating in the western part of the trough, destroyed the recently founded town of Port-au-Prince and overthrew buildings on the neighboring plains. Lyell refers to a submergence of part of the coast at this time so as to form a bay of the sea,[13] but it has not been possible to verfy the statement.

The great earthquake of June 3, 1770, which has been described in some detail by Scherer,[14] was most destructive in a zone extending from Croix de Bouquets through the plain of the Cul de Sac and along the north coast of the Tiburon Peninsula as far as Miragoâne. The shock was felt all over Jamaica, being strong enough to crack the walls of some houses and throw down a few old chimneys. It was strong at Santo Domingo City but no great damage resulted. Landslides occurred in the mountains, damming some of the rivers so that they ceased flowing for hours or even for weeks. A sea-wave was reported from points along the shore of the Gulf of Gonaïve and this must have been caused by a sudden vertical displacement of the sea floor in that vicinity. The displacement causing the earthquake and sea-wave possibly continued eastward into the plain of the Cul de Sac.

Southey states that in 1775 "three shocks of an earthquake were felt at Española [the island of Haiti] ; several store houses were thrown

[13] Lyell, Sir Charles, "Principles of Geology," 1, 440. London, 1830.

[14] Scherer, Rev. J., *Op. cit.*, pp. 174–179.

down, and great damage done by the sea,"[15] but he fails to give the precise location.

The earthquake of April 8, 1860, originated a little farther west than the shock of 1770, the intensity being greatest near Anse à Veau where 124 houses were destroyed or cracked. Other towns on both sides of the peninsula and as far east as Port-au-Prince had some houses thrown down or badly damaged. The earthquake was due to vertical faulting under the Gulf of Gonaïve as is evidenced by the accompanying sea-wave. At Anse à Veau the sea first withdrew and then broke with a crash on the shore.

The last severe earthquake originating along faults connected with the great southern trough occurred May 11, 1910. Scherer states that the shock was strongest "in the Bay of Ocoa where the sea wall was broken," and that "it was equally strong at Bani, Christobal and Barahona,"[16] towns lying on opposite sides of the fault zone. At Azua and Santo Domingo houses were cracked.

The earthquakes of October, 1751, and May, 1910, are here attributed to adjustments along faults of the great southern trough, although Scherer correlates them with the central depression of Haiti. The sea-wave that followed the shock of 1751 is proof of an origin off the south coast; and the distribution of intensities at the time of the earthquake in May, 1910, indicates that this disturbance also probably originated along the same fault zone.

The central or "intermediate depression," as defined by Scherer, would comprise not only the plains of the great valley extending from St. Michel in Haiti to San Juan in Santo Domingo, but also the plains of Azua, and even the coastal plain in the southeast as far as Cape Engano. The correlation of the plains of Azua with the San Juan Valley is possibly correct. The front of the Sierra de Ocoa north of Azua marks a fault which brings limestones and shales, probably Eocene or older, against beds of Miocene age.[17] The Sierra de Ocoa is approximately in alignment with the north side of the San Juan Valley, but Condit and Ross who ran a geological traverse along the Rio Yaque del Sur, between the two regions, make no reference to the possible

[15] Southey, Thomas, "Chronological History of the West Indies," 2, 422. London, 1827.

[16] Scherer, Rev. J., *Op. cit.*, p. 172.

[17] Cook, Wythe, in "A Geological Reconnaissance of the Dominican Republic," pp. 78–79. Washington, 1921.

westward extension of the fault.[18] In passing eastward this fault intersects the north-south fault of Loma el Número. No reason exists, certainly, for including the coastal plain of the southeastern part of the Dominican Republic in the same physiographic province with the great central valley.

Scherer assigns seven destructive earthquakes to the central depression; but one of these, the shock of 1882, originated in the eastern part of the island near the inner margin of the coastal plain, the towns of Seybo and Higuey being the chief sufferers, while two, possibly five, of the others should be correlated, as stated above, with the fault zone extending through the great southern valley.

The earthquake of October 6, 1911, probably had its origin along a fault located in the central valley or on the south flank of the Cordillera Central, for Scherer states that the intensity was greatest in the upper basins of the Yaqui del Sur, and the Artibonite, the towns of Azua, San Juan, Cerca La Source, Banica and Hinche being the principal places affected.

The earthquake of April 23, 1916, which had an intensity of VIII-IX in the eastern part of Santo Domingo, seems to have originated near the inner margin of the coastal plain or on the southern flank of the Cordillera Central, but farther west than the epicentral area of the earthquake of 1882.

Jamaica Earthquakes.

The earthquakes of Jamaica have been discussed recently[19] in some detail, and it has been shown that the earthquakes of 1692 and of 1907, the greatest in the history of the island, both originated off the north coast. Both were accompanied by waves from the sea; in 1907 the water first withdrew from the shore and then returned, and in 1692 the sequence was probably the same though it is impossible to verify this from the meager accounts that have been preserved. Other shocks of less intensity have probably had their origins in the fault zone along the north coast of Jamaica; no great earthquakes have originated elsewhere in the immediate vicinity of the island during historic time.

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[18] Condit, D. D. and Ross, C. P., "Geology of the Provinces of Barahona and Azua" in "A Geological Reconnaissance of the Dominican Republic," pp. 206–209. Washington, 1921.

[19] Taber, Stephen, "Jamaica Earthquakes and the Bartlett Trough," *Bulletin of the Seismological Society of America,* **10**, 55–89, 1920.

Earthquakes in the Island of Cuba.

In a brief review of Cuban earthquakes, Salterain distinguishes two seismic districts; one in the east near Santiago de Cuba, the other in the Cordillera of Vuelta-Abajo near the western end of the island.[20] The first district, which includes the precipitous mountains of the Sierra Maestra and forms part of the Cayman Islands-Sierra Maestra-North Haiti fault zone, has long been recognized as a region of high seismicity, but Havana and the western portion of the island were generally regarded as exempt from damage by earthquakes until the occurrence of the destructive shocks of 1880. No shocks of importance have originated in the northern and central portions of Cuba. In the following discussion most of the facts relating to earthquakes in Cuba have been abstracted from the paper by Salterain.

Most of the earthquakes which have damaged property in eastern Cuba have probably had their origins along the precipitous scarp that forms the north side of the Bartlett Trough, but, because of sparse population in the mountain region, seismic records are very imperfect, and it is today impossible definitely to locate the origins of these earthquakes. Until recently Santiago de Cuba, founded in 1514, has been practically the only town in the immediate vicinity of the great fault scarp of the Sierra Maestra. In examining the records of earthquakes felt in this region it is found that many of the weak shocks have been reported only from Santiago de Cuba while the strong shocks have been much more destructive there than in the towns situated north of the mountains.

The first earthquake listed by Salterain was felt at Bayamo in 1551, and another was felt there in 1624. In 1578, 1675, and 1677 severe earthquakes were recorded at Santiago. The earthquake on February 11, 1678, recorded in Cuban tradition as the *great earthquake,* caused enormous destruction in Santiago; and on February 11th of the following year between 9 and 10 a.m. another strong shock destroyed the cathedral. The severe earthquake of 1755 was accompanied by a wave from the sea that almost completely inundated the town of Santiago. This proves that the earthquake resulted from a sudden vertical displacement a short distance off the coast. The entrance to Santiago harbor is long and winding with a very narrow mouth so that

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

the town is partially protected from the effects of seismic sea-waves. This may be the reason why more waves have not been reported as accompanying Cuban earthquakes.

The strongest earthquake recorded at Santiago, according to Salterain, occurred June 11, 1766, at 11:45 p.m. During the remainder of the night about fifty shocks were felt which were of relatively low intensity except for one at 4 a.m. June 12th, which is said to have completed the destruction of the city. Many buildings were completely destroyed and others were so badly damaged that they had to be abandoned. The city fort, Moro Castle and the jails were all rendered unserviceable. This earthquake was also strongly felt all over the island of Jamaica.

Between 1777 and 1852, eighteen important earthquakes are listed by Salterain. In describing the earthquakes in 1852 he quotes from an account by D. Miguel Storch who witnessed the disturbances. The first shock occurred without warning on August 20th, at 8:36 a.m., and it consisted of a strong up and down motion, which greatly frightened the inhabitants of Santiago, causing many to flee from the city. It was followed by numerous after-shocks, and one of these, occurring at 3:35 a.m., August 21st, is said to have been as strong as the first but shorter in duration. The movement is described as oscillatory instead of up and down as in the first shock. Another strong shock on August 28th, preceded by a prolonged noise like thunder, terrified the people who had begun to return to the city. On November 23rd, at 3:08 a.m., a terrifying noise was again heard and the earthquake which followed, Storch thought, was the strongest of the series. He states that happily the movement was one of oscillation, and it was because of this fact that no more buildings were destroyed. This earthquake was not felt over so large an area as the initial disturbance on August 20th.

In the Vuelta-Abajo of western Cuba earthquakes seem to have been practically unknown until 1880; certainly no destructive shocks are mentioned in histories of the region between 1519 when Havana was founded and 1880. This freedom from earthquakes was in such marked contrast to the high seismicity of the eastern end of the island as to cause comment by several of the early writers.

The earthquakes of 1880 began at 11 p.m. January 22nd with a severe shock which caused much damage to property throughout the western portion of the island. It was felt from Cienfuegos on the east to beyond Mantua on the west and probably as far as Cape San An-

tonio. It was felt in the Isle of Pines on the south and as far north as Key West, Florida.[21] The area affected was therefore probably more than 81,000 square miles (210,000 square kilometers). The destructive effects were greatest in the towns of San Cristóbal and Candelaria where many buildings were thrown down and some lives lost, the intensity at these towns being probably between VIII and IX, R.-F. The distribution of intensity suggests that the origin was on the south side of the Sierra de los Organos not far from San Cristóbal and Candelaria. The intensity was somewhat less through the mountains than on the lowlands to the north and south. While the earthquake was strongly felt along the sea coasts there was no noticeable disturbance of the sea during or after the shock.

After-shocks were numerous and continued into the following year, but none had so high an intensity nor was felt over so large an area as the initial disturbance. One of the most widely felt after-shocks occurred at 4 a.m. January 23, 1880.

The movement during the earthquakes is described as a horizontal oscillation accompanied or followed by an up and down motion. From the effects of the earthquake on buildings and other structures Salterain concluded that in most places the horizontal oscillation was chiefly in a northeast-southwest direction.

Since the cessation of the after-shocks seismic activity in the Vuelta-Abajo has been no greater than it was prior to 1880.

Earthquakes in the Cayman Islands.

The Cayman Islands, lying along the north side of the Bartlett Trough, are the exposed portions of a submarine ridge which farther east rises high above sea level to form the Sierra Maestra of Cuba. Earthquakes are occasionally reported in these islands, one having been felt on Grand Cayman in 1921,[22] but no definite information is available. Earth-sounds have been recorded on Cayman Brac.[23]

Earthquakes at Swan Island.

Swan Island is an isolated peak rising barely above sea level on the south side of the Bartlett Trough. The main island is only 2.5

[21] Rockwood, C. G., Jr., "Recent American Earthquakes," *American Journal of Science*, Ser. 3, **19**, 299, 1880.

[22] Written communication from Mr. H. H. Hutchings, Commissioner, Grand Cayman, dated January 16, 1922.

[23] Forel A., "Bruits souterrains entendus le 26 aout 1883 dans l'ilot de Caiman-Brac." *Compt. Rend. Acad. Sci.*, **100**, 755, 1885.

kilometers in length, and the submarine slopes descend to depths ranging from 2,136 meters on the south to 5,505 meters on the north. It is 110 miles (175 kilometers) north of the Honduras coast, the nearest land. Seismologic data are available for only a few years. The earthquake on January 1, 1910, is probably the strongest so far reported. Instrumental records indicate an origin a short distance south of Swan Island. An earthquake occurred on July 11, 1920, and a stronger one on August 18th, both being characterized by vertical vibrations.[24] A light shock was felt on September 20, 1921, at 9:58 p.m., 90th meridian time, and another the next morning at about 5:15 a.m.[25] All of these shocks probably originated close to Swan Island for they were not felt at Grand Cayman or elsewhere in the Antilles, and none of them except that of January 1, 1910, was recorded on the seismographs at Panama, Port-au-Prince or Viequez.

Earthquakes in the Bay Islands.

The seismicity of the Bay Islands, Utilla and Ruatan, is rated high by Ballore, and Omoa on the coast of Honduras suffered severely in 1856. The Bay Islands, which are probably the eastern continuation of the Sierra de Omoa of Honduras, are in alignment with Swan Island and the southern scarp of the Bartlett Trough, and it is a mistake to correlate them with the Sierra Maestra-Cayman Islands ridge as has been done by Ballore.[26]

Discussion and Conclusions

With very few exceptions all Antillean earthquakes having intensities high enough to cause damage have originated along a few well defined belts which coincide with the major fault zones of the region. The earthquakes of highest intensity have been so distributed that few if any of their epicenters are in exactly the same localities. Haiti has suffered more severe earthquakes than any of the other islands, chiefly because it is crossed by two of the major zones of active faulting while other islands have merely a coast line that coincides with one of the zones.

The eastern portions of the two fault zones that delineate the Bartlett Trough and cross the island of Haiti seem to have a much

[24] Taber, Stephen, "The Great Fault Troughs of the Antilles," *Journal of Geology*, 30, 97–98, 1922.

[25] These earthquakes were observed and reported by D. H. Foley, Chief Operator of the Swan Island Radio Station.

[26] Ballore, F. de Montessus de, *Op. cit.*, pp. 385 and 387.

higher seismicity than their western portions extending from southern Cuba and Jamaica toward Central America; but this difference in seismicity may be more apparent than real, since earthquake records are necessarily meager and incomplete at a distance from the larger and more densely populated land areas.

There is no evidence either of a continuous change in the seismicity of the region or of any well-defined regular periodic variation. When severe earthquakes have been separated by only a short time interval they have had their epicenters in the same fault zone and only a short distance apart, thus indicating that the displacement was being extended along the strike of the faults; the earthquakes in the Anegada Trough on November 18, 1867, and March 17, 1868, and the earthquakes in the southern valley of Haiti during October and November of 1751 being good illustrations.

The close relation between high relief and high seismicity has been emphasized by Ballore.[27] Precipitous slopes and great differences in elevation are marked characteristics of the Antillean seismic belt as a whole, but there appear to be several exceptions to the general rule that the steeper side of a valley or of a mountain range is the more unstable. The north side of the Anegada Trough has had a much higher seismicity during recent time than the south side, although the latter is very much more precipitous and is in fact one of the most magnificent fault scarps known. The northern escarpment of the Caribbean Basin has been practically aseismic during the historic period.

High relief is not necessarily a cause of high seismicity. On land precipitous scarps are indicative of active faults along which displacements resulting in earthquakes have recently occurred, for steep slopes are rapidly reduced by erosion and deposition; but below sea level, especially at a distance from large land masses furnishing much rock waste, precipitous scarps may persist long after stability has been attained. Moreover, on land where steep slopes are not protected from erosion, the rapid unloading of certain areas and the loading of neighboring areas renew the stresses which must be relieved by further displacements so that stability can not be maintained while the relief is great.

The northern escarpment of the Caribbean Basin seems to be relatively stable; the southern scarp of the Anegada Trough may still be active, for, although no important earthquakes can be correlated with

[27] Ballore, F. de Montessus de, "Relation entre le Relief et la Seismicité," *Comt. Rend. Acad. Sci.*, **120**, 1183–1187 (1895).

it, the scarp is not very long and the north coast of St. Croix furnishes physiographic evidence of quite recent faulting.

Severe earthquakes in the Antillean belt are evidently caused by vertical displacements. Strong vertical vibrations near the epicentral areas have characterized several earthquakes for which accurate descriptions are available; and such vibrations would be set up by a sudden vertical displacement while it is difficult to explain them in any other way. In several instances observers have reported that the movement during strong after-shocks was chiefly a horizontal oscillation which was in marked contrast to the vertical movement of the initial earthquake of the series. Most of the great earthquakes originating along the shores have been accompanied by sea-waves such as may be started only by sudden vertical displacements of the sea-bottom. Twelve shocks are known to have had accompanying sea-waves, and if the records were more nearly complete this list would probably be longer. In descriptions of two Haitien earthquakes containing no reference to waves it is stated that parts of the coast sank into the sea. Several sea-waves of unknown origin, such as the one which destroyed Savanna la Mar in 1780, may have been seismic in origin. Some of the earthquakes which have had their epicenters entirely on land are stated to have been accompanied by subsidence of the ground. In addition there is the physiographic and geologic evidence of recent vertical displacements of great magnitude throughout the length of the major fault zones. In some places, as along the west coast of Porto Rico, vertical movements have been observed in historic time,[28] and in the Bay of Port-au-Prince, islands shown on early maps have entirely disappeared.[29]

Few, if any, of the earthquakes have been accompanied by a sudden permanent change in the elevation of a coast. In several instances the subsidence of a coast has been reported, but it is sometimes difficult to distinguish between true subsidence and the downward slumping of unconsolidated superficial materials; the elevation of an Antillean coast at the time of an earthquake has not been reported. Gradual changes in shore lines, however, both of elevation and of depression, have occurred during the last half century.

[28] Reid, H. F., and Taber, Stephen, "The Porto Rico Earthquakes of October-November, 1918," *Bulletin of the Seismological Society of America,* **9**, 121–122, 1919.

[29] Scherer, Rev. J., "Les Tremblements de Terre de l'Ilel d'Haiti," *Bulletin Semestriel de l'Observatoire Meteorologique du Seminaire-College St. Martial,* July-December, 1912, pp. 136–137, 1913.

Many of the severe earthquakes have originated along the sides of the great submarine troughs and are thought to be the direct result of their continued growth. Geologic, physiographic and biotic evidence indicate that the formation of the troughs is due primarily to the subsidence of long narrow blocks and only secondarily to the elevation of the areas on each side. The distribution of earthquakes indicates that the deepening of the troughs is due to relatively small local displacements, now in one place and now in another. Simultaneous displacements on both sides of a trough would result in twin earthquakes and these have not been observed.

There is no evidence that the recent faulting is due to compression; late Tertiary and Pleistocene beds have been displaced vertically but overthrusting and close folding in these rocks have not been observed. The topography of the fault zones exhibits the characteristics of normal rather than of thrust faulting. On the other hand, the faults could not have been caused, in the beginning at least, by tension, for they are remarkably persistent and are in no way affected where they cut across the earlier tectonic lines.

If the recent activity is due neither to compression nor to tension it must result from vertical forces though there is not much positive evidence in favor of this hypothesis. The fact that the relatively narrow strip between the fault zones outlining the Bartlett Trough is depressed in its central and western parts and elevated in the east, suggests that the major fault planes are approximately vertical, but as yet this inference has not been confirmed by direct observation.

The area of some of the troughs is so large and their depth so great that the difference in relief must be to a considerable extent compensated by difference in the density of the underlying rocks. Hayford[30] and Bowie[31] think that areas as small as seventy miles square (12,700 square kilometers) are probably very closely compensated for differences in elevation. The Bartlett Trough has a length of 1,570 kilometers, a maximum width of 150 to 160 kilometers and a depth of over 8,000 meters. This suggests that the formation of at least the larger troughs must be due in large part to the greater density of the material underlying the troughs as compared with the density of the material under the elevated areas on either side.

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[30] Hayford, John F., "The Figure of the Earth and Isostasy from Measurements in the United States," *Coast and Geodetic Survey*, Washington, 1909, p. 169.

[31] Bowie, William, "Some Geologic Conclusions from Geodetic Data," *Proc. Nat. Acad. Sci.*, 7, 23, 1921.

The crustal adjustments causing earthquakes in the Antillean region can not be attributed to changes in surface loading due to erosion and deposition of sediments. In these islands erosion is slow considering the steepness of the slopes, and while most of the earthquakes have had their epicenters close to the coasts several are known to have originated at a distance of 175 kilometers from any important land area.

The type of sea-wave accompanying Antillean earthquakes is also evidence bearing on the nature of the displacements. Each of these waves, so far as known, has been propagated in every direction with the trough in advance of the crest, this being true irrespective of whether the waves originate along the deepest troughs or in relatively shallow water such as in the Gulf of Gonaïve near the north coast of the Tiburon Peninsula. Seismic sea-waves which advance with the crest in front of the trough are not so common as the other type but they have been occasionally observed, especially in the Pacific Ocean. In a few instances the reports indicate that a wave has spread outward on one side of an epicenter with the trough in advance of the crest, while on the opposite side the wave has moved with the crest in advance of the trough; and this is to be expected, according to the elastic rebound theory, in all cases of vertical displacement along a single fault.

The type of sea-wave accompanying Antillean earthquakes has been observed under such a variety of conditions as to prove that it does not result from any peculiar features of submarine topography; therefore it is probably to be attributed to the nature of the displacement. The wave seems to indicate a sudden downward displacement of the ocean bottom, and, if there is an upward rebound on the opposite side of the fault, it must take place so slowly or be so small as to produce little or no effect on the surface of the water.

The conclusion that destructive earthquakes in the Greater Antilles have been limited almost entirely to a few well-defined belts is of practical importance, for in the future, earthquakes and their accompanying sea-waves may be expected to originate from time to time along these belts. The records now available indicate that disastrous earthquakes seldom recur in exactly the same place except after long periods of time; therefore those places along the zones of active faulting near which severe earthquakes have not originated during historic time are to be regarded as seismically most dangerous.

The destructiveness of a shock depends not only upon proximity

to the ruptured fault but also upon the character of the underlying rock and soil; and, in the mountainous Antilles, most of the larger towns are, unfortunately, built, in part at least, on the least stable ground—the water-logged alluvium of the narrow coastal plains or *playas*. Formerly, as a precaution against easy attack from the sea, it was customary to locate these towns farther back, on the lower slopes of the hills, but in recent years this has ceased to be a controlling factor.

The danger from seismic sea-waves is of course greatest along flat low shores, especially on the south and west coasts where freedom from the heavy surf of the northeast trade winds, as well as the extremely low tides, has permitted the building of houses close to the water's edge.

The destruction of property and loss of life accompanying many Antillean earthquakes have been due, in large part, to the type of buildings common in the islands. In this as in other districts there is a limit to the intensity of the shocks, and if proper precautions were taken in the location and construction of buildings and other structures, the inhabitants would have little to fear from the earthquakes or sea-waves. The evidence summarized in this paper indicates definitely the localities in which the hazard is greatest.

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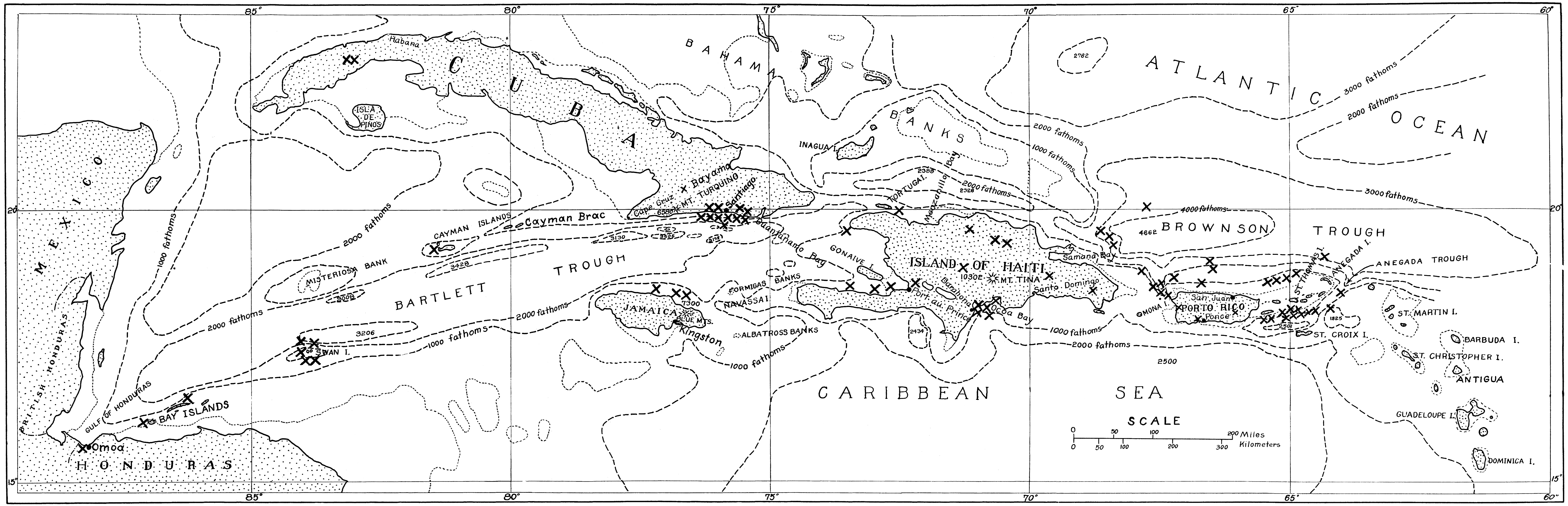

Map of the Greater Antilles Showing Fault Troughs and Earthquake Epicenters. Contour interval 1,000 fathoms (6,000 feet). Areas within the dotted lines less than 100 fathoms.