THE PORTO RICO EARTHQUAKE OF 1918

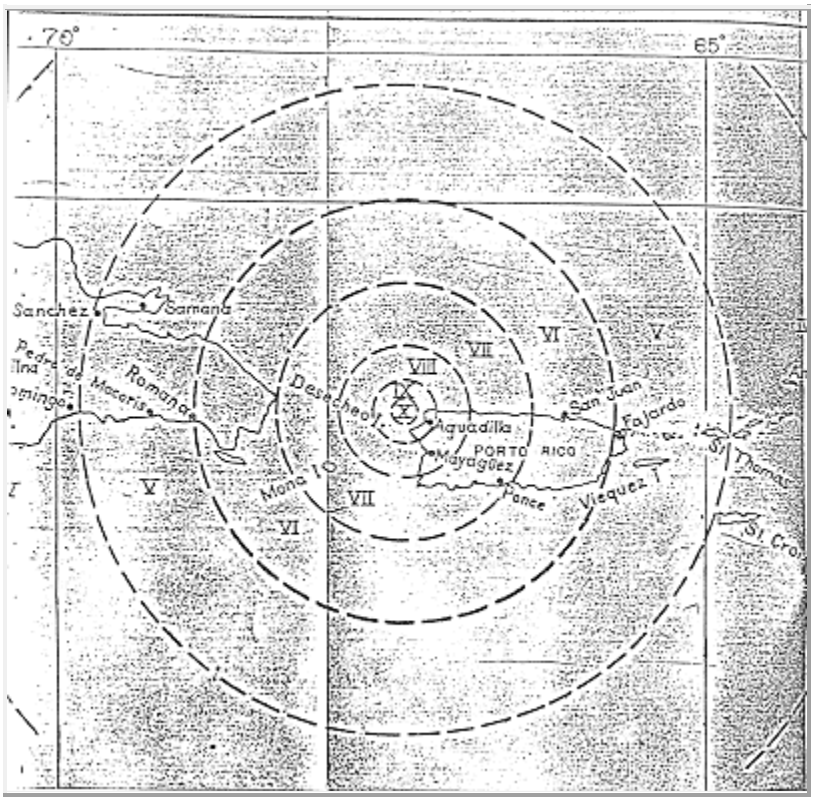
66th CONGRESS : : : : 1st SESSION
MAY 19 NOVEMBER 19, 1919

HOUSE DOCUMENTS
Vol. 33

WASHINGTON : : government printing office : : 1919

INTRODUCTION

On the morning of October 11, 1918, a little after 10 o'clock, Porto Rico was visited by one of the most severe earthquakes felt on the island since its occupation by Europeans. Immediately following the shock a great sea wave broke upon the shore, drowning many persons and destroying native huts.



According to official figures, 116 persons lost their lives, and the property loss amounted in value to about $4,000,000.

In the northwestern part of the island, where the damage was greatest, a number of persons left their dwellings and repaired to the hills. The alarm in this part of the island was serious; it was increased by the aftershocks, which were almost continuous for a day or two and then gradually decreased in frequency, with an occasional shock stronger than the others. No one knew whether the danger was over; or whether more, and perhaps even stronger, earthquakes were likely to add to the calamity.

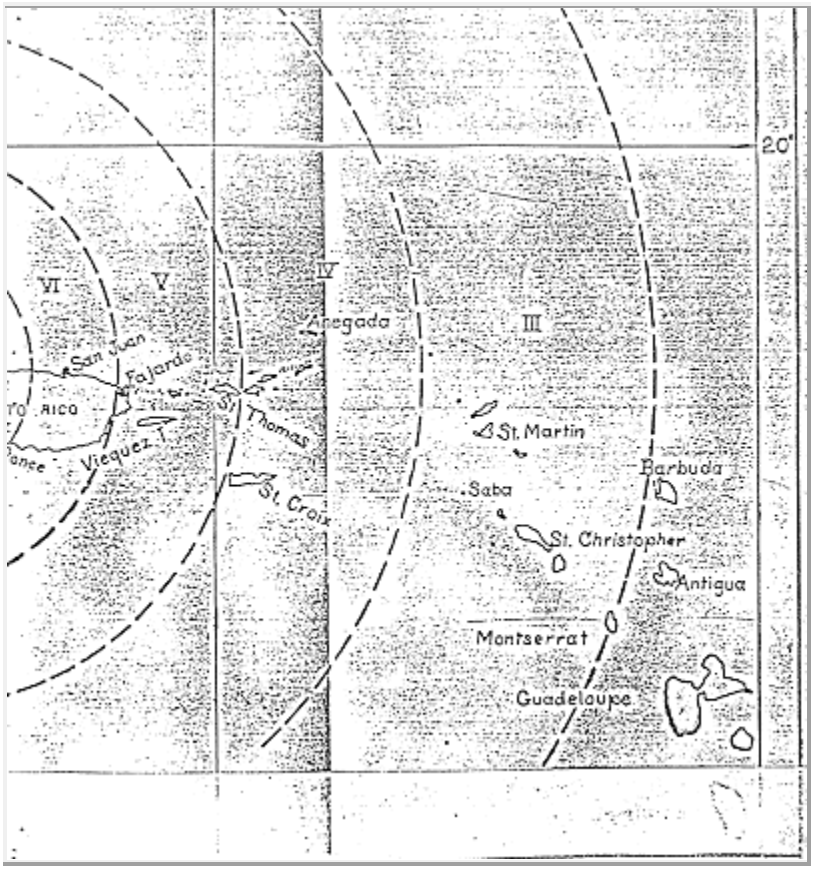
This situation led the Secretary of War, at the request of the Governor of Porto Rico, to invite the writers of this report to go to Porto Rico and investigate the earthquakes. We spent four weeks in Porto Rico, including a short visit to St. Thomas and Vieques, from November 21 to December 18. Before leaving the island we made a short preliminary report to the governor, in which we were fortunately able to say that "the indications are that the present disturbance is reaching its end." Up to the present time (July, 1919) there has been no recurrence of strong shocks.

The excellent roads in Porto Rico made it possible to visit comfortably nearly all parts of the island in automobiles kindly placed at our disposal by Gov. Yager, who also facilitated our investigators in many ways. Point Borinquen and Point Agujereada were visited on horseback from Aguadilla, Point Jiguero from Rincon and El Boqueron and Lajas, in a railroad automobile lent to us by the American Railway Co. Building, bridges, and other structures - indeed, everything that could throw light on the earthquake - were carefully examined. The experiences and observations of a large number of persons were collected; some of them had felt the shock in Santo Domingo or in one of the islands to the east of Porto Rico. Mr. F. E. Hartwell, meteorologist in charge of the weather bureau at San Juan, collected information for us from his many cooperative observers. Information was also gained through correspondence with persons in the several islands where the shock was felt. The uniform courtesy with which we were everywhere, the hospitality and the many kindness shown us, the readiness to answer all our questions, and to give us all information possible increased the sympathy which we naturally felt for persons who had experienced so great a misfortune.

We must thank the directors of the many seismological observatories who have sent us their records, and even their original seismograms, of the Porto Rico shocks.

Besides letters to the daily papers, several articles have been published regarding the earthquakes. On October 19 the department of agriculture and labor of Porto Rico issued Bulletin No. VI, entitled "Earthquakes," written by Assistant Commissioner Ramón Gandia Córdova. The Porto Rico School Review for December, 1918, contained an article by Señor José González Ginorio, inspector general, departamento de instrucción, entitled "El terremoto de Puerto Rico." Both of these gentlemen correctly assigned cause of the earthquakes to earth movements, and gave no sanction to the theory of a volcanic outburst. Señor J. A. Canals wrote an article in the Boletin Eclesiástico de la Diocesis de Puerto Rico, 2 Ser. No. 15, 1919, "El terremoto ultimo, informe preliminar acerca de los Daños causados a las iglésias de la Mitad Occidental de la isla por el terremoto del 11 de Octubre de 1919." The January-February (1919) number of Modern Building contains an article by E. K. Burton, "Earthquake in Porto Rico leaves

reinforced concrete intact." Profs. M. L. Vicente and C. F. Joslin, of the College of Agriculture and Mechanic Arts, Mayagüez, have published an article, entitled "Effect on structures of the recent Porto Rico earthquakes," in the Engineering News Record of April 24, 1919. A copy of "A Report of damages Caused to Property and Persons by the Earthquake of October 11, 1918," completed by the insular police under Col. Geo. R. Shanton, was kindly given us by him, but has not yet been published.



DESCRIPTION OF THE EARTHQUAKE

The earthquake occurred in daytime, and a region where the people are accustomed to shocks of moderate intensity. These facts probably explain the unusually close agreement in the descriptions of the shock given by different individuals. The best observers in all parts of Porto Rico are unanimous in stating that the earthquake began a pronounced vertical vibration, which was followed by horizontal oscillations. In regard to the direction of the horizontal movement there is more difference of opinion, but in nearly all portions of Porto Rico the majority of observers report the the principal horizontal vibrations were east and west, and this testimony is supported by much confirmatory evidence. Many facts indicate that in the extreme western and southern part or the island the principal horizontal component was in a northwest-southeast direction and, perhaps, in places nearly north and south.

The following statement was compiled from an interview with Messrs. Añeses, mayor of Aguadilla, with Manuel Jimenez, Arturo Reichard, and several other citizens of that place.

The earthquakes began suddenly without warning. No shocks had been felt in this part of the island for seven or eight months. At about 10:15 a. m. on October 11 there were two severe shocks, separated by an interval of two or three minutes. The first shock was the more severe, and is described as having a strong vertical movement; it was followed by horizontal oscillations, which caused much of the damage. Shocks of less intensity were felt at frequent intervals thereafter for several weeks, and in the beginning the ground appeared to tremble without cessation for considerable periods. The strong aftershocks on October 24 and November 12 differed from the first disturbance in that they seemed to consist chiefly of horizontal disturbance in that they seemed to consist chiefly of horizontal oscillations; thought apparently having a considerable amplitude, the period of these oscillations was relatively slow, and therefore the produced little damage, but some loose objects, left standing by by the first shock, were thrown down.

A description of the earthquake at San Juan by Mr. F. E. Hartwell, meteorologist of the United States Weather Bureau, follows:

By the time as obtained from the radio station here, the first shock was felt at this office at 10.16.30 a. m. on the 11th, and this shock continued without cessation for two minutes. I sat at the desk, watching the clock, waiting for the movement to stop. The first minute and a half of this time the motion seemed to be more vertical than otherwise, and was accompanied by sounds which I attributed to creaking of the timbers of the building. However, many others have described similar sounds from other localities in San Juan in buildings of concrete and other materials, so the sounds may had another source. The remaining half minute of the first shock had a horizontal motion in this vicinity which was very noticeable and almost sufficient to cause nausea, and which set the electric fixtures to swinging through and arc of perhaps 45^{o} in a north - south direction. The office clock, which faces south, so that the pendulum swings east - west, stopped during the second face of the shock, while the house clock which faces east continued to run. A second shock, almost as severe as the first, lasting half a minute, occurred at 10.20, and a third of short duration at 10.24.30. Small oscillations were noticeable thereafter at intervals of few minutes until after 1 p. m.

In addition to the testimony of witnesses, considerable evidence relative to the character of the vibrations was obtained from a study of displaced objects and the effects of the earthquake on buildings and other structures, but we were unable, in the time at our disposal, to make a detailed statistical investigation along this line.

As evidence of a vertical motion the following facts are cited. In some of the churches, as at Arecibo and Moca, mamposteria columns supporting arches between the nave and the aisles were crushed as though they had been subjected to strong vertical compression. At Rincon the bars of doors were raised permitting the doors to open. At a house near Mayagüez wooden columns supporting a porch roof jumped up and down, and after the earthquake a shoe was found between the base of the column and the floor of the porch.

In the vicinity of Arecibo the dominant horizontal movement appears to have been in an east-west movement appears to have been in an east- west direction. The tower of the Arecibo church was badly cracked and tilted toward the east; a steel smokestack near the Puente de Hierro was bent in an easterly direction just above the guy

wires; the cracks in the brick roof of the municipal building ran chiefly in a north-south direction. At the Central Los Canos, 4 kilometers south of Arecibo, the superintendent states that the swaying was east and west. Books in a concrete vault were thrown from the shelves on the northwest wall but not from the other shelves. The brick smokestack at the Central Santa Teresa fell in a direction S. 57° E. At Hatillo, 12 kilometers west of Arecibo, observers report a vertical motion and an east-west of Arecibo, observers report a vertical motion and an east-west vibration. The west wall of the church pulled away from the other walls; and part of a brick wall enclosing the cemetery topped to the west.

At Isabela the front and west wall of the Catholic church pulled away from the side wall, the upper portion together with two small towers being thrown down; the east and rear wall also pulled away from the side walls but was not badly cracked. (See fig.1.) The municipal building, which was built of brick and faced toward the south, had its west wall partly thrown down while its east wall was bulged outward. An inside wall, running north and south , only one brick in thickness, was partly thrown down.

At Aguadilla the front and the west wall was cracked horizontally at the height of the side walls and the upper portion nearly topped over. The side walls were not affected. A large building facing east of the plaza has a flat brick roof which showed large cracks running parallel and close to the east and west parapet walls. These walls were badly cracked above the roof line, and one was tilted toward the west, while similar walls running east and west remained intact. Another nearby building had north-south cracks near the walls but no east west cracks.

At the Point Jiguero Lighthouse, on the other hand, the evidence is indicative of a dominant north and south movement. The lighthouse tower was badly cracked horizontally and the north side was offset toward the south about 15 millimeters ; the parapet was enclosing the roof were damaged by damaged by cracking and scaling on the north and the south sides, while the east and west walls were uninjured. Interior walls, one brick thick running north and south, showed well developed diagonal shearing cracks intersecting at angles about 90°.

At the Central Corsica, 4 kilometers south of Rincon, observers report visible undulations in the surface soil moving in a southeasterly direction, and the upper third a the brick smokestack, 38 meters high, fell i a direction N. 30° W. At the Central Eugenia, between Rincon and Añasco, numerous cracks running about northeast and southwest were formed throughout the cane fields, which are in soft alluvial ground.

At Mayagüez the administration building of the agricultural experiment station, built of concrete blocks, shows almost no damage, but there are cracks in the corners of some of the rooms, where the north wall of the buildings has pulled away from the partition walls. At the parish house of the Redemptorist Fathers books were thrown from the shelves on the east and the west walls but not from the shelves on the north and south walls. At the College de la Milagrosa, which is a rectangular building with the longer dimension running north and south, the north wall was bulged outward and the south wall so badly cracked that it had to be taken down. The was wall was oldest than the others and it was rather badly damaged, but the east wall showed few minor cracks. On the opposite side of the steer a two-story building had the upper half of the wall thrown out; the west wall was badly cracked but remained standing. A neighboring house, with the first story of brick and the second story of wood , had both the north and

south brick walls pushed outward and partly thrown down by movements of the frame structure above; the other walls remained standing but showed shearing cracks.

Although this instrument only magnifies the vibrations ten times, the pens were driven off the recording drum within a few seconds of the arrival of the shock, so that the magnitude of the earth movements at Vieques can not be determined. But it was not less than 1 ½ centimeters, and it may have been twice as much; for the beams of the instrument were flung with some force against the stops. It began with a sharp displacement in a direction of little south of east that is away from the origin of the shock. At Port-au-Prince, distance 520 kilometers, the instrument has higher magnifying power, namely 40; and in the beginning of the shock recorded very rapid vibrations; the early part of the movement was along the line from the origin, and had a range of nearly half a centimeter. On the arrival of the transverse waves about a minute later, the pens went beyond the limit of the record. During this and the following phases the range was more than a centimeter. At Ottawa, distant 3,100 kilometers, the range was less than 2 millimeters, and at Denver, distant 4,400 kilometers, it was less than 1 millimeter.

A consideration of the earth movements at Vieques and Port-au-Prince leads to the conclusion, that the range of the movement in the northwestern part of Porto Rico, may have been as much as 10 centimeters.

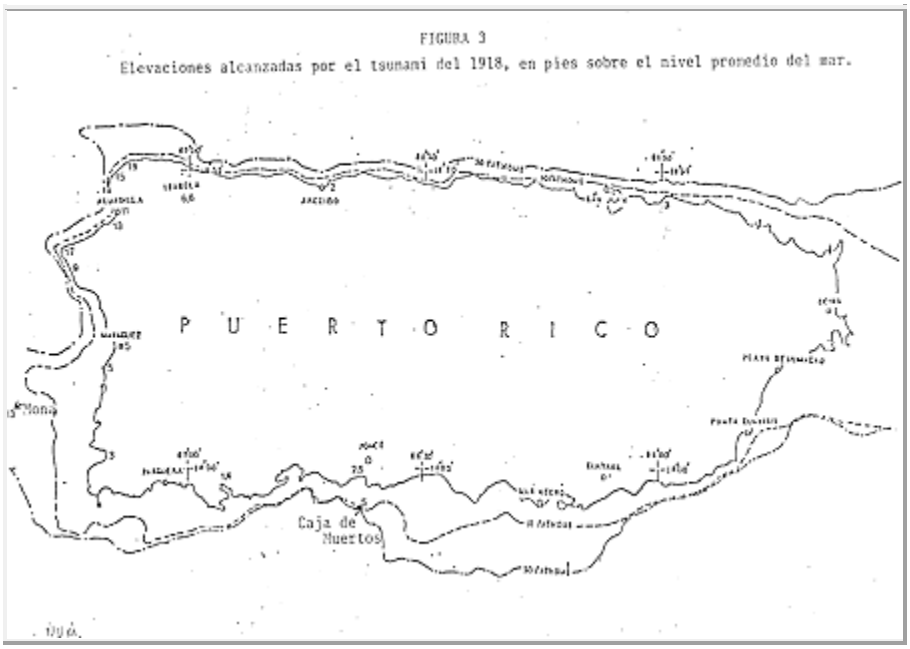
DESCRIPTION OF THE SEISMIC SEA WAVE

The great sea wave which followed the earthquake of October 11, was highest at the points near the corner northwestern of Porto Rico where it was observed almost immediately after the earthquake. In passing along the coast toward the east the wave decreased in height, thought not uniformly, and the time, and the time interval between the earthquake shock and the arrival of the sea wave gradually increased. Wherever the wave was seen on the coast of Porto Rico and neighboring islands, observers report that the ocean first withdrew from the land, in places exposing reefs and stretches of sea bottom never visible during the lower tides, and then the water returned, reaching height that were equally high above normal. Al some places the great wave was followed by one or more smaller ones, and, especially in shattered bays, the water continued to ebb and flow for some time.

At the Point Borinquen Lighthouse the keeper, who was up in the tower when the earthquake began, immediately started down the stairs, and as he went down he noticed that the water along the shore had already begun to recede. It returned quickly and measurements to point indicated by him show that the height reached by the water, not counting the wash of the wave, was about 4.5 meters above the sea level. Just the southwest of the lighthouse, where the land is lower, the water is reported to have washed inland 100 meters into a grove of coconut palms. The lighthouse keeper had the impression that the wave came from the northwest.

Near Point Agujereada the limestone cliffs are 100 to 120 meters in height, and their base is a narrow strip of beach which in the wider spaces was planted with coconut palms and used for pasturage. Several hundred palms were uprooted by the wave, and the beach was turned into a sandy waste. In this vicinity a few small housed were destroyed and eight people reported to be drowned Several persons visiting the district soon after the occurrence

estimated the height of the wave as 5.5 to 6 meters, and the evidence remaining at the time of our visit supported this estimates.



At many places we were able to make fairly accurate measurements of the height of the wave, as the water has entered the ground floors of houses staining wall paper and leaving a record that was plainly visible for a long time afterwards. At Aguadilla the height of the wave seems to have varied somewhat in different parts of the city, but at no place were the measurements less than 2.4 meters above sea level and near the head of the bay the crest of the wave must have been at least 3.4 meters in height. In this town, 32 people are said to have been drowned and about three hundred little huts, built along the beach were destroyed. Estimates at the time interval between the earthquake shock and the arrival of the sea wave, made by different observers, range from 4 to 7 minutes. One of the best estimates (5 to 6 minutes) was made by Mr. Manuel Jimenez, who, during the interval, ran a distance of 564 meters to meet his children and then walked with them 267 meters. He timed himself over the same course at a later date. The calculated time for the wave to travel from the earthquake origin to Aguadilla is 5 minutes.

The Columbus Monument, which stood on the beach near the mouth of the Culebrinas River, about four kilometers southwest of Aguadilla, was thrown down, probably by the earthquake, and rectangular blocks weighting over a ton were carried inland and slightly down hill by the wave to distances of 45 and 75 meters. The water washed over dune sand which was 3.4 meters above sea level and the effects on the vegetation indicated that the wave could not have been less than four meters high.

At the Point Jiguero Lighthouse the keeper, shortly after the earthquake, saw the ocean retire from the shore; and, upon returning about two minuets later, it uprooted coconut palms a short distance north of the lighthouse and crossed the railroad track, leaving fish between the rails, which are here 5.2 meters above sea level. At the time of our visit the vegetation by the track still showed marks of the rush of the water. For a short distance the coast to the southeast was somewhat protected by the point and the wave was much smaller. About a kilometer from the lighthouse it was 2.75 meters high, and a kilometer further it was only 2.6 meters in height.
At Mayagüez the sea wave entered the lower floors of buildings near the water front and destroyed a few native huts along the beach but did comparatively little damage. One small house was carried seaward by the retiring wave and left stranded a short distance from the shore. (See fig. 6.) Lighters and other small boats anchored 300 to 400 meters off shore were not affected. In the northern part of the city a narrow brick wall running S. 76^{o} E. was overturned by the wave. In this vicinity the water marks on houses indicates that the wave reached a height of 1.1 to 1.2 meters above sea levels. Farther south a water mark extending all around the office of the Bull Insular Line (Inc.) is 1.5 meters above sea levels; 3 gentlemen who left the Central Corsica near Rincon by automobile immediately after the earthquake arrived at Mayagüez before the sea wave was observed and this trip cannot be made in lass that 25 or 30 minutes. Some others estimated than an hour or more elapsed between the earthquake and the arrival of the sea wave; but perhaps they saw a latter wave, for the calculated interval is about 23 minutes.

About four kilometers southwest of Mayagüez the height of the wave was 1.4 to 1.5 meters, according to the measurements made to marks indicated by eyes witnesses.

At El Boqueron measurements made to some marks pointed out by observers indicate that the wave was about a meter high,; one observer stated that the ocean withdrew about about an hour after the earthquake, the water going out gradually during a period of twenty minutes. The calculated interval is about three quarters of an hour a small bout anchored about 50 meters from shore were the water is normally 1.5 meter in depth, rested of the bottom for a few minutes. The ocean returned more rapidly than its retired and the first wave was followed by several smaller ones.

At Guanica along the Plaza the waters reached a height of 38 to 48 centimeters above mean sea levels and a kilometers south east nearer the entrance to the bay the height was about 50 centimeter. The time when the water rose is indefinite. One observer put it at the time of the shock; but the sea wave could not have arrive until a halve hour latter.

At the Ponce Municipal Dock Mr. Lillian Gonzalez stated that there was a slight depression and revelation of the water level immediately after the earthquake, and that a similar phenomenon was observed at 2 p. m. Mr. Girdle keeper in charge of the Cordon Islands Light Station, reports that on the west side of the island the sea was rose 75 centimeters coming about 5 meters inland at El Metros Island Light Stain Mr. Bermuda the keeper in charge states that an hour after the earthquake the sea receded and then returned covering about 15 meters of beach about the normal shorelines. He estimates the the water rose about 1.5 meters above sea level.

The reports from point near Poncho are not very consistent, though this probably been expected were the wave has become small and less noticeable. Disturbances of water, such as those reported at Poncho and Guanaco immediately after the earthquake are probably due to oscillations of the lands.

The north coast of Porto Rico is beaten by the heavy waves of the trade winds belt, and therefore small fluctuations in the height of sea level are less noticeable than they are on the south and west side of the island. Moreover the houses, are not built so close to the shore as they are on the coast were there is more protection. For these reasons the wave especially are more distant places were it has become small, was noticed chiefly in the estuaries of large rivers.

At Isabela the wave was seen by several people who think that it came in about in half- hour or more after the earthquake. This estimate like many of the others is too long for the wave most have arrived in less that 15 minutes. The water withdrew slowly, and the returned slowly until is barely covered a ledge of rock about 2 meters above the mean sea level.

At Arecibo the wave is said to have been noticed ten or fifteen minutes after the shock witch correspond to the calculated time. It was 30 to 60 centimeters high. Mr. R. M. Palmer, the municipal engineer who washed the wave advanced up the Arecibo river estimated that it was about 10 centimeters height in the river and took perhaps three minutes to pass a given point

The wave was not noticed in the bay at San Juan, probably because it was small and was obstructed by the narrow entrance. Mr. H. W. R. Bunbury reports that near Convenes the water in the Rio Grande de Loisa receded and then rose about 1 meter above its normal height, the phenomenon occurring 25 or 30 minutes after the earthquake. The wave should have reached the mouth of the river about 20 minutes after the shock.

On the west coast of Mona Island the waters first retired, according to information obtained through Mr. Mare Lejeune, leaving the reef bare, and then after a short interval it returned, washing away a small pier and filling with salt water an open cistern about 4 meters above the sea level.

At Santo Domingo the director of the meteorological office reports that the earthquake was left at 9.32 a.m. Local time, and at 10.50 a.m. He noticed that the waters of the Ozama River had fallen about 70 centimeters (2 ½ feet). The water remained at this elevation about 10 minutes and rose nearly as high above its normal level. Other reports indicate that the water first fell about an hour after the first earthquake (the calculated interval is 53 minutes), leaving some small boats stranded until it rose again. The water continued to rise and fall with the period of about 40 minutes, for two or three hors.

This periodic movement of the waters is called a seiche, and is merely the oscillation of the water in its basin, just as waster swings back and forth in a small vessel when disturbed. The seiche at Santo Domingo was started by the arrival of the sea wave.

The wave was apparently noticeable as far east as the islands of St. Thomas and Tortola, although the timer of arrival reported by observers is much later than would be expected. Mr. S. Fisher, captain of the harbor at Charlotte Amalia, states that at about 1p.m. The waters in the bay rose and fell several times, the maximum height being about 45 centimeters. Mr. Lewis Monsanto reported to Capt. Fisher that at Krum Bay, just west of St. Thomas Harbor, the water commenced to rise about 12.30 p.m. And reached its maximum height of about 1.2 meters a half hour later, after which oscillations continued until 4 p.m. When the water was still unusually high. By evening it has returned to normal. This is another example of seiches started by the arrival of the sea wave.

The sea waves had an unobstructed sweep across the deep waters of the north Atlantic and were registered on the tide gauge at Atlantic City, N.J., about 2,200 kilometers north of the origin. The disturbance appears to have begun at 2 p.m., seventy-fifth meridian standard time, with a depression of the sea followed by an elevation, though this can not be determined with certainty; and the oscillations of the water level lasted for several hours. The amplitude of the waves was between 3 and 6 centimeters and the period between 10 and 15 minutes. This long continued movement does not seem to be a true seiche, but is probably due to the natural development of auxiliary waves following a short group set up by a sudden disturbance.

The tide gauges in N.Y. Harbor, at Key West, and at Colon, Canal Zone, did not register the waves. The first is apparently too well protected to register small waves with periods as low as 10 or 15 minutes; the second is protected by the great Bahamas bank; and the comparatively shallow water of the Mona Passage may have reduced the wave too much for registration at Colon.

LOCATION OF THE ORIGIN AND TIME OF THE SHOCK

All of the evidence collected is in accord with the conclusion that the earth vibrations and the sea wave were propagated from an origin in the north eastern part of Mona Passage. As the seat of the disturbance was under the ocean it is impossible to determine its exact location; but it could not have been far from latitude 18 30 north and longitude 67 20 west or, roughly, 15 kilometers west of Point Borinquen Lighthouse. The facts on which this conclusion is based are as follows

- The intensity of the earthquake shock was greater in the northwestern corner of Porto Rico that on any other place on land, and the isoseismals are roughly concentric about an area lying a short distance west of Point Borinquen.
- The direction i which many structures and movable objects were displaced in the western part of the island suggest that the principal horizontal motion was approximately along lines radiating from the area west of Point Borinquen. The evidence on this point is not conclusive but it is at least in accord with the other facts.
- The sea wave was highest along the northwest coat of Porto Rico and decreased progressively in all directions.
- The time interval between the earthquake and the arrival of the sea wave was shortest at points along the northwest coast of Porto Rico, and increased with the distance from that region.
- The submarine cables were broken at several places within the area bounded by parallels 18 25 and 18 35 north and meridians 67 15 and 67 30 west. Another cable a little to the east to this area was not broken.

The seismographic records of the earthquake do not fix the position of the origin with a high degree of accuracy. This is not to be wondered at when we remember that an error of one second in the record time of arrival of vibrations at the various stations in eastern North America would correspond to a difference of 10 kilometers in the distance of the origin; and unfortunately, we have not yet succeeded in making observations with that degree of accuracy. But, nevertheless, the errors to some extent balance and the records show without doubt that the origin lay in the northeastern part of the Mona Passage in the neighborhood of the position given.

The errors of the ordinary clocks, and the difficulty of exact observations at the time of a severe earthquake, make the general reports of the time of the shock mere approximations; but the seismographs at the various observations give, in general, pretty accurately, the time of the arrival of the vibrations, and form these it is possible to calculate the time of occurrence of the shock. By this means we find that the shock of October 11 occurred within a very few seconds of 10h. 14m. 38s. a. m. sixtieth meridian standard time, and it must have been felt all over Porto Rico and as far as Vieques Island within half a minute of this time.

CAUSE OF THE EARTHQUAKE AND THE SEA WAVE

The majority of severe earthquakes are believed to be due to the sudden relief of stress (slowly accumulated in the rocks near the surface of the earth) by the formation of new fractures or by new displacements along old fractures. A fracture along which there has been some slipping of the rocks is called a "fault". After a fault has been formed it often remains a place of weakness where stresses developing slowly in the adjacent rocks are relieved from time to time by renewed displacements. Some earthquakes may attributed to volcanic activity but they are seldom severe and are relatively few in number.

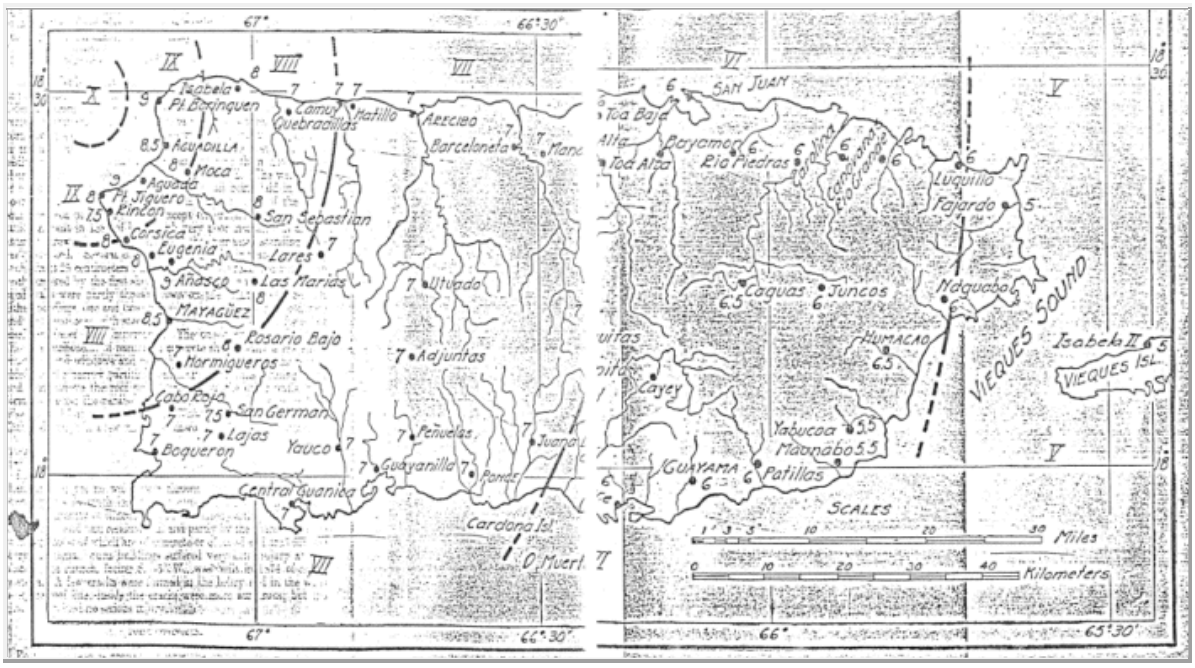
There is no evidence of volcanic activity in Porto Rico or in any of the other islands of the greater Antilles at the present time or in recent geologic time, although earthquakes have been of frequent occurrence throughout the region. On the other hand, there is conclusive geologic and topographic evidence that movements of elevation and depression, accompanied by folding and fracturing of rock strata, have been going on the region with relative rapidity in recent geologic time, and the indications are definite that these movements are still going on. Therefore there seems to be no escape from the conclusion that the recent earthquakes were due to sudden fractures of the rocks forming the bed of the ocean; and probably the fractures and displacements occurred along an old fault.

The displacement which caused the earthquake of October 11 appears to have been vertical. This reference is based on the evidence outlined below:

There has been a slow depression of the coast in the vicinity of Aguadilla during the last half century, and a gradual movement of this kind would account for the accumulation of the stress which resulted in the sudden displacement of the sea bottom. All the older residents of the town agree that the sea has been slowly encroaching on the land during the last 50 to 70 years; their estimates of the advance of the sea in that time range from 25 to 70 meters. They state that there was formerly sufficient space for enclosed gardens back of the houses on the west side of Comercio Street where now there is only a narrow strip of sandy beach. At times of low tide one can still see the piles which formerly supported a large frame house.

Observers in Porto Rico are unanimous in stating that the earthquake began with a marked vertical vibration. Such a movement is readily explained on the assumption of a sudden vertical displacement at the origin, for this would necessarily set up transverse vibrations of relatively large amplitude in which the motion would be vertical, and these vibrations would be readily propagated in all directions throughout the elastic rocks.

A seismic sea wave may be caused by a sudden vertical displacement of the sea bottom, but not a horizontal displacement, such as caused the California earthquake of April 18, 1906. The great wave which accompanied the Porto Rico earthquake approached the shore with the trough in front of the crest, for the water first withdrew from the land and them returned. This fact is in accord with the hypothesis that there was a sudden downward displacement of a limited area of the sea bottom.



The vertical displacement was probably at a maximum along the assumed fault and decreased progressively with the distance from the fault. This is to be inferred from the known behavior of elastic bodies when strained and fractured. The magnitude of the movement can not be accurately determined, but the maximum vertical displacement could hardly have exceeded 6 or 7 meters and may have been considerably less. Likewise, it is impossible to determine the distance the displacement extended along the fault, in a horizontal direction, although, judging from the distribution of the intensities, it was probably not more than a few tens of kilometers. The vertical displacement could hardly have been noticeable on the island of Porto Rico; the vertical motion generally reported was due to the vibrations mentioned above, in which the to-and-fro motion was in an interval plane.

A vertical displacement along a fault leaves an escarpment at the surface of the earth on the side that is uplifted; and where similar displacements are repeated many times the fault scarp may become a prominent topographic feature, providing it is not too rapidly reduced by erosion. A submarine scarp would suffer little from erosion, but in the

course of time it would be buried tales and marine deposits, Deposition is necessary slow, however, off the coast of a small island, such as Porto Rico, and therefore in this region submarine fault scarps should persist for a relatively long time.

An examination of hydrographic charts giving soundings made near the northwest coast of Porto Rico reveals the presence in that region of a most extraordinary submarine valley lying between Point Borinquen and Point Jiguero and extending in a northwesterly direction. It is characterized by slopes which are so precipitous that they can be explained only as the result of faulting. The descent into this valley from the 100-fathom line northwest of Point Borinquen amounts to 3,500 meters in a distance of less than 15 kilometers, thus exceeding in precipitousness the eastern scarp of the Sierra Nevada Mountains, where the descent from Mount Withney to Owens Valley is only 3,284 meters in 21 kilometers. For shorter distances both slopes are in places very much steeper. The slopes into the submarine valley from Desecheo Island, on the opposite side, are almost equally precipitous. The bottom of the valley slopes steeply down into Brownson Deep, which appears to be a troughlike depression extending in general east-west direction with its axis about 120 kilometers north of Porto Rico. The deepest sounding obtained in the Atlantic Ocean, 4,662 fathoms (8,526 meters), was made near the western end of this deep.

The axis of the submarine valley northwest of Porto Rico is in line with the smaller land valleys occupied by the Culebrinas River and the Rio Blanco, a tributary of the Añasco; and moreover, the Culebrinas River is closely parallel for a distance of over 30 kilometers to the contact between the Tertiary formations and the older rocks. These facts suggest that the position of the land valleys also may have been determined by faulting, but the evidence at hand is insufficient to warrant a definite conclusion, and detailed field investigations will be necessary before the suggestion can be tested.

Near the head of the submarine valley there are very steep slopes which fall into appropriate alignment with the similar slopes north of Desecheo Island and with the high cliffs east of Point Agujereada. These topographic features seemingly indicate the presence of a fault running transverse to the axis of the valley, but unfortunately the soundings are so widely spaced in this vicinity that definite conclusions can not be drawn. There is, however, good evidence for believing that the line of cliffs , extending eastward from Point Agujereada does represent a fault scarp which has been cut back only a short distance by wave erosion, for the youthful topography of the region near these cliffs indicates a geologically recent elevation of the land, whereas a long period of time would have been required to cut the cliffs by wave erosion, if the high land originally extended much further north.

A wave-cut bench at the foot of these cliffs marks the latest uplift of the land, amounting to several meters, and this uplift seems to have extended some distance toward the west, for a similar sea terrace is shown in a photograph by Lobick recently published by Jonhson, In the submarine valley and on the north side of the assumed fault there is evidence of a recent and rapid depression of the sea bottom; broken coral has been found at a depth of 1019 fathoms, although the reef-building coral can not live at depths of more than 25 fathoms, and in the lower part of the valley at a depth of 1761 fathoms the bottom is rocky, although at such depth the bed of the ocean is normally covered with ooze or clay; especially where there are no large land areas in the vicinity to furnish sedimentary materials. The currents in Mona Passage are weak and therefore unable to transport even the finer sediments.

A sudden fracture and vertical displacement of the rock along a fault near the head or on one side of the submarine valley would account for all the phenomena observed at the time of the earthquake of October 11; and the topography of the region indicates that such movements have taken place at various times in the past. The possibility of movement on several neighboring faults can not be excluded, for although many earthquakes have been caused by displacement on a single fault, others have been due to displacements on several related faults.

The cables ruptured by the earthquake swung around the head of the submarine valley avoiding the extreme depths, and lay near the top of the steep slopes. There is no evidence that the ruptures occurred directly above the fault and were caused by a displacement along it; rather it would appear that the cables were ruptured by landslides precipitated down the steep slopes by the violent vibrations of the earthquake.

AFTERSHOCKS

All severe earthquakes are followed by aftershocks which decrease gradually, though not uniformly, in frequency and in intensity. In some instances they continue for several years, while in others they die out rapidly. Some of the aftershocks may due to the extension

---

THE VIRGIN ISLANDS' EARTHQUAKES OF 1867-68

The end of 1867 was an unfortunate period for the West Indies. A disastrous hurricane swept over the northern islands of the 29th of October; and 20 days later came the destructive earthquake and great sea wave of November 18. Following the great shock numerous minor trembling were felt for a period of about six months, the greater number weak, but with occasional shocks of rather high intensity. The last severe shock occurred on March 17, 1868.

DESCRIPTION

The earthquake had its greatest intensity in the general region of the Virgin Islands; Mr. Otto Frederick Raupach sent the following account from St. Thomas to the Secretary of State in Washington, under date of December 28, 1867:

*The 18th of November was a beautiful clear day with a fine blue West India sky. * * * There was not the least sign of any kind to foretell this great convulsion in nature, when suddenly , at about a quarter of 3 o' clock in the afternoon, there was heard an underground rumbling noise which was immediately followed by a terrific earthquake, which seemed to come from south-by-west, and pass on to the north-by-east. The earth seemed as if composed of small waves rising and sinking under your feet, so that if you made a step forward, your foot seemed to meet higher ground, and if you put it backward it also there met higher ground. To stand still in one spot was impossible, and when trying to walk it was as if something kept you back. The underground sound, while the first shocks was going on, for for about one minute and a half was most dreadful. It terrified every living soul. The sun seemed at once to*

become dim; it was as if eclipsed, and this dimness lasted that first day until sunset, and continued the whole of the next day, but in the less degree, and it only wore away entirely in the course of two days more. It was as if the sun, though apparently as bright as usual, had lost some of its warming and illuminating, power. After the first terrific shock the ground continued groaning and trembling, when about 10 minutes after a second strong shock was felt. Directly after this second shock the ocean, which shortly before the first shock had receded from the land several hundred feet seen to rise like one huge wave and come in toward the harbor. It stood up like a straight white wall, about from 15 to 20 feet high, and advanced very fast into the harbor, sweeping or upsetting small vessels before it, and rising the large men of war and steamers to its top. The appearance of this wave was like a white masonry wall, erect and straight as if built with the aid of a rule; it had not the appearance of ordinary waves. It broke in over the lower parts of the town to the height of a couple of feet and the extent of about 250 feet inland, according to the level of the locality. The rising of the waves was repeated a second time after an interval of about ten minutes, and the second appeared to be even a little larger than the first and went a little farther inland. After these two waves had passed away, the ocean remained, as fast as the eye could see quite calm again, just as it was before the first shock of the earthquake had occurred.

The shocks continued and were felt every few minutes, it was as if the shocks on the first day hung together in one chain, but from 2.45 o' clock on the morning of the 19th of November, the shocks were felt more separately and distinct and therefore , seemed as if they were more frequent.

From 2.45 o' clock p.m. On the 19th till 2.45 a.m. On the 19th there were 89 shocks. From 2.45 o' clock a.m. The 19th till midnight there were 233 shocks. The shocks became less severe from the 21st of November

The effects of the great waves in the harbor of St. Thomas are graphically described in the following reports of United States naval officers:

Flagship "Susquehanna,"

St. Thomas, W. I., November 19, 1867.

SIR: I beg to inform the department of an extraordinary occurrence producing much disaster which took place in the harbor yesterday afternoon.

The weather was clear though extremely hot-barometer 30. Whilst writing in my cabin about half past 2 p. m., my attention was attracted by a sudden tremor seizing of a vessel upon a rough bottom; the gradually subsiding until it ceased; the hole last in about two minutes. I recognized it immediately as an earthquake and look in towards the town saw from the dust and confusion there must be destruction among its building. Concluding it was now over I resumed my occupation and had been ceased about 10 minutes when the report was bought to me that the sea outside of the harbor has risen, and was coming in a huge volume as if to engulf us all.

I went on deck and here the extraordinary expectable of a heavy wall of sea, some 20 feet in height apparently distant about three miles , was coming toward the harbor with terrible power.

The second anchor was immediately dropped, men sent to the helm; which was all we could do , and then stood prepared to meet it as it advanced with a skirmish line of tumultuous rollers in front. I saw with some comfort it

came from about SSW., and would consequently strike the entrance of the harbor on in an oblique direction. With a felling of awe we awaited its arrival, it came rushing on tumbling over the rocks that formed the entrance, carrying everything before it. A small steamer and sailing vessel, that were trying to get in were at once engulfed and never again seen and the vessels at anchor near the entrance were lifted from their moorings and carried on to the rocks to leeward.

Receiving this check the heavy rollers swept in to the harbor. The De Soto which was anchored outside of us, and was lying rather broad side to, was carrying from our moorings both chains snapping, and thrown apart the iron piles of a new wharf lately constructed the necks roller swept her of into deep water again and soon she made signal she was leaking

In the meanwhile, however, we had risen upon the roller which we met nearly stand on- encountered three in succession- the anchor and chains holding on bravely the sea was now rushing in and receding with great violence the sunken incocks where rising the ship in the harbors swept in their moorings were coming into us every few minutes, the small craft in shore were lifted up and thrown into streets and left stranded along the water front- boats were capsized and men in the water swimming for their lives.

At last the water in the bay subsided into a sort of whirlpool; so soon as we could with any propriety man our boats, they were sent to the rescue of the drowning men- several were picked up, one already dead.

The De Soto was now adrift whirling about the harbor, her pumps going, and getting up her steam as rapidly as possible. I went on board of her and found she could keep herself free, and with her steam up and two kedges down she would remain in safety for the night.

Constant shocks of earthquakes occurred every 10 or 15 minutes and so continued with more or less severity through the night, and as I am now writing this, are still going on.

The damage on shore has been far more ruinous to the merchants than that accessioned by the hurricane. The first heavy roller went up into the town swapping the stores which were mostly on the bay front, throwing out and finally stranding their goods in unheard of directions.

The panic the seized the inhabitants was painful, rushing up the hillsides, crying for mercy, and listening to no attempts to pacify them. As I went ashore in the evening I found all the stone dwelling were abandoned, their owners either in the streets or in the wooden buildings of their friends, the alarm being still kept up by the constant shocks still occurring.

This morning the shocks are less frequent and the bay perfectly quiet.

The English mail steamer which had lately arrived and was coaling in the bay on the other side of the harbor, was nearly being lost as possible. Her passengers speak of having felt the shock as we did, and looking behind them saw a small islet in their rear cleft in twain, flames and smoke issuing from the fissure. Shortly afterwards the sea arose and came wall-nigh carrying them down. Their cables parted, but they were thrown most fortunately under a lee which placed them in comparative safety. The passengers all but three (females) who were lost in the surf, reached the shore. Just now a vessel has arrived from Santa Cruz bringing an officer of the Honongahela, who brought me a

verbal message from Commodore Bissell, saying the shock of the earthquake had been most violent at that island, that the sea has risen, and thrown his vessel high and dry on the beach, that three of his men who were in the boats alongside were drowned. I leave this evening for Santa Cruz to see what assistance I can render him.

The damage sustained by this ship is not material.

Very respectfully, your obedient servant,

J. S. Palmer,

Rear Admiral Commanding North Atlantic Squadron.

Hon. Gideon Welles

Secretary of the Navy, Washington, D. C.

****

U. S. S. "De Soto," (2 RATE)

Island of St. Thomas, November 21, 1867.

Sir: I respectfully submit the following report of the earthquake of the afternoon of the 18th of November and the situation of this ship during that time.

This ship was anchored near the southeast of the harbor nearer the shore and the mouth of the harbor than any other vessel; in 4 ¾ fathoms starboard anchor, 15 fathoms of chain; and on the following bearings, viz., Prince Rupert Rock S. ¼ E., Fort Christian N. W. by N. ¼ N., the small pox hospital W. ½ N., and the iron wharf of the Liverpool Steamship Co., S. S. E.

At 2.50 p. m. when in the cabin, experienced a very heavy shock of an earthquake; (severe at first, then lighter and lasting with slight intermissions, from two to four minutes), on reaching the deck, found the water rushing out of the harbor with great violence. Immediately gave orders to get to the port, and sheet anchor, and veer chain, getting an equal strain on all.

In a few minutes a great wave was seen approaching from the southeast between the islands of St. Thomas and St. Croix. Reaching soundings it began to break, assuming the appearance of a great "bore," not less than 23 feet in height; this wave was broken and retarded more and more by the shoal water, especially by Prince Rupert's Ledge. At the mouth of the harbor. "Called all hands save ship. "This wave as it passed into the harbor swung ship with extraordinary rapidity with her head to the southward, closing a great rise in the water of the harbor that raised above the wharves is in front of the city about 8 feet, and at the same time swamping our boats at the booms; the receded as violently, the ship appearing as a mere feather on the surface this ebb parted both bower chains, leaving us with only a light sheet anchored of 1500 pounds and 45 fathoms of cable. We swung toward the shore, were the current was most irregular and full of whirlpools. At the first swing of the ship we had six fathoms under our stern; the ebb was so rapid that in a few minutes we took the bottom, having only 1 ¼ fathoms under us. Just before

swinging to the ebb the middle part of the iron wharf suddenly gave way, and when we took the bottom we seemed to be deposited among the debris of the iron piles. A second wave soon came in much in greater volume than the first, or any of them. I think the water rose 20 feet above were it had fallen: the island appeared to be sinking when the next ebb came we swung against the ends of the iron wharf that still stood (but soon gave way and disappeared entirely), injuring the starboard wheel and forcing a 6-inch iron pile through the ship forward the wheel, starboard side, and about two feet below the water line. Other injuries appeared to be sustained, the ship leaking badly. All the guns were manned.

During this time the chief engineer was making every effort to fill his boilers and get up steam. The crew employed from the hold, and heaving in the parted chains the steam anchor was dragged at every change of the current; we were spinning around and toward the mouth of the harbor with frightful rapidity, as much as if she had been under a heavy head of steam.

The third wave was not so large as the two first, and the forth did not appear to rise more than 12 or 15 inches. By this time we had driven over toward the western entrance of the harbor, when as she swung her stern took the bottom, scraping on the rocks. At this moment the engineer reported steam, and turning the engine over we took her sufficiently far from the rocks to let go a small anchor that had been gotten up from the hold. From this time we were able to control the motions of the ship so far as to keep her clear of the bottom, and starting the steam pumps we were able to control the leaks. The ship must have swung around all points of the compass not less than 20 times. The waves still came in at unequal intervals until long after dark, when, heaving up the anchors, we were able to take a more central position in the harbor.

****

Acting Chief Engineer Hebard and all in his department are deserving of great praise for the rapidly with which steam was raised (being one hour and five minutes from empty boilers), besides rendering revise wherever they could be useful.

****

The soundings during the ebb flood of the water, taken from the stern and stem of the ship, varied from 1 to 8 fathoms at places where in ordinary state of water there is 4 ½ fathoms.

I have the the honor to be, very respectfully, your obedient servant,

W.H. Boggs,

Commodore Commanding, St. Thomas, W.I.

Rear Admiral J.S. Palmer,

Commanding North Atlantic Squadron

The mail steamer *La Plata,* referred to by Admiral Palmer, lay at anchor near Water Islands, outside the harbor. She reported heavy shocks about 2.30 p.m., followed by two immense waves. The first caused no important injury, but the second carried off two or three boats. The shocks were repeated during the day and the night, but the sea remained quiet.

From other reports we learn that many walls were thrown down in St. Thomas, and that practically all houses sustained injuries. The people camped in the open.

In St. Croix the shocks was nearly as severe as in St. Thomas; there were two severe shocks, one immediately after the other, lasting about three minutes, and many minor shocks; nearly every plantation suffered some injury to the dwelling house, the mill, or the works. The waves broke upon the northern and western coasts of the island with great violence, washing many vessels and boats ashore, sweeping away some ,smaller houses and doing great injury to others.

The U.S.S. *Monongahela* had a most thrilling experience in the harbor of Frederiksted, on the west coast. Her commander, Commodore Bissell, sent the following report to Rear Admiral Palmer:

U.S.S. "Monongahela" (2 RATE)

St. Croix, November 20, 1867

Sir: I have to state with deep regret that the Monongahela under my command is now lying on the beach in front of the town of Frederiksted, St. Croix, were she was thrown on the 18th instant by an influx of the sea, the effect of the most fatal earthquake ever known here. Shock occurred about 3 o' clock p.m. Up to that time the weather was serene. No indication of a change shown by the barometer, which stood at 30° 15. The first indication we had of the earthquake was a violent trembling of the ship, resembling the blowing off of steam from the boilers . This lasted some 30 seconds, and immediately after the water was observed receding rapidly;y from the beach. The current changed almost immediately and drove the ship toward the beach carrying out all the cable and drawing the bolts from the keelson without the slightest effect in checking her terrific speed toward the beach.

Another anchor was ordered to be let go, but in a few seconds she was in too shoal water for the anchor to be of any avail.

When within a few yards of the beach the reflux of the tide checked her speed for a moment, and a light breeze from the land gave ma a momentary hope that the jib and foretop-mast stay sail might pay her head off shore and thus in the reflux of a wave be taken in water sufficiently deep to float, and be then brought up by the other anchor these sails are immediately set and she paid off so as to bring her broadside to the beach.

When the sea retuned in the form of a wall of water 25 or 30 feet high it carried her over the warehouse into the first street fronting the bay. The reflux of this wave carried her back toward the beach leaving her nearly perpendicular

on a coral reef, where she has now keeled over to an angle of 15°. All this was the work of only some 3 minutes of time.

Soon after the waters of the bay subsided into their naturally quiet condition, leaving us high and dry on the beach.

During her process toward the beach she stuck heavily two or three times.

The first lurch carried the rifle gun on the forecastle overboard. Had the ship been carried some 10 or 15 feet farther out she must inevitably have gone on her beam end, resulting I fear , in her entries destruction and in the loss of many lives. Providently only three men were lost, these were in the boats at the time the shock commenced. The boats that were down were swamped with the exception of my gig which was crushed under the keel killing my coxswain, a most valuable man. During this terrible scene the officers and crew behaved with coolness and subordination.

****

Gentlemen ashore who were looking at the ship when the shock occurred declared that the bottom of the bay was visible were there was before and is now 30 or 40 fathoms of water.

****

Very respectfully your obedient servant,

S. B. Bissell,

Commodore, Commanding.

Rear Admiral J. S. Palmer

Commanding N. A. Squadron

It is a satisfaction to know that the *Monogahela* was latter floated off. The US gunboat *Wateree* had a similar experience in the harbor of Africa, Peru, at the time of the great earthquake and wave of August 13, 1868. She was carried a quarter mile inland and left hi and dry at the shore without serious injuries; but she was never refloated.

Dr. Taylor, "Leaflets from the Danish West Indias," writes of St. Croix:

Basin [Christiansted on the north shore] was a suffer; but to no so great of degree [as Fredericksted] owing to its reef thought at a place called"Gallows Bay" some 20 houses were demolished.

He apparently is referring to the effect of the wave.

The other islands of the Virgin group felted the shock twice as almost as severely. In Tortola the main shocks lasted 15 minutes; and were followed by scores of weaker ones; all the buildings were injured. In the beginning the movements was vertical but later became horizontal. The sea sank and then roused 5 feet above its usual level submerging the lowest part of the town and sweeping away most of the smaller houses. At Peters Island 3 or 4 miles

farther south the people were so alarmed by the earthquake and the wave that they took to their boats and were to Tortola.

Still farther east some damage was done in the island of Saba, St. Martin, and St. Bartholomew; a high wave is said to have invaded Saba islands; and the sea rose pretty high at St. Christopher. In Antigua that shock was called"severe, " which must be an exaggeration probably due to the alarm caused by the sea which was reported to have arisen 8 or 10 feet in the harbor of St. John on the west coast of the island. The shock was weakly felt in Guadeloupe and Marie Galante and apparently not art all in Martinique. There is no report from Dominica, but it is possible that the shock was barley sensible there. At Basseterre, Guadeloupe, toward three o'clock the sea suddenly retired a long distance and then after a certain interval advanced; this phenomenon was repeated once and then all was quiet. The total range in the height of the sea in its lowest to its highest level was about 2 meters. From Deshayes and Sainte Rose in the northwestern part of the island comes a more sensational report; the sea is said to have withdrawn and to have returned in a wave "at least 60 feet high" which broke over the shore and carried off all floatable objects. Three of this great waves are described. The account is undoubtedly much exaggerated. In both the accounts from Guadeloupe the waves are said to have arrives at three o'clock and immediately after the live shocks. There was an error either in the reports or in the clocks of the islands; probably in both; for the shock must have been felt about three o'clock local time, and the waves must have arrived about an hour later.

Point-a-Pitre and the southern side of the island seems to have felt the shock; but it is so protected, at the head of the Petit Cul de Sac that the waves were barely, if at all noticeable there.

The waves were also noticed at Martinique, but have no description of them; at St. Vincent "the water was observed to be unusually high; but nothing occurred to attract attention", though at Becquia Islands or 10 of 15 miles farther south there were three great slow waves, the water rising about six feet above its usual level the whole event lasted about 40 minutes, and the water was not in the least agitated.

The next island from which we have a report is Grenada; at St. George about 5.20 p. m., the sea suddenly sank 4 or 5 feet leaving the reef in front of the lagoon bare; it these rose as much. This was repeated six times and then all was quit at Gouyabe, near by the sea began to ebb and flow at five p. m. with a rage about 20 feet, doing some damage to the town. Twenty feet seems to be an exaggeration; the time of the waves seem also inaccurate; the would have arrived there about 4.30 p. m. local time. The shock was not felt in Grenada the slight shock felt in that island at 9 p. m. November 18, and at 1 a. m. of the 19th, where probably connected with the strong shock on the South American coast on the 19th .

Turning now toward the west, we find the the shock was very severe in Vieques and in Culebra but we have no details. Immediately after the shock a high wave broke on the south side of Vieques and later washed its northern shore.

The shock was strong all over Porto Rico, very severe in the eastern part, and diminishing in strength towards the west. At Fajardo the church, badly built of mamposteria, was left in ruins there was a small wave at the coast, the water withdrawing first and then advancing. At Naguabo, the church already injured by the hurricane of October 29, received further injuries so that it had to be closes; the sea advanced several meters on the shore. At Yabucoa the

church was severely injured; and the road of to Maunabo over the Panduras Ridge was blocked by landslides. The alcalde at Yabucoa that the sea retired a 150 yards and then advanced a equal distance over the land. At Loiza many cracks were made in the church on account of the poor material used in constructing the newer parts, the sustained the greater damage. Caguas did no suffer so much, some cracks appeared on the church, but they were not very serious and the church was not closed. At Guayama the church suffered much, a part of the roof falling in. On the coast at Arroyo, to the east and Salinas to the west the sea wave was high; at Arroyo it advanced 40 meters over the land. The church at Cayey suffered some slight damage. The cornices felt and wide cracks open in the walls of the church at Cidra, then recently constructed the next morning the front wall fell. At Guaynabo cracks appeared in the walls and roof of the church, allowing the rain water to pour in at many places. Buildings were damaged also in Rio Piedras and Bayamon. In San Juan the cathedral as well as the church of San Jose, and many houses, received more or less injury though no walls were thrown down; the repetition of the shocks caused a general panic. The parochial church at Manati suffered serious damage and had to be closed for repairs; but this was due to the fact that it had been much weakened by the earthquake of August 30, 1885, and the hurricane of October 29, 1867. The churches of San Francisco and Santa Ana, in the same town, suffered less, and were not closed. At Ponce cracks were formed in the walls and roof of the church; but this building had been weakened by the earthquake of August 30, 1865; and it suffered also because there were delays in making the necessary repairs to the leaking roof. The church at Guayanilla and the old abandoned church of Santo Domingo, at San German, were slightly cracked. Along the western part of the southwestern coast of Porto Rico, following the earthquake, the sea retired and then advanced, but the wave was small. Slight cracks were developed in the churches at Camuy and Isabela, but none at Qubradillas. Though the shocks were strongly felt along the western shore of the island, no reports of damage have come to us except at Añasco, where the church is said to have suffered severely. It is probable that the report is exaggerated, though the foundation on which Añasco is built would account for greater damage there than in other neighboring places, just as in 1918.

Earthquake shocks were felt at Santo Domingo in the latter part of 1867 and the early part of 1868. This very indefinite report probably refers to the Virgin Islands shocks, as the strongest ones must have been felt in Santo Domingo.

The shocks were reported to have caused damage in Cuba, Jamaica, and even in Mexico; but they were certainly not felt west of Santo Domingo.

ORIGIN OF THE EARTHQUAKES

Porto Rico is bordered by a fairly bench, having a depth of 10 to 20 fathoms, which extends to the east as far as the Anegada Passage. From the rise the islands, Vieques, Culebra, and the whole Virgin group with the exception of St. Croix. At the edge of the bench the sea bottom drops at a very steep slope to a depth of many hundred fathoms. On the southwestern coast of Porto Rico the edge lies within three or four kilometers of the shore, it then strikes a little north of east, passing within about 6 kilometers of Vieques, and about 16 kilometers of St. Thomas. It then passes around the Virgin group and returns along the northern coast of Porto Rico. Near the middle of the triangle formed

by Vieques, St. Thomas , and St. Croix, the depth is very great, amounting 2,500 fathoms. This is the deepest part of a great channel, connected with the Caribbean Sea to the southwest at depths of 900 to 1,00 fathoms, and with the Atlantic through the Anegada Passage at depths of over 1,000 fathoms. St. Croix partially limits this channel on the south rising with extraordinary steepness from great depths. At one point only 6 kilometers from the shore the depth is 2,376 fathoms. Vaughan considers that this channel has been formed by the depression of its bed between great fractures in the rock, being what geologist call a fault trough; and that the depression was formed in very recent geological times. All considerations favor this view, and it is fairly certain that the trough, even at the present time, is growing deeper.

We may place the origin of the earthquake near the northern limit of this channel, 16 to 17 kilometers south of St. Thomas, and consider that the shock was due to a vertical movement along a fault, the rock to the south of the fault springing down, and that to the north springing up. The length of the fault active at this time was probably some tens of kilometers, but there are no means of determining it.

The evidence for this location is fairly good.

The shock was about equally strong in St. Croix and the northern Virgin Islands, becoming weaker at points more distant from this group. This would require the origin to be about equally distant from these islands-that is, practically between them.

The sea waves approached St. Croix from the north, which again places the origin between these islands.

The great speed with which earthquake vibrations are transmitted, and the approximate character of ordinary time observations, make it useless to attempt to derive information from the reported times of occurrence of the shock at different places. But the interval of time between the shock and the arrival of the wave enables us to form fairly good estimate of the distance of the origin. Commodore Bogg's account suggest a very short time between the shock and the arrival of the waves, and a short time before the latter subsided; but his praise of his chief engineer for raising steam so quickly, "one hour and five minutes from empty boilers," and the fact that the water in the harbor had not quieted down when the engineer "reported steam," make it evident that the disturbance continued a much longer time than would be inferred from a casual reading of his report.

Rear Admiral Palmer is more definite as to time. He felt the shock for about 2 minutes; he then sat in his cabin about 10 minutes; he then went on deck and saw the great wave, "apparently distant about 3 miles." The depth of the water in front of St. Thomas, about 11 fathoms, is such that the wave would travel this distance in about 6 minutes. Making due allowance for errors in the estimates we conclude that the wave reached the harbor of St. Thomas between 14 and 18 minutes after the shock. A simple calculation shows that the wave would require 16 minutes to travel from the edge of the shelf to the harbor.

Commodore Bissell describes the various changes in the currents in Fredericksted Harbor, St. Croix, the letting go of the anchor on the *Monongahela*, the setting of the staysails, the approach of the great wave, and the stranding of his ship, and adds: "All this was the work of only some three minutes of time." This estimate seems impossible, unless it refers merely to the action of the great wave. A wave From the assume origin of the earthquake would, on

account of the great depth of the water, have taken about nine and half minutes to reach Fredericksted, though the distance is between three and four times as far as to St. Thomas; the course to St. Croix is over very deep water.

CHARCTERISTICS OF THE SHOCKS

The various descriptions of the earthquakes are not entirely consistent, but they enable us to from a pretty good idea of what happened. Light shocks had been felt a pretty good idea of what happened. Light shocks had been felt in St. Thomas an November 12, and again on the 17th, the day before the great earthquake; and they probably directly connected with it. But light shocks were not uncommon at St. Thomas and those mentioned did not arouse any apprehensions. The great earthquake began about 2.50 p. m. without definite warning, and was accompanied by a deep rumbling sound. The shock was very violent and lasted about two minutes, destroying the houses in the neighboring islands, and sending clouds of fine dust from mamposteria of which the houses wee built; it took more than a day for this dust to settle. Landslides an Little Saba Island, 6 or 7 kilometers southwest of the harbor, gave rise to a rumor of volcanic action there. The earth continued to tremble, but whit much less violence, and at the end of about 15 minutes came a second shock more violent than the first. The trembling continued, but soon quiet intervals appeared and gradually the disturbance changed into separate light shocks, the quiet intervals increasing in length. In St. Thomas and Tortola we have pretty clear evidence that the motion was vertical during the heaviest shock, becoming horizontal later. In St. Thomas, St. John, Tortola, St. Croix, Vieques, and Culebra the intensity was about IX, in the eastern part of Porto Rico it was about VIII, diminishing to about VI in the western part of the island, and getting as low as III in Santo Domingo. On the islands of St. Martin and Saba the intensity was about VI, at St. Bartholomew, V-VI, at Antigua about IV, and at Guadeloupe And Dominica about III. Thus the greatest distance to which the shock was felt was about 500 kilometers from the origin.

A great sea wave was started by the first shock, and the second larger one by the second shock some 15 minutes later. Other waves followed