Caribbean Earthquakes and Hurricane Technical Report
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Acknowledgment

Ms. Billie Foster edited, formatted, and provided the necessary support required to finish the report. Dr. Tony DiRienzo contributed to the report the technical description of the Richter Scale used as a tool to measure the magnitude of earthquakes since 1935. Dr. DiRienzo has provided several examples showing the effects of parametric changes of the equation that impacts the magnitude of the earthquake and its effects.

Introduction

The purpose of this report is to assess what is the best area to invest in a commercial enterprise with minimum risk of being exposed to hurricanes and earthquakes. There are three areas addressed in this report: Costa Rica, Dominican Republic and Puerto Rico. The stability of the governments of Costa Rica and Dominican Republic have been scrutinized and analyzed. Costa Rica is exposed to earthquakes, volcanoes and hurricanes. Costa Rica's governance and economy have been stable for over 60 years. Costa Rica has had ten earthquakes (3.0 to 7.6) for the period December 12, 2009 to 24 January, 2010. The Dominican republic is exposed to hurricanes, frequent mild earthquakes, and Tsunamis. The Dominican Republic has won the Turismo first place in the Caribbean since 2007, previously held by Puerto Rico. The Dominican Republic ha had two major earthquakes (8.0 and 1.3 magnitude) in 1946 and 2003. Puerto Rico had four major earthquakes (1670, 1787, 1867, and 1918) and several major hurricanes. Puerto Rico had several minor earthquakes below a magnitude of 3.0. Adjuntas had a 2.1 indirect earthquake one hundred years ago. Annex A provides a chronology of hurricanes for the period 1780 thru 2007. Annex B provides a chronology of the earthquakes in the Caribbean.

The report is comprised of the main body, a technical report of the history of earthquakes, its effect on the Caribbean Islands and mainland, and the risks associated with each region. Great emphasis was placed on the Puerto Rican trench that is about 25,000 feet deep (the deepest spot in the Caribbean Sea). A brief description of the Richter Scale is explained. There are three sections: A Chronology of Hurricanes in the Caribbean and a Chronology of Earthquakes in the Caribbean.

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The Dominican Republic is exposed to hurricanes, frequent mild earthquakes, and Tsunamis. The Dominican Republic has won the Tourism’s First Place in the Caribbean award in 2007, previously held by Puerto Rico. The Dominican Republic has had two major earthquakes (8.0 and 7.3 in magnitude) in 1946 and 2003. Puerto Rico has had four major earthquakes (1670, 1787, 1867, and 1918) and major hurricanes. The major earthquakes were in 1867 and 1918. Puerto Rico has had several minor earthquakes below a magnitude of 3.0. Adjuntas had a 7.1 indirect earthquake one hundred years ago. Annex A provides a chronology of hurricanes for the period 1780 thru 2007. Annex B provides a chronology of the earthquakes in the Caribbean for the period 1615 thru 2009.

Earthquake History

It is estimated there are 500,000 detectable earthquakes in the world each year. 100,000 of those can be felt, and 100 of them cause damage.

It was recognized as early as 350 BC by the Greek scientist Aristotle that soft ground shakes more than hard rock in an earthquake. The deepest earthquakes typically occur at plate boundaries where the Earth's crust is being subducted into the Earth's mantle. These occur as deep as 750 km (400 miles) below the surface.

The earliest recorded evidence of an earthquake has been traced back to 1831 BC in the Shandong province of China, but there is a fairly complete record starting in 780 BC during the Zhou Dynasty in China.

The earliest reported earthquake in California was felt in 1769 by the exploring expedition of Gaspar de Portola while the group was camping about 48 kilometers (30 miles) southeast of Los Angeles. The largest recorded earthquake in the world was a magnitude 9.5 in Chile on May 22, 1960.

It is thought that more damage was done by the resulting fire after the 1906 San Francisco earthquake than by the earthquake itself. Florida and North Dakota have the smallest number of earthquakes in the United States.
Alaska is the most earthquake-prone state and one of the most seismically active regions in the world. Alaska experiences a magnitude 7 earthquake almost every year, and a magnitude of 8 or greater on average every 14 years.

The average rate of motion across the San Andreas Fault Zone during the past 3 million years is 56 mm/yr (2 in/yr). This is about the same rate at which your fingernails grow. Assuming this rate continues, scientists' project that Los Angeles and San Francisco will be adjacent to one another in approximately 15 million years.

The world's greatest land mountain range is the Himalaya-Karakoram. It contains 96 of the world's 109 peaks of over 7,317m (24,000 ft). The longest range is the Andes of South America which is 7,564km (4700 mi) in length. Both were created by the movement of tectonic plates.

Each year the southern California area has about 10,000 earthquakes. Most of them are so small that they are not felt. Only several hundred are greater than magnitude 3.0, and only about 15-20 are greater than magnitude 4.0. If there is a large earthquake, however, the aftershock sequence will produce many more earthquakes of all magnitudes for many months.

The magnitude of an earthquake is a measured value of the earthquake size. The magnitude is the same no matter where you are, or how strong or weak the shaking is in various locations. The intensity of an earthquake is a measure of the shaking created by the earthquake, and this value does vary with location.

The Wasatch Range, with its outstanding ski areas, runs North-South through Utah, and like all mountain ranges it was produced by a series of earthquakes. The 386 km (240-mile) long Wasatch Fault is made up of several segments, each capable of producing up to a M7.5 earthquake. During the past 6,000 years, there has been a M6.5+ about once every 350 years, and it has been about 350 years since the last powerful earthquake, which was on the Nephi segment.

There is no such thing as "earthquake weather." Statistically, there is an equal distribution of earthquakes in cold weather, hot weather, rainy weather, etc. Furthermore, there is no physical way that the weather could affect the forces several miles beneath the surface of the earth. The changes in barometric pressure in the atmosphere are very small compared to the forces in the crust, and the effect of the barometric pressure does not reach beneath the soil.

From 1975-1995 there were only four states that did not have any earthquakes. They were: Florida, Iowa, North Dakota, and Wisconsin.

Earthquakes occur in the central portion of the United States too! Some very powerful earthquakes occurred along the New Madrid fault in the Mississippi Valley in 1811-1812. Because of the crustal structure in the Central US which efficiently propagates seismic energy, shaking from earthquakes in this part of the country are felt at a much greater distance from the epicenters than similar size quakes in the Western US.

Most earthquakes occur at depths of less than 80 km (50 miles) from the Earth's surface.

The world's deadliest recorded earthquake occurred in 1556 in central China. It struck a region where most people lived in caves carved from soft rock. These dwellings collapsed during the earthquake, killing an estimated 830,000 people. In 1976 another deadly earthquake struck in Tangshan, China, where more than 250,000 people were killed.

Florida and North Dakota have the smallest number of earthquakes in the United States. The deepest earthquakes typically occur at plate boundaries where the Earth's crust is being subducted into the Earth's mantle. These occur as deep as 750 km (400 miles) below the surface.

The majority of the earthquakes and volcanic eruptions occur along plate boundaries such as the boundary between the Pacific Plate and the North American plate. One of the most active plate boundaries where earthquakes and eruptions are frequent, for example, is around the massive Pacific Plate commonly referred to as the Pacific Ring of Fire.

The cause of earthquakes was stated correctly in 1760 by British engineer John Mitchell, one of the first fathers of seismology, in a memoir where he wrote that earthquakes and the waves of energy that they make are caused by "shifting masses of rock miles below the surface."

In 1663 the European settlers experienced their first earthquake in America.

Earthquake Facts

Table I illustrates the total frequency of occurrence of earthquakes with its magnitude based on observations made by the US Geological Survey National Earthquake Information Center. Table II illustrates the magnitude change associated with ground motion change and energy changes of the earthquake. Table III illustrates the number of earthquakes worldwide for the period 2000 - 2010.

Table I - Occurrence Frequency of Earthquakes

Magnitude	Average Annually
8 and higher	1 [1]
7 - 7.9	17 [2]
6 - 6.9	134 [2]
5 - 5.9	1319 [2]
4 - 4.9	13,000
(Est)	
3 - 3.9	130,000
(Est)	
2 - 2.9	1,300,000
(Est)	

[1] Based on observations since 1900.
[2] Based on observations since 1990.

Table II - Magnitude vs. Ground Motion and Energy

Magnitude Change	Ground Motion Change (Displacement)	Energy Change
1.0	10.0 times	Est 32 times
0.5	3.2 times	Est 5.5 times
0.3	2.0 times	Est 3 times
0.1	1.3 times	Est 1.4 times

This table shows that a magnitude 7.2 earthquake produces 10 times more ground motion than a magnitude 6.2 earthquake, but it releases about 32 times more energy. The energy release best indicates the destructive power of an earthquake.

Modified Mercalli Intensity Scale

The lower degrees of the Modified Mercalli Intensity scale generally deal with the manner in which the earthquake is felt by people. The higher numbers of the scale are based on observed structural damage. The table on the right is a rough guide to the degrees of the Modified Mercalli Intensity scale. The colors and descriptive names shown here differ from those used on certain shake maps in other articles. The table on the left gives Modified Mercalli scale intensities that are typically observed at locations near the epicenter of the earthquake.[1]

Richter Magnitude	Typical Maximum Modified Mercalli Intensity
1.0 - 3.0	**I**
3.0 - 3.9	**II - III**
4.0 - 4.9	**IV - V**
5.0 - 5.9	**VI - VII**
6.0 - 6.9	**VII - IX**
7.0+	**VIII** or higher

I. Instrumental	Not felt by many people unless in favorable conditions.
II. Feeble	Felt only by a few people at best, especially on the upper floors of buildings. Delicately suspended objects may swing.
III. Slight	Felt quite noticeably by people indoors, especially on the upper floors of buildings. Many do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.
IV. Moderate	Felt indoors by many people, outdoors by few people during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rock noticeably. Dishes and windows rattle alarmingly.
V. Rather Strong	Felt outside by most, may not be felt by some outside in non-favorable conditions. Dishes and windows may break and

	large bells will ring. Vibrations like large train passing close to house.
VI. Strong	Felt by all; many frightened and run outdoors, walk unsteadily. Windows, dishes, glassware broken; books fall off shelves; some heavy furniture moved or overturned; a few instances of fallen plaster. Damage slight.
VII. Very Strong	Difficult to stand; furniture broken; damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by people driving motor cars.
VIII. Destructive	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture moved.
IX. Ruinous	General panic; damage considerable in specially designed structures, well designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X. Disastrous	Some well built wooden structures destroyed; most masonry and frame structures destroyed with foundation.

	Rails bent.
XI. Very Disastrous	Few, if any masonry structures remain standing. Bridges destroyed. Rails bent greatly.
XII. Catastrophic	Total damage - Everything is destroyed. Total destruction. Lines of sight and level distorted. Objects thrown into the air. The ground moves in waves or ripples. Large amounts of rock move position.

Correlation with Physical Quantities

The Mercalli scale is not defined in terms of more rigorous, objectively quantifiable measurements such as shake amplitude, shake frequency, peak velocity, or peak acceleration. Human perceived shaking and building damage is best correlated with peak acceleration for lower-intensity events, and with peak velocity for higher-intensity events.

The USGS estimates that several million earthquakes occur in the world each year. Many go undetected because they hit remote areas or have very small magnitudes. The NEIC now locates about 50 earthquakes each day, or about 20,000 a year.

As more and more seismographs are installed in the world, more earthquakes can be and have been located. However, the number of large earthquakes (magnitude 6.0 and greater) has stayed relatively constant.

Table III - Number of Earthquakes Worldwide for 2000 - 2010

Mag.	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
8.0-9.9	1	1	0	1	2	1	2	4	1	0	0
7.0-7.9	14	15	13	14	14	10	9	14	12	16	2
6.0-6.9	146	121	127	140	141	140	142	178	168	142	9
5.0-5.9	1344	1224	1201	1203	1515	1693	1712	2074	1768	1700	171
4.0-4.9	8008	7991	8541	8462	10888	13917	12838	12078	12291	6955	364

3.0-3.9	4827	6266	7068	7624	7932	9191	9990	9889	11735	2896	76
2.0-2.9	3765	4164	6419	7727	6316	4636	4027	3597	3860	2997	80
1.0-1.9	1026	944	1137	2506	1344	26	18	42	21	26	1
0.1-0.9	5	1	10	134	103	0	2	2	0	1	0
No Mag	3120	2807	2938	3608	2939	864	828	1807	1922	20	3
Total	22256	23534	27454	31419	31194	30478	29568	29685	31777	14754	706
Est Dths	231	21357	1685	33819	228802	82364	6605	712	88011	1787	0

In 1935 Charles Richter defined the magnitude of an earthquake to be

$$M = \log \frac{I}{S}$$

where I is the intensity of the earthquake (measured by the amplitude of a seismograph reading taken 100 km from the epicenter of the earthquake) and S is the intensity of a "standard earthquake" (whose amplitude is 1 micron $=10^{-4}$ cm).

The magnitude of a standard earthquake is

$$M = \log \frac{S}{S} = \log 1 = 0$$

Richter studied many earthquakes that occurred between 1900 and 1950. The largest had magnitude of 8.9 on the Richter scale, and the smallest had magnitude 0. This corresponds to a ratio of intensities of 800,000,000, so the Richter scale provides more manageable numbers to work with.

Each number increase on the Richter scale indicates intensity ten times stronger. For example, an earthquake of magnitude 6 is ten times stronger than an earthquake of magnitude 5. An earthquake of magnitude 7 is $10 \times 10 = 100$ times strong than an earthquake of magnitude 5. An earthquake of magnitude 8 is $10 \times 10 \times 10 = 1000$ times stronger than an earthquake of magnitude 5.

Example 1: Early in the century the earthquake in San Francisco registered 8.3 on the Richter scale. In the same year, another earthquake was recorded in South America that was four time stronger. What was the magnitude of the earthquake in South American?

Solution: Convert the first sentence to an equivalent mathematical sentence or equation.

$$M_{SF} = \log \frac{I_{SF}}{S} = 8.3$$

$$8.3 = \log \frac{I_{SF}}{S}$$

Convert the second sentence to an equivalent mathematical sentence or equation.

$$M_{SA} = \log \frac{I_{SA}}{S}$$

$$I_{SA} = 4I_{SF}$$

$$M_{SA} = \log \frac{4I_{SF}}{S}$$

Solve for M_{SA}.

$$
\begin{aligned}
M_{SA} &= \log \frac{4I_{SF}}{S} \\
&= \log 4I_{SF} - \log S \\
&= \log 4 + \log I_{SF} - \log S \\
&= \log 4 + (\log I_{SF} - \log S) \\
&= \log 4 + \log \frac{I_{SF}}{S} \\
&= \log 4 + 8.3 \\
&= 0.602059991328 + 8.3 \\
&= 8.90205999133 \\
M_{SA} &= 8.9
\end{aligned}
$$

The intensity of the earthquake in South America was 8.9 on the Richter scale.

Example 2: A recent earthquake in San Francisco measured 7.1 on the Richter scale. How many times more intense was the San Francisco earthquake described in Example 1?

Solution: The intensity (I) of each earthquake was different. Let I_1 represent the intensity the early earthquake and I_2represent the latest earthquake.

$$First \ : \ 8.3 = \log \frac{I_1}{S}$$

$$Second \ : \ 7.1 = \log \frac{I_2}{S}$$

What you are looking for is the ratio of the intensities: $\frac{I_1}{I_2}$. So our task is to isolate this ratio from the above given information using the rules of logarithms.

$$\begin{aligned}
\log \frac{I_1}{S} - \log \frac{I_2}{S} &= 8.3 - 7.1 \\
\left(\log \frac{I_1}{S}\right) - \left(\log \frac{I_2}{S}\right) &= 8.3 - 7.1 \\
(\log I_1 - \log S) - (\log I_2 - \log S) &= 1.2 \\
\log I_1 - \log S - \log I_2 + \log S &= 1.2 \\
\log I_1 - \log I_2 &= 1.2 \\
\log \frac{I_1}{I_2} &= 1.2
\end{aligned}$$

Convert the logarithmic equation to an exponential equation.

$$\log \frac{I_1}{I_2} = 1.2$$

$$10^{1.2} = \frac{I_1}{I_2}$$

$$\frac{I_1}{I_2} = 15.8489319246$$

$$\frac{I_1}{I_2} \approx 16$$

The early earthquake was 16 times as intense as the later earthquake.

Moonquakes

Moonquakes are earthquakes on the moon. Moonquakes (“earthquakes” on the moon) do occur, but they happen less frequently and have smaller magnitudes than earthquakes on the Earth. It appears they are related to the tidal stresses associated with the varying distance between the Earth and Moon. They also occur at great depth, about halfway between the surface and the center of the moon.

Earthquake Instrumentation

Before electronics allowed recordings of large earthquakes, scientists built large spring-pendulum seismometers in an attempt to record the long-period motion produced by such quakes. The largest one weighed about 15 tons. There is a medium-sized one three stories high in Mexico City that is still in operation.

The first “pendulum seismoscope” to measure the shaking of the ground during an earthquake was developed in 1751, and it wasn’t until 1855 that faults were recognized as the source of earthquakes.

Human beings can detect sounds in the frequency range 20-10,000 Hertz. If a P wave refracts out of the rock surface into the air, and it has a frequency in the audible range, it will be heard as a rumble. Most earthquake waves have a frequency of less than 20 Hz, so the waves themselves are usually not heard. Most of the rumbling noise heard during an earthquake is the building and its contents moving.

When the Chilean earthquake occurred in 1960, seismographs recorded seismic waves that traveled all around the Earth. These seismic waves shook the entire earth for many days! This phenomenon is called the free oscillation of the Earth.

The interior of Antarctica has ice quakes which, although they are much smaller, are perhaps more frequent than earthquakes in Antarctica. The ice quakes are similar to earthquakes, but occur within the ice sheet itself instead of the land underneath the ice. Some of our polar observers have told us they can hear the ice quakes and see them on the South Pole seismograph station, but they are much too small to be seen on enough stations to obtain a location.

Caribbean Earthquake Science

The earthquake that recently devastated Port Au Prince occurred along the boundary of two tectonic plates — great slabs of crust that slide past one another slowly over time.

In this case, the Caribbean plate is moving east in relation to the North American plate. Large earthquakes frequently occur on these plate boundaries.

The Caribbean plate has been moving about a quarter of an inch per year relative to the North American plate. But the two plates don't simply glide past one another. Strain builds up along faults at the plate boundaries until it's released in a sudden burst of energy. That's an earthquake.

Origin of Caribbean Plate

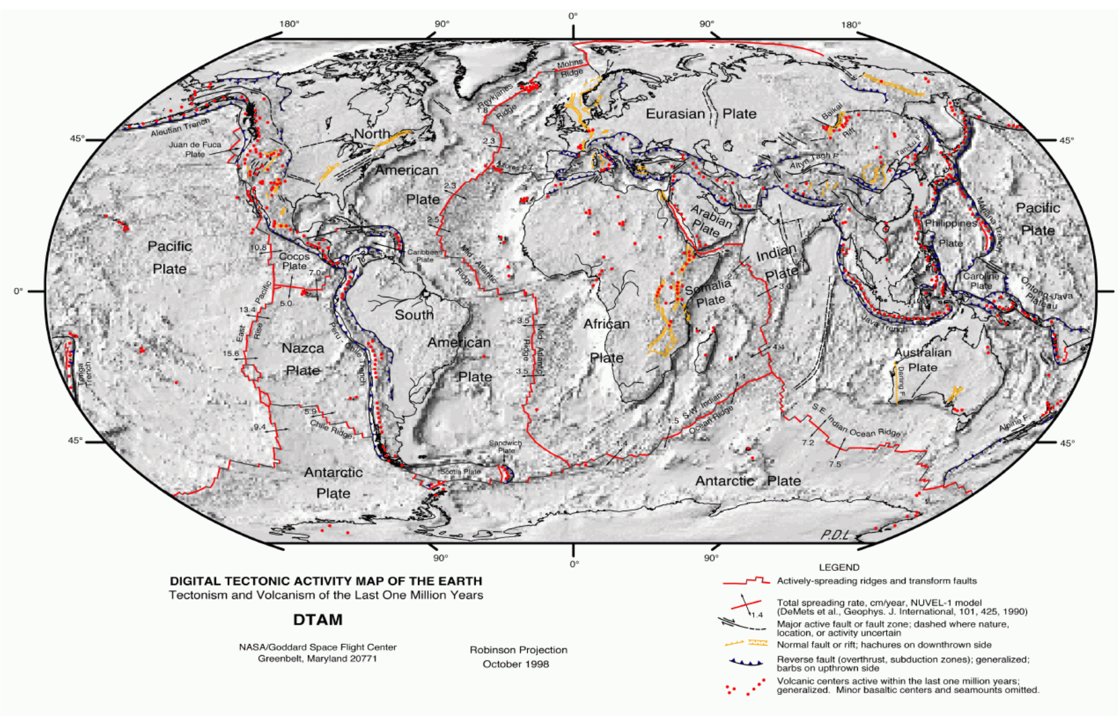

Figure 1. Digital Tectonic Activity of the Earth

There are two contending theories as to the origin of the Caribbean Plate: One holds that it is a large igneous province that formed in the Pacific Ocean tens of millions of years ago. As the Atlantic Ocean widened, North America and South America were pushed westward, separated for a time by oceanic crust. The Pacific Ocean floor is subducted under this oceanic crust between the continents. The Caribbean Plate drifted into the same area, but as it was less dense (although thicker) than the surrounding oceanic crust, it did not subduct, but rather overrode the ocean floor, continuing to move eastward relative to North America and South America. With the formation of the Isthmus of Panama 3 million years ago, it ultimately lost its connection to the Pacific.

A more recent theory asserts that the Caribbean Plate came into being from an Atlantic hotspot which no longer exists. This theory points to evidence of the absolute motion of the Caribbean Plate which indicates that it moves westward, not east, and that its apparent eastward motion is only relative to the motions of the North American Plate and the South American Plate.

The Caribbean Plate is a mostly oceanic tectonic plate underlying Central America and the Caribbean Sea off the north coast of South America.

Roughly 3.2 million square kilometers (1.2 million square miles) in area, the Caribbean Plate borders the North American Plate, the South American Plate, the Nazca Plate and the Cocos Plate. These borders are regions of intense seismic activity, including frequent earthquakes, occasional tsunamis, and volcanic eruptions.

Boundary Types

The northern boundary with the North American Plate is a transform or strike-slip boundary which runs from the border area of Belize, Guatemala (Motagua Fault), and Honduras in Central America, eastward through the Cayman trough south of the southeast coast of Cuba and north of Hispaniola, Puerto Rico, and the Virgin Islands. Part of the Puerto Rico trench, the deepest part of the Atlantic Ocean (roughly 8,400 meters), lies along this border. The Puerto Rico trench is at a complex transition from the subduction boundary to the south and the transform boundary to the west.

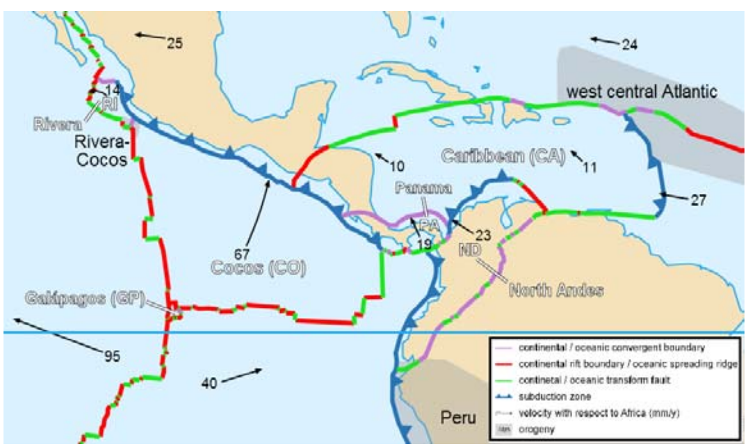

Figure 2. Caribbean Plates

The eastern boundary is a subduction zone, but since the boundary between the North and South American Plates in the Atlantic is as yet undefined, it is unclear which one, or possibly both, is descending under the Caribbean Plate. The subduction forms the volcanic islands of the Lesser

Antilles Island arc from the Virgin Islands in the north to the islands off the coast of Venezuela in the south. This boundary contains seventeen active volcanoes, most notably Soufriere Hills on Montserrat, Mount Pelée on Martinique, La Grande Soufrière on Guadeloupe, Soufrière Saint Vincent on Saint Vincent, and the submarine volcano Kick-'em-Jenny which lies about 10 km north of Grenada.

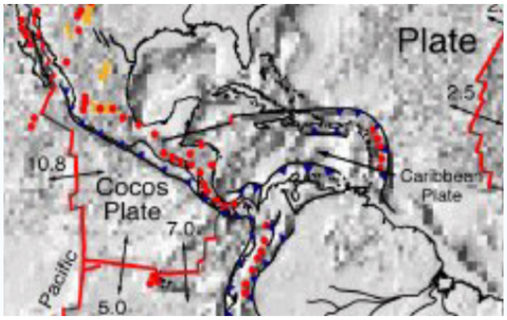

Figure 3. Cocos Plate Map

Along the geologically complex southern boundary, the Caribbean Plate interacts with the South American Plate forming Barbados, Trinidad and Tobago (all on the Caribbean Plate) and islands off the coast of Venezuela (including the Leeward Antilles) and Colombia. This boundary is in part the result of transform faulting along with thrust faulting and some subduction. The rich Venezuelan petroleum fields possibly result from this complex plate interaction.

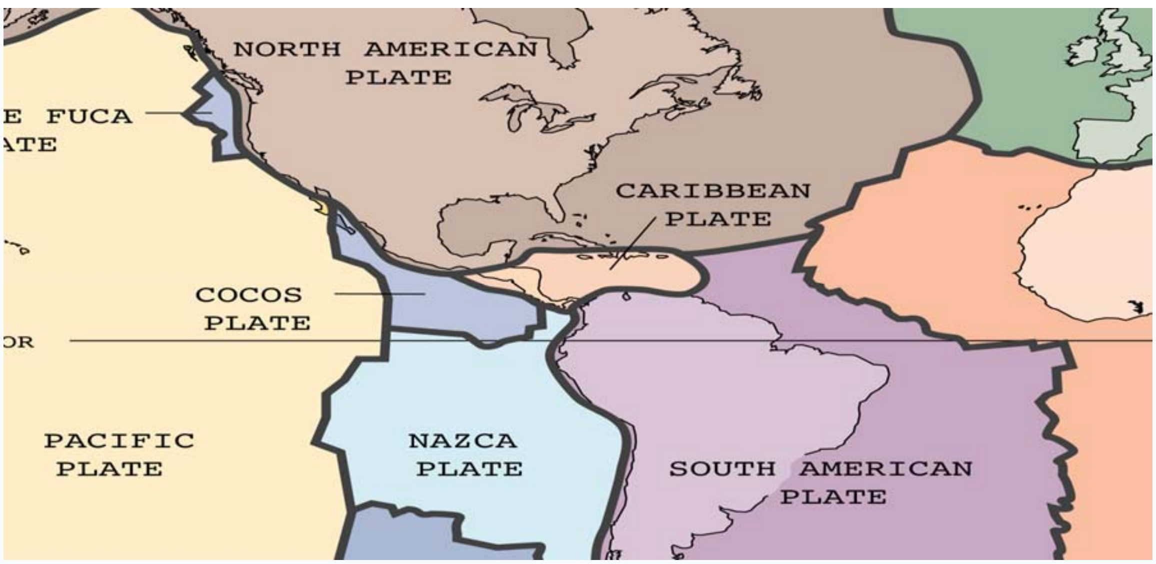

Figure 4. World Plates Map

The western portion of the plate is occupied by Central America. The Cocos Plate in the Pacific Ocean is subducted beneath the Caribbean Plate, just off the western coast of Central America. This subduction forms the volcanoes of Guatemala, El Salvador, Nicaragua, and Costa Rica, also known as the Central America Volcanic Arc.

Caribbean Earthquake Model

Model to Predict Earthquakes

University of Arkansas researchers Pamela Jansma and Glen Mattioli, together with Purdue University researchers D. Manaker and Eric Calais, have monitored tiny tectonic movements in the Caribbean to create the first comprehensive and quantitative kinematic model describing potential earthquake activity in the region.

Background

Several large earthquakes have struck the Caribbean region in the past 500 years in the vicinity of Puerto Rico, the U.S. Virgin Islands and the island of Hispaniola, shared by Haiti and the Dominican Republic. Millions of residents live in the Caribbean Islands, so a better understanding of the likely location of earthquakes could help people better prepare for the possibility.

For the past 12 years, Jansma and Mattioli have used global positioning satellite geodesy to monitor very small movements along the tectonic plates in the Caribbean basin to determine the relative motion between the Caribbean and the North American plates. Caribbean plate boundaries are interesting because the plates move extremely slow - about 2 centimeters a year - making the region an important part of the global picture of how plates interact.

After 12 years of gathering data, the researchers felt they had enough information to build a preliminary model. In doing so, they try to build a model that explains the movement along the plate interface to see if there is sticking going on between the two plates. According to Scientist Mattioli: "If the plates are stuck and not moving past each other smoothly, at some time they will break, and if they break, it will release a lot of energy" in the form of an earthquake.

Model Input Data

The model contains data on the slip rates of the main faults and strain accumulation at various sites, based both on GPS sites and geological evidence. It also includes information on the locked zone of the faults, the depth on the fault that is partially stuck-- and the location of known fault boundaries.

Findings of the Researchers

Coupling, or sticking, was low in Puerto Rico and the Virgin Islands, but was much higher in the Dominican Republic, Haiti and Hispaniola, which implies an elevated risk of earthquakes in that region. "This result isn't surprising if you look at the geomorphology of the region," Jansma said. The Dominican Republic is more mountainous than Puerto Rico, implying more deformation. The next step will be to refine the model using more data gathered from the region over time. "Regional models like these show you where the important data holes are. They make predictions about where you should put additional sites," Jansma said.

Model Revision

The next version of the model will include new data collected in 2006 and 2007 and should be better still.

More Strong Quakes Possible

Earthquakes in this region often originate at a point in the earth that's relatively shallow. In this case, preliminary estimates say the rupture started about six miles below the surface. Since Port Au Prince was only about ten miles away from the quake's epicenter (which is the spot on the surface directly above the origin of the earthquake), the ground motion in the city of two million people was especially intense.

Geologists say the fault is a "strike-slip" fault, like the San Andreas in California. That means the relative motion between the two tectonic plates is mostly a side-to-side slip, rather than up and down.
The second fault system on Hispaniola runs mainly on the eastern end of the island, in the Dominican Republic. That Septentrional Fault system has not experienced a major quake for more than 800 years, but it holds the potential for producing other devastating quakes — quite possibly larger than the one that recently struck Haiti.

Earthquake History of Puerto Rico

Puerto Rico is said to be due for an earthquake of large proportions any time. The last such earthquake to affect Puerto Rico happened in 1918. Since that date, only minor quakes have been felt. The western part of Puerto Rico lies on a fault which is said to be active.

Four strong earthquakes have affected Puerto Rico since the beginning of its colonization.

The other strong earthquake, whose magnitude has not been determined, occurred in 1670, significantly affecting the area of San German District.

Possibly the strongest earthquake that has affected Puerto Rico since the beginning of colonization occurred on May 2, 1787. This was felt strongly throughout the Island and may have been as large as magnitude 8.0 on the Richter Scale. Its epicenter was possibly to the north, in the Puerto Rico Trench.

It demolished the Arecibo church along with the El Rosario and La Concepcion monasteries and damaged the churches at Bayamon, Toa Baja and Mayaguez. It also caused considerable damage to the castles of San Felipe del Morro and San Cristobal, breaking cisterns, walls and guard houses.

On November 18, 1867, 20 days after the Island was devastated by Hurricane San Narciso, a strong earthquake occurred with an approximate magnitude of 7.5 on the Richter scale. The epicenter was located in the Anegada Passage, between Puerto Rico and St. Croix, Virgin Islands. The earthquake produced a tsunami that ran inland almost 150 meters (490 feet) in the low parts of the coast of Yabucoa. This quake caused damage in numerous buildings on the Island, especially in the eastern zone.

The most recent of these occurred on October 11, 1918. The epicenter was located northwest of Aguadilla in the Mona Canyon (between Puerto Rico and the Dominican Republic). This earthquake had an approximate magnitude of 7.5 on the Richter scale and was accompanied by a tsunami ("tidal" wave) which got up to 6 meters (19.5 feet) high. Damage was concentrated in the western area of the Island because this was the closest zone to the earthquake. The earthquake killed about 116 people and caused more than 4 million dollars of damage. Numerous houses, factories, public buildings, chimneys, bridges and other structures suffered severe damage.

Geology of Puerto Rico

Figure 5. Image of Puerto Rico taken by NASA.

Puerto Rico is composed of Jurassic to Eocene volcanic and plutonic rocks, which are overlain by younger Oligocene to recent carbonates and other sedimentary rocks. Most of the caverns and karst topography on the island occurs in the northern Oligocene to recent carbonates. The oldest rocks are approximately 190 million years old (Jurassic) and are located at Sierra Bermeja in the southwest part of the island. These rocks may represent part of the oceanic crust and are believed to come from the Pacific Ocean realm.

Puerto Rico lies at the boundary between the Caribbean and North American plates. This means that it is currently being deformed by the tectonic stresses caused by the interaction of these plates. These stresses may cause earthquakes and tsunamis. The seismic events, along with landslides, represent some of the most dangerous geologic hazards in the island and in the northeastern Caribbean. The most recent major earthquake occurred on October 11, 1918 and had an estimated magnitude of 7.5 on the Richter scale. It originated off the coast of Aguadilla and was accompanied by a tsunami.

Lying about 75 miles (120 km) east of Puerto Rico in the Atlantic Ocean at the boundary between the Caribbean and North American plates is the Puerto Rico Trench, the largest and deepest trench in the Atlantic. The trench is 1,090 miles (1,754 km) long and about 60 miles (97 km) wide. At its deepest point (named Milwaukee Depth), it is 27,493 feet (8,380 m) deep.

Puerto Rico Trench

Figure 6. Location Map Puerto Rico Trench - USGS

Coordinates: 19°50′9″N 66°45′16″W19.83583°N 66.75444°W. The Puerto Rico Trench is an oceanic trench located on the boundary between the Caribbean Sea and the Atlantic Ocean.

The trench is associated with a complex transition between the subduction zone to the south along the Lesser Antilles Island arc and the major transform fault zone or plate boundary that extends west between Cuba and Hispaniola through the Cayman Trench to the coast of Central America.

Scientific studies have concluded that an earthquake occurring along this fault zone could generate a significant tsunami.

The island of Puerto Rico lies immediately to the south of the fault zone and the trench. The trench is 800 kilometers (500 mi) long and has a maximum depth of 8,605 meters (28,232 ft) at Milwaukee Deep, which is the deepest point in the Atlantic Ocean.

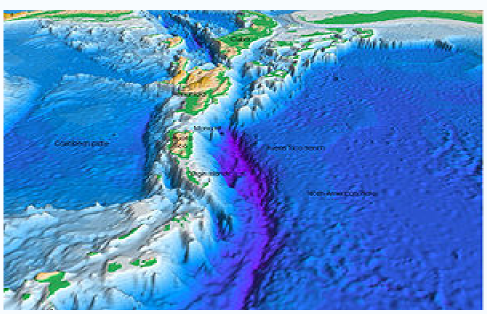

Figure 7. Perspective View of Sea Floor of the Atlantic Ocean and the Caribbean Sea.

The Lesser Antilles are on the lower left side of the view and Florida is on the upper right. The purple sea floor at the center of the view is the Puerto Rico trench, the deepest part of the Atlantic Ocean and the Caribbean Sea.

Geology

This subduction zone explains the presence of active volcanoes over the southeastern part of the Caribbean Sea. Volcanic activity is frequent along the island arc southeast from Puerto Rico to the coast of South America.

Puerto Rico, the United States Virgin Islands, British Virgin Islands and the Dominican Republic do not have active volcanoes; however they are at risk from earthquakes and tsunamis

Significant Earthquakes in Puerto Rico's Trench

1918 Puerto Rico Earthquake

Figure 8. Brick house in Mayaguez, Puerto Rico destroyed by the earthquake.

The Puerto Rico earthquake of 1918 was a major earthquake that struck the island of Puerto Rico at 10:14am on October 11, 1918. The magnitude for the earthquake has been reported at around 7.5 (or Level IX in the Rossi-Forel scale used at that time); however, that might not be an exact number. The main-shock epicenter occurred offshore about 10 miles (5 km) from the northwestern coast of the island, somewhere along the Puerto Rico Trench.

The earthquake triggered a tsunami with waves measured at approximately 5.5 meters (20 feet) that lashed the west coast of the island and is remembered as one of the worst natural disasters that have struck the island. The losses resulting from the disaster were approximately 116 casualties and $4 million in property.

Geology of the Earthquake

The epicenter of the 1918 Puerto Rico Earthquake was located in the Mona Passage about 10 miles (5 km) from the northwestern coast of the island, probably along an old fault close to the Puerto Rico Trench. The strongest shakings have been estimated at around 7.3 or 7.5 (Richter scale) or Level IX (Rossi-Forel scale). The resulting tsunami affected primarily the west coast city of Mayaguez and other adjacent towns as well.

Immediate Effects

As a result of the earthquake, numerous structures in the west coast suffered irreparable damages. Factories and production centrals were virtually destroyed, while bridges and roads were severely damaged.

The earthquake caused several mudslides in areas where the magnitude exceeded Level VII, but none of it was deemed as tragic. Also, the river currents were affected, which, in many cases affected the foundations of many bridges which ended up collapsing.

Tsunami

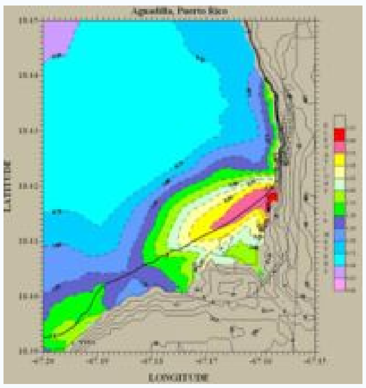

Figure 9. Simulation of the Results of the Tsunami on the Coast of Aguadilla, Puerto Rico.

It has been estimated that 40 people were drowned as a direct result of the tsunami. The tsunami reached Galveston, Texas as a disturbance on tide gauges.

Aftershocks

Several aftershocks were reported immediately after the main earthquake. On October 24 and November 12, two strong aftershocks were reported in the island. However, no damages were reported as a result.

Tsunamis of the Caribbean

A significant tsunami, ocean waves which can be caused by the displacement of the seafloor during an earthquake was generated. It reached its greatest elevation in the northwestern corner of the island (20 feet), where it was observed almost immediately after the earthquake.

In all the places that the wave was observed, people reported that the sea first retreated, exposing in some parts reefs and the seafloor which had never been seen, even in the lowest of tides. Afterwards, the water returned, reaching equally high elevations. At some localities, the large wave was followed by one or two smaller ones. In the closed bays the water remained disturbed for some time.

The two figures below depict the damage done by the Tsunami.

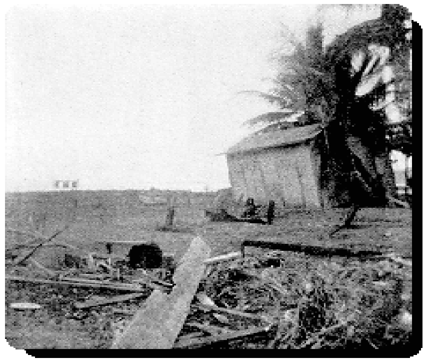
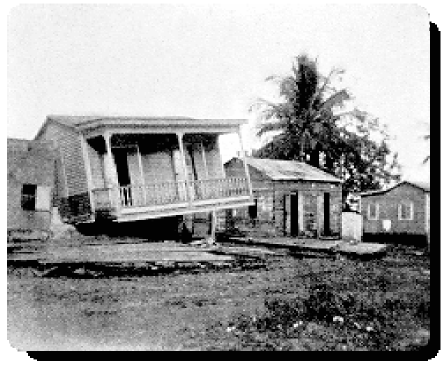

Figure 10. Debri at the Beach in Mayagüez.

Notice the house stuck against the palm tree; it was pulled towards the sea by the earthquake.

At Punta Borinquen in Aguadilla, the lighthouse keeper reported that the water began to recede during the earthquake itself and then reached an elevation of 15 feet. Near Punta Agujereada, the elevation of the wave was between 18 and 20 feet and it arrived 4 to 7 minutes after the earthquake. In the town of Aguadilla 32 people drowned and near 300 huts along the beach were destroyed.

The tsunami reached Mayagüez 20 minutes after the earthquakes and had a height of 5 feet.

Figure 11. Major Caribbean Earthquake Damage

Major Caribbean Earthquake Damage

Major Caribbean earthquake damage and tsunamis are a real threat. A dozen major earthquakes of magnitude 7.0 or greater have occurred in the Caribbean near Puerto Rico, the U.S. Virgin Islands and the island of Hispaniola, shared by Haiti and the Dominican Republic in the past 500 years. Several have generated tsunamis.

The most recent major earthquake, a magnitude 8.1 in 1946, resulted in a tsunami that killed a reported 1,600 people. With nearly twenty million people now living in this tourist region and a major earthquake occurring on average every 50 years, scientists say it is not a question of if it will happen but when. They are calling for the establishment of tsunami early warning systems in the Caribbean Sea, Gulf of Mexico and Atlantic Ocean, and better public education about the real tsunami threats in these regions.

In a new study published December 24, 2004 in the Journal of Geophysical Research from the American Geophysical Union, geologists Uri ten Brink of the U.S. Geological Survey in Woods Hole and Jian Lin of the Woods Hole Oceanographic Institution (WHOI) report a heightened earthquake risk of the Septentrional Fault zone, which cuts through the highly populated region of the Cibao Valley in the Dominican Republic.

In addition, they caution, the geologically active offshore Puerto Rico and Hispaniola trenches are capable of producing earthquakes of magnitude 7.5 and higher.

The Indonesian earthquake on December 26, which generated a tsunami that killed (to date) an estimated 150,000 people, came from a fault of similar structure, but was a magnitude 9.0, much larger than the recorded quakes near the Puerto Rico Trench.

The deepest point in the Atlantic Ocean, the trench is 8,340 meters (27,362 feet) below the sea surface. The Hispaniola Trench parallels the north coast of the Dominican Republic and Haiti, and is 550 kilometers (344 miles) long and only 4,500 meters (14,764 feet) deep.

Earthquakes typically occur near faults or fractures in the Earth's crust where rock formations, driven by the movements of the crustal or tectonic plates that make up the Earth's surface, grind slowly past each other or collide, building up stress.

At some point, stress overcomes friction and the rocks slip suddenly, releasing seismic energy in the form of an earthquake, which drops the stress in one area but raises the stress elsewhere along the fault line. Eighty percent of earthquakes on Earth occur on the sea floor and most of them along the plate boundaries.

Hispaniola, Puerto Rico and the U.S. Virgin Islands sit on top of small crustal blocks that are sandwiched between the North American and Caribbean plates. The island of Hispaniola faces a double risk: an earthquake from the Septentrional Fault on the island itself as the plates move past each other, and an earthquake deep in the earth in the subduction zone on which the island sits. Both could cause severe damage and loss of life, although the researchers say an earthquake in the subduction zone could be more devastating and has the potential to cause a tsunami.

Two scientists studied the geology of the northern Caribbean plate boundary, looked at historical earthquake data in the region, and used three-dimensional models to calculate the stress changes in and near the trenches after each earthquake.

Ten Brink, who studies earthquakes, tsunamis and geology in the Caribbean and Puerto Rico region, and has studied earthquake hazards in the Dead Sea in the Middle East, says there are a number of possible sources for tsunamis in the Caribbean.

Ten Brink, who is also an adjunct scientist at WHOI, and Lin say stress has increased for the Hispaniola area, and that the potential threat of earthquakes and resulting possible tsunamis from the Puerto Rico and Hispaniola trenches is real and should be taken seriously.

In addition to establishing warning systems and informing the public about the risk, they call for improved documentation of prior earthquake and tsunami events and better estimates of future threats from the Puerto Rico and Hispaniola trenches through underwater studies.

"Every earthquake has its own character," says Lin, who has studied mid-ocean ridges, hotspots and undersea volcanoes as well as earthquakes in Southern California, China and the Pacific. "And not all earthquakes generate tsunamis, which form when large areas of the seafloor rise or drop suddenly, causing the ocean above them to move. Many factors come into play in tsunami formation, including the size and type of an earthquake and how much the quake has ruptured the seafloor."

Lin, a senior scientist and a marine geophysicist in the WHOI Geology and Geophysics Department, says that each time an earthquake occurs on the offshore Puerto Rico and Hispaniola trenches, it adds stress to the Septentrional Fault zone on Hispaniola.

Since the fault is in a highly populated region and is capable of generating magnitude 7.7-7.9 earthquake, the public should be educated about the risk of this earthquake prone area. The region has a long history of destructive earthquakes. Historical records show that major earthquakes have struck the Puerto Rico, Virgin Islands region many times during the past 500 years although the locations and sizes of events that occurred more than a few decades ago are poorly known.

Major earthquakes, greater than magnitude 7.0, damaged Puerto Rico in 1670, 1787, 1831, 1844, 1846, 1865, 1867, 1875, 1890, 1906, 1918, 1943 and 1946. The 1867, 1918 and 1946 earthquakes were accompanied by destructive tsunamis.

"Our results indicate that great subduction zone earthquakes, which often occur in the deep trenches off shore, have the potential to add stress or trigger earthquakes on other types of faults on the nearby islands," Lin says.

"We don't want people to overreact, just make them aware of the potential risk of such rare and yet deadly events so they are prepared. It is similar to knowing about hurricanes or tornadoes and being prepared to react when one is coming."

"The threat of major earthquakes in the Caribbean, and the possibility of a resulting tsunami, are real even though the risks are small in the bigger picture," Ten Brink said. "Local earthquakes, such as from the fault on Hispaniola, or effects from distant earthquakes can be severe. Landslides and volcanic eruptions can also cause major earthquakes and potential tsunamis in this region. It has happened before, and it will happen again."

He cautions that the threat of submarine landslides near Puerto Rico is real and residents and tourists, including those on cruise ships, would have very little warning given the close proximity to shore. However, the risk is small and should be put into perspective.

The Puerto Rico Trench, which is capable of producing earthquakes of magnitude 7 to 8 or greater, faces north and east into the Atlantic Ocean. There are few land areas or islands to block a tsunami generated near the Puerto Rico Trench from entering the Atlantic Ocean. The direction of the waves would depend on many factors, including where in the trench the earthquake occurred.

Long-term ocean observatories, new generations of seismic and oceanographic sensors and information technologies offer great promise to earthquake and tsunami research, Lin says. He and colleague Dezhang Chu of the WHOI Applied Ocean Physics and Engineering Department received WHOI Institution seed funding in 2004 to develop a new technology to measure seafloor change, which could be a step forwards in understanding the processes that trigger underwater earthquakes and tsunamis.

Costa Rica Earthquake - 1991

At 15:57 pm local time, April 22, 1991, a large (M = 7.5) earthquake struck Limon Province, Costa Rica killing 53 people, injuring 198, and causing widespread damage to constructed works (EERI, 1991). In particular, the transportation system in Limon Province was devastated. Both rail and highway traffic was immediately obstructed due to widespread disruption of pavements and roadway grades and the collapse of several bridges. Most of the damage to the highway and railway systems was caused by liquefaction and consequent ground failure, primarily lateral spreading.

The US National Science Foundation awarded a grant to Professor Kyle Rollins at Brigham Young University to conduct a post-earthquake investigation of liquefaction and its consequences following the 22 April 1991 earthquake. The purpose of that investigation was to document ground displacements and related damage caused by liquefaction. We conducted field studies in Limon Province between May 27 and June 6, 1991 (5 to 7 weeks after the earthquake). Our team surveyed three railroad and two highway bridge sites and estimated displacements at two additional sites. We used an electronic total station to measure distances and angles. We also used metric tapes to measure distances and displacements. From this data, we calculated ground and structural displacements and compiled topographic maps for the sites.

Liquefiable Sediments

Limon Province lies in the eastern part of Costa Rica in a geologic province dominated by a broad plain that gently slopes from the Cordillera de Talamanaca to the Caribbean Sea. That plain is dissected by several large and many small river valleys that generally broaden as they approach the coast. Most liquefaction occurred in alluvial and fluvial deposits that underlie river floodplains or in deltaic, lagoonal or estuarine deposits that underlie lowlands along the coast.

Within the epicentral region, liquefaction was rather pervasive in these lowland areas. For example, the EERI reconnaissance team (EERI, 1991) estimated that about thirty percent of the highway pavement in these areas was disrupted by fissures, scarps and ground settlements caused by liquefaction. Similarly, several segments of railway grade were misaligned by the ground movements. The greatest damage occurred river crossings, however, where bridge decks were thrust over abutments, piers shifted riverward, and fills settled as much as 2m.

Rio Martina Railroad Bridge

Southeast of the community of Matina, the railroad crosses the floodplains and channel of the Rio Matina on a 400-m long bridge. On each side of the river, the bridge over the floodplain is composed of five simply-supported steel plate-girder sections resting on concrete piers. Over the main channel, the bridge consists of three truss sections resting on concrete caissons.

During the April 22 earthquake, liquefaction of sediments beneath the floodplains on both sides of the river caused the ground to spread laterally toward the incised river channel. These lateral displacements carried bridge piers and caissons toward the river causing several plate girder sections to drop off their supports and fall to the floodplain.

The truss sections were also pushed off their seatings on the caissons at the river banks, but the trusses did not tip or fall.

Figure 12. Bridge Damage Caused by Earthquake

The railroad had been temporarily repaired by placing the plate girder sections on cribs of timber shoring and by re-leveling and realigning the truss and girder sections. In so doing, the rails had been restored approximately to their pre-earthquake elevations and alignment. This temporary repair allowed trains to cross the bridge at reduced speed and also provided a reference (distance between a seating plate on the plate girder and its former anchorage on the shifted pier) for us to measure displacement of the shifted piers.

Two surveys were conducted at the Matina Bridge site. First, the realigned plate girders were used as a reference for measurement of horizontal and vertical pier displacements. Visual sighting of the rails across the bridge indicated that no major misalignment (more than a few centimeters) had occurred in realigning that structure, and hence our measurements are probably accurate within a few centimeters.

Secondly, a topographic survey was conducted from which a compiled site map showing positions of bridge foundations, elevation contours, and major fissures and sand boils visible at the time of our investigation. On the northwest side of the river, displacements increased riverward from 11 cm horizontal and 16 cm vertical at the abutment to 44 cm horizontal and 34 cm vertical at Pier M4, the pier nearest the river. On the southeast side of the river, horizontal displacements increased from 75 cm horizontal at the abutment to 120 cm at the Pier M12, the pier nearest the river. (A recent realignment of the bridge now indicates that the latter displacements should be about 30 cm greater for piers M12, M14, and the southern abutment than those determined from our initial investigation.)

At each bank of the river, the girder-truss connections were supported on two 2.8-m diameter steel-lined and concrete-filled caissons. Each of those caissons tilted 4 to 5 degrees with the tops moving 66 cm and 120 cm riverward on the northwest and southeast sides of the river, respectively. Those displacements sheared the bridge connectors from the caisson, but the truss sections remained upright on the caisson. The floodplain soils pushed past the caissons on both sides of the river, leaving gaps as wide as one meter on the river sides of these shafts.

The caissons also rocked back and forth during the earthquake as evidenced by circular voids as wide as tens of centimeters the bases of the caissons. The floodplain soils also settled around the caissons by as much as 30 cm.

Rio Banalito Railway Bridge

The railway bridge over the Rio Banalito near Banalito Sur is a 50-m long, single-truss structure supported on elliptically-shaped caissons 1.46 m by 2.16 m across the major axes. The caissons are constructed of a 12 mm cast-steel shell filled with concrete. During the April 22 earthquake, ground displacements caused by liquefaction and lateral spreading pushed the supporting caissons out from under the seating plates on both ends of the bridge. This loss of support allowed the truss to tip downstream or eastward by about 15 degrees.

The site was surveyed and caisson displacements measured beneath the bridge. At the northwest end of the bridge, the tops of the caissons shifted displaced 4.3 m and 5.7 m toward the river and the caissons were tilted 26 and 37 degrees, on northeast and southwest sides, respectively. The 0.9 m high capital on the north caisson pulled off during the earthquake and had fallen to the ground. A concrete wall in the abutment had shifted 2.8 m toward the river and tilted slightly. These measurements indicate that lateral ground displacements beneath the north end of the bridge were between 2.0 m to 2.5 m.

Beneath the southeast end of the truss, the tops of the two supporting caissons were displaced 2.83 m and 1.90 m, respectively, with reference to seating plates on the truss. The greater displacement occurred on the northeast side, the direction in which the truss tilted. The caissons tilted toward the river 19 and 7 degrees, respectively. A retaining wall in the abutment shifted 1.43 m toward the river and tilted slightly. These measurements indicate that horizontal ground displacements beneath the southeast end of the bridge were approximately 1 m to 1.5 m.

Rio Estella Railway Bridge

The bridge across the floodplain near Pandora was constructed of simply-supported plate girder spans resting on the steel piers. The spans over the river are steel trusses supported on caissons. During the earthquake, permanent and transient ground and bridge displacements shifted and tilted the piers causing most of the plate girder sections to fall onto the floodplain.

The piers had been up righted by pulling on them with cables attached to the winch on a crane. When the piers were pulled back into a vertical position they were no longer in alignment nor were they equally spaced as they had been. The site was surveyed to determine the positions of the up righted piers. Assuming that the piers were equally spaced and in line before the earthquake, the survey data indicate that the pier nearest the camera in Figure 15 shifted about 0.8 m to the right (in an upstream direction) and the second pier back shifted about 0.8 m inland (away from the river). The other piers shifted as much as 0.15m and some rotated clockwise a few degrees.

Fissures, as wide as 30 cm, and sand boils were found in the banana plantation northeast of the damaged bridge. These features indicate that liquefaction and lateral spreading occurred in the vicinity of the bridge. By the time of our visit, however, any fissures or boils under the bridge had been obliterated by construction activities.


Figure 13. Rio Estrella Highway Bridge Damage

Rio Estrella Highway Bridge Damage

The highway bridge over the Rio Estrella incorporated two 75-m long trusses and a 25-m long plate girder section. During the earthquake the ends of the two trusses fell from their common support and dropped into the river. Other damage at the site included spalling of concrete at the tops of the piles supporting the north abutment, and as much as 2 m settlement of the fill behind the south abutment. The roadway approach south of the bridge settled, broke up and spread laterally as a consequence of liquefaction of the underlying soils. During the survey, walks through banana plantations near the south abutment noted several large fissures that trended parallel to the river. Those fissures are indicative of riverward ground displacements up to 2 m.

The site was surveyed with an electronic total station to determine the post-earthquake positions of piers and abutments. Then calculated distances between these elements and compared them with distances listed on the bridge plans (Table 1). The differences between these distances fall within the range of expected survey and construction error and show that significant permanent displacement did not occur between these components. In particular, the foundation for the southern abutment apparently was sufficiently strong to resist the ground displacements that occurred in the immediate area.

2009 Costa Rica Earthquake

The 2009 Costa Rica earthquake ,also known as Cinchona Earthquake, occurred at 1:21:34 pm local time (19:21:34 UTC) on January 8, 2009. The epicenter of the 6.1 M_w earthquake was in northern Costa Rica, 30 kilometers (19 mi) north-northwest of San José. The earthquake was felt all over Costa Rica as well as in southern central Nicaragua.

Damage

The earthquake took at least 34 lives, including at least three children, left about 64 people missing, and injured at least 91. Hundreds of people were trapped and two villages had been cut off. Most of the victims died when a landslide occurred near the La Paz waterfall by the Poás Volcano, and 452 people including 369 tourists were evacuated from the area in helicopters. 1,244 people were displaced, and 1,078 people are living in shelters. In addition, a hotel, houses, roads, and vehicles were damaged, and several bridges were also destroyed. The town of Cinchona was heavily hit, and all of the buildings there were heavily damaged. Power was temporarily disrupted in San José.

Aftermath

The Costa Rican Red Cross sent 400 personnel to assist in the recovery. The agency said, "Some 42 communities were affected and sustained serious impacts on civil and electrical infrastructure... [They] are going to need a lot of help." Four helicopters were also dispatched in order to help aid efforts. The Comisión Nacional de Emergencias (National Emergency Commission) also requested four private helicopters to help with the aid. Additionally, the United States and Colombia dispatched helicopters with aid to assist with the relief and recovery efforts.

About 2,000 aftershocks have been felt throughout Costa Rica.

On January 12, the president Oscar Arias declared National Grieving for 5 days with respect for the victims and asked the organizers of the *Fiestas de Palmares* to postpone them.

On January 13, the 'Banco de Costa Rica' announced that it would offer home financing credit to homeowners who want to rebuild or fix their home.

Liquefaction Contributes to Damage in Earthquakes

Figure 14. Road /Damage of an Earthquake in Costa Rica

Ground failure caused by liquefaction is a major cause of earthquake damage and casualties. Most of the damage to highways and bridges generated by the April 22, 1991 Limon Province in Costa Rica earthquake was caused by liquefaction. Ground failures generated by liquefaction caused floodplains to press into river channels, compressing bridge structures, and caused soils to weaken under highway and railway grades, causing embankment fills to settle and spread laterally.

Similarly spectacular damage as a consequence of liquefaction also occurred during 1906 San Francisco, the 1964 Alaska, and the 1964 Niigata earthquakes. Because of the potential for damage considerable studies of the liquefaction phenomenon have occurred in the past few years to provide criteria for evaluating liquefaction and ground failure hazard. Such evaluations are a major element in earthquake hazard assessment and mitigation studies.

Liquefaction is a process by which clay-free soil deposits, primarily sands and silts, temporarily lose strength and behave as a viscous liquid rather than as a solid. Disruptions to the particulate structure generated by these collapses cause transfer of load from grain-to-grain contacts in the soil to the interstitial pore water. This transfer of load increases pressure in the pore water, causing drainage to occur. If drainage is restricted, a transient build up of pore-water pressure will occur.

Ground Failures Types

Four primary types of ground failure are caused by liquefaction: lateral spread, ground oscillation, flow failure, and loss of bearing strength. In addition, liquefaction may enhance ground settlement and lead to eruption of sand boils (fountains of water and sediment emanating from the pressurized, liquefied zone).

Lateral Spreads

Lateral spreads involve lateral displacement of large, superficial blocks of soil as a result of liquefaction of a subsurface layer. Displacement occurs in response to combination of gravitational forces and inertial forces generated by an earthquake. Lateral spreads generally develop on gentle slopes (most commonly less than 3 degrees) and move toward a free face such as an incised river channel. Horizontal displacements commonly range up to several meters, but where slopes are particularly favorable and ground shaking durations are long, displacements may range up to several tens of meters. The displaced ground usually breaks up internally, causing fissures, scarps, horsts, and grabens to form on the failure surface.

Figure 15. Road Damage caused by Lateral Spreads

Lateral spreads commonly disrupt foundations of buildings built on or across the failure, sever pipelines and other utilities in the failure mass, and compress or buckle engineering structures such as bridges founded on the toe of the failure.

For example, during the 1964 Alaska earthquake, more than 200 bridges were damaged or destroyed by the spreading of floodplain deposits toward river channels. The spreading compressed the superstructures, buckled decks, thrust stringers over abutments, and shifted and tilled abutments and piers. Similar damage occurred during the 1991 Costa Rica earthquake and during many previous large earthquakes.

Ground Oscillation

Where the ground is flat or the slope is too gentle to allow lateral displacement, liquefaction at depth may decouple overlying soil layers from the underlying ground, allowing the upper soil to oscillate back and forth and up and down in the form of ground waves. These oscillations are usually accompanied by opening and closing fissures and fracture of rigid structures such as pavements and pipelines.

Flow Failures

Figure 16. Bridge Damage Caused by Flow Failures

Flow failures are the most catastrophic ground failure caused by liquefaction. These failures commonly displace large masses of soil tens of meters and in a few instances, large masses of soil have traveled tens of kilometers down long slopes at velocities ranging up to tens of kilometers per hour. Flows may be comprised of completely liquefied soil or blocks of intact material riding on a layer of liquefied soil. Flows usually develop in loose saturated sands or silt on slopes greater than 3 degrees.

Loss of Bearing Strength

When the soil supporting a building or other structure liquefies and loses strength, large deformations can occur within the soil which may allow the structure to settle and tip. Conversely, buried tanks and piles may rise buoyantly through the liquefied soil. For example, many buildings settled and tipped during the 1964 Niigata, Japan earthquake. The most spectacular bearing failures during that event were in the Kwangishicho apartment complex where several four-story buildings tipped as much as 60 degrees. Apparently, liquefaction first developed in a sand layer several meters below ground surface and then propagated upward through overlying sand layers. The rising wave of liquefaction weakened the soil supporting the buildings and allowed the structures to slowly settle and tip.

Findings/Causes

Liquefaction and associated ground failure are major causes of damage during large earthquakes. Liquefaction-induced lateral spread was the primary cause of extensive damage to highway and railway bridges during the April 22, 1991 magnitude 7.7 earthquake.

Lateral displacements as great as 2 m pushed piles and abutments from under decks causing collapse of at least 7 bridges and severe damage to several others. In at least one instance, the highway bridge over the Rio Estrella, the foundation of a bridge abutment was sufficiently strong to resist ground displacements, which in the near vicinity were as great as 2 m.

Liquefaction, lateral spreading and ground settlement caused additional damage to the transportation system by shattering about 30 percent of highway pavements in lowland areas and by misaligning several railway grades.

Haiti's First Major Quake in Two Centuries

There are two major faults along Hispaniola, the island shared by Haiti and the Dominican Republic. This earthquake occurred on the southern fault, the Enriquillo-Plaintain Garden fault system. There hasn't been a major quake on this system for about 200 years. That means stress has been building up there for quite some time. When the strain finally grew too large, rock along the fault failed, and released a huge burst of energy in less than a minute.

Geologists are still working on the details, but it appears that 30 to 60 miles of the fault gave way. That triggered not only the original quake, but it has also generated more than a dozen aftershocks of Magnitude 5 or higher. Those are also strong quakes, and they pose a risk to the buildings that were damaged in the original shock. Aftershocks are common after large quakes, and they continue for days, weeks and even longer, though they become less frequent as time passes.

Haiti Earthquake Cause

The Caribbean is well known for earthquakes and volcanic activity. But while islands such as Puerto Rico, Jamaica, and the Antilles chains are fairly well studied, Haiti hasn't received the same attention, since working in a country that is no stranger to poverty and hardship can be downright unsafe.

The Caribbean Plate was born deep beneath the ocean some 90 million to 100 million years ago, Dr. Lin explains, during a virtual tectonic tour of the Caribbean. It likely emerged via a "hot spot" in the Pacific at a time when the world's land masses were configured in a dramatically different way.

Haiti Earthquake in Comparison to Previous Earthquakes in the Caribbean

The geology underlying the devastating Haiti earthquake: The region is no stranger to volcanoes and earthquakes. Thanks to the interaction of one of the smallest, yet one of the most complex, crustal plates on the planet. Known as the Caribbean Plate, this slowly migrating, slowly morphing patch of Earth's crust exhibits virtually every feature found on the world's largest plates.

The spreading center, one of the deepest on Earth is where new material emerges from deep beneath the crust to replenish the sea floor. Some of these trigger the formation of volcanoes. It has a platelet, a kind of smaller plate within a plate, on which the island of Hispaniola, home to Haiti and the Dominican Republic rides. And it exhibits the kind of long, side-slipping faults similar to California's San Andreas Fault.

According to Dr. Jian Lin, a geophysicist at the Woods Hole Oceanographic Institution in Woods Hole, Mass.: "The Caribbean is very complicated, and you have everything in plate tectonics in this very small region."

Instead of leading to towering volcanic islands, the way a hot spot has formed the Hawaiian chain, the hot spot spawning the Caribbean Plate extended over a wide region, with magma oozing through fissures and vents and spreading horizontally to form a vast undersea plateau.

The same earthquake fault that lies under Haiti also runs through the Dominican Republic. Geologists warn that the Haiti quake – at the Enriquilla-Plantain Garden Fault – may have added strain elsewhere and more quakes are possible.

The magnitude 7 earthquake that leveled much of Haiti's capital recently – the strongest temblor to hit the country in some 200 years -- may have increased strain on a segment of the same fault that lies across the border in the Dominican Republic.

Comparison to Previous Earthquakes

1843: That eclipses the previous record-holder, a quake that hit the Leeward Islands in 1843. It struck as a magnitude 8.3 earthquake killing 5,000 people, according to US Geological Survey data.

1902: It took a volcanic eruption on Martinique in 1902 to approximate the devastation of last week's quake inflicted on Haiti. That year Mt. Pelee erupted, hurling ash and superheated gas toward the town of St. Pierre. The eruption destroyed the town and killed some 30,000 people.

Strain Track Changes

The rupture slid to the east. While strain would build at both ends of the ruptured segment, another rupture farther to the west would occur in a sparsely populated, hard to reach portion of Haiti. To the east, however, the fault traces a path through the mountains separating Haiti from the Dominican Republic and into the more-heavily populated southwestern portion of Haiti's neighbor, the Dominican Republic.

Hispaniola sits squarely atop a boundary between two plates in Earth's crust: the North American Plate and the Caribbean Plate. The Caribbean Plate is trying to slide past a particularly tough block of crust underlying the Bahamas. The two are grinding past each other, much like the motion along another plate boundary, the California's San Andreas Fault.

Why Haiti's Fault Received Less Attention

The tragic event has struck a broad patch of the globe -- the Caribbean -- well known for earthquakes and volcanic activity. But while islands such as Puerto Rico, Jamaica, and the Antilles chains are fairly well studied, Haiti hasn't received the same attention, since working in a country that is no stranger to poverty and hardship can be downright unsafe.

Haiti's quake occurred along the Enriquilla-Plantain Garden Fault, an east-west crack in the Earth that also runs west through Jamaica and out to the Cayman Islands. But Hispaniola also is home to another major fault, which cuts across its northern interior and heads toward Cuba.

These two fault systems trace their origins to a broader interaction between the North American plate and the Caribbean Plate. The North American plate is plunging under the Caribbean plate north of Hispanola and Puerto Rico. But one portion of the North America plate dubbed the Bahamas Platform is too buoyant to make the plunge easily. According to researchers: "The giant collision is deforming Hispanola."

Over millions of years, Hispaniola's northern fault, the Septentrional, has been the major pathway for building and releasing strain from the sideways motion of the two plates. According to researchers: "They argue that activity may be shifting; the Enriquilla-Plantain Garden Fault may slowly be taking over as the main strain-relief valve for the plate boundary, explains Uri ten Brink, a geophysicist with the US Geological Survey's office in Woods Hole, Mass."

Consequences: Given the number of people who live on the island, as well as the number who visit, "this was really a wake-up call to me to try and understand this system."

Summary of Caribbean Earthquakes and Tsunamis

A dozen major earthquakes of magnitude 7.0 or greater have occurred in the Caribbean near Puerto Rico, the U.S. Virgin Islands and the island of Hispaniola, shared by Haiti and the Dominican Republic, in the past 500 years, and several have generated tsunamis. The most recent major earthquake, a magnitude 8.1 in 1946, resulted in a tsunami that killed a reported 1,600 people.

With nearly twenty million people now living in this tourist region and a major earthquake occurring on average every 50 years, scientists say it is not a question of if it will happen but when. They are calling for the establishment of tsunami early warning systems in the Caribbean Sea, Gulf of Mexico and Atlantic Ocean, and better public education about the real tsunami threats in these regions.

In a new study published December 24, 2004 in the Journal of Geophysical Research from the American Geophysical Union, geologists Uri ten Brink of the U.S. Geological Survey in Woods Hole and Jian Lin of the Woods Hole Oceanographic Institution (WHOI) report a heightened earthquake risk of the Septentrional fault zone, which cuts through the highly populated region of the Cibao valley in the Dominican Republic.

The geologically active offshore Puerto Rico and Hispaniola trenches are capable of producing earthquakes of magnitude 7.5 and higher. The Indonesian earthquake on December 26, which generated a tsunami that killed (to date) an estimated 150,000 people, came from a fault of similar structure, but was a magnitude 9.0, much larger than the recorded quakes near the Puerto Rico Trench.

The Puerto Rico Trench, roughly parallel to and about 75 miles off the northern coast of Puerto Rico, is about 900 kilometers (560 miles) long and 100 kilometers (60 miles) wide. The deepest point in the Atlantic Ocean, the trench is 8,340 meters (27,362 feet) below the sea surface. The Hispaniola Trench parallels the north coast of the Dominican Republic and Haiti, and is 550 kilometers (344 miles) long and only 4,500 meters (14,764 feet) deep.

Earthquakes typically occur near faults or fractures in the Earth's crust where rock formations, driven by the movements of the crustal or tectonic plates that make up the Earth's surface, grind slowly past each other or collide, building up stress. At some point, stress overcomes friction and the rocks slip suddenly, releasing seismic energy in the form of an earthquake, which drops the stress in one area but raises the stress elsewhere along the fault line.

The two scientists studied the geology of the northern Caribbean plate boundary, looked at historical earthquake data in the region, and used three-dimensional models to calculate the stress changes in and near the trenches after each earthquake. Ten Brink, who is also an adjunct scientist at WHOI, and Dr. Lin say stress has increased for the Hispaniola area, and that the potential threat of earthquakes and resulting possible tsunamis from the Puerto Rico and Hispaniola trenches is real and should be taken seriously.

In addition to establishing warning systems and informing the public about the risk, they call for improved documentation of prior earthquake and tsunami events and better estimates of future threats from the Puerto Rico and Hispaniola trenches through underwater studies.

"Every earthquake has its own character," says Dr. Lin, who has studied mid-ocean ridges, hotspots and undersea volcanoes as well as earthquakes in Southern California, China and the Pacific." And not all earthquakes generate tsunamis, which form when large areas of the seafloor rise or drop suddenly, causing the ocean above them to move. Many factors come into play in tsunami formation, including the size and type of an earthquake and how much the quake has ruptured the seafloor."

Dr. Lin, a senior scientist and a marine geophysicist in the WHOI Geology and Geophysics Department, says that each time an earthquake occurs on the offshore Puerto Rico and Hispaniola trenches, it adds stress to the Septentrional fault zone on Hispaniola. Since the fault is in a highly populated region and is capable of generating magnitude 7.7-7.9 earthquakes, the public should be educated about the risk of this earthquake prone area.

The region has a long history of destructive earthquakes. Historical records show that major earthquakes have struck the Puerto Rico, Virgin Islands region many times during the past 500 years although the locations and sizes of events that occurred more than a few decades ago are poorly known. Major earthquakes, greater than magnitude 7.0, damaged Puerto Rico in 1670, 1787, 1831, 1844, 1846, 1865, 1867, 1875, 1890, 1906, 1918, 1943 and 1946. The 1867, 1918 and 1946 earthquakes were accompanied by destructive tsunamis.

"Our results indicate that great subduction zone earthquakes, which often occur in the deep trenches off shore, have the potential to add stress or trigger earthquakes on other types of faults on the nearby islands," Lin says. "We don't want people to overreact, just make them aware of the potential risk of such rare and yet deadly events so they are prepared. It is similar to knowing about hurricanes or tornadoes and being prepared to react when one is coming."

Ten Brink, who studies earthquakes, tsunamis and geology in the Caribbean and Puerto Rico region, and has studied earthquake hazards in the Dead Sea in the Middle East, says there are a number of possible sources for tsunamis in the Caribbean. "The threat of major earthquakes in the Caribbean, and the possibility of a resulting tsunami, are real even though the risks are small in the bigger picture," Ten Brink said. "Local earthquakes, such as from the fault on Hispaniola, or effects from distant earthquakes can be severe.

Landslides and volcanic eruptions can also cause major earthquakes and potential tsunamis in this region. It has happened before, and it will happen again." He cautions that the threat of submarine landslides near Puerto Rico is real and residents and tourists, including those on cruise ships, would have very little warning given the close proximity to shore. However, the risk is small and should be put into perspective.

The Puerto Rico Trench, which is capable of producing earthquakes of magnitude 7 to 8 or greater, faces north and east into the Atlantic Ocean. There are few land areas or islands to block a tsunami generated near the Puerto Rico Trench from entering the Atlantic Ocean. The direction of the waves would depend on many factors, including where in the trench the earthquake occurred.

Long-term ocean observatories, new generations of seismic and oceanographic sensors and information technologies offer great promise to earthquake and tsunami research, Lin says. He and colleague Dezhang Chu of the WHOI Applied Ocean Physics and Engineering Department received WHOI seed funding in 2004 to develop a new technology to measure seafloor change, which could be a step forwards in understanding the processes that trigger underwater earthquakes and tsunamis.

Woods Hole Oceanographic Institution (WHOI) is a private, independent marine research and engineering and higher education organization located in Falmouth, MA. Its primary mission is to understand the oceans and their interaction with the Earth as a whole, and to communicate a basic understanding of the ocean's role in the changing global environment.

Established in 1930 on a recommendation from the National Academy of Sciences, the Institution operates the U.S. National Deep Submergence Facility that includes the deep-diving submersible Alvin, a fleet of global ranging ships and smaller coastal vessels, and a variety of other tethered and autonomous underwater vehicles. WHOI is organized into five departments, interdisciplinary institutes and a marine policy center, and conducts a joint graduate education program with the Massachusetts Institute of Technology.
Findings and Summary of Major Caribbean Earthquake Findings

The Caribbean is well known for earthquakes and volcanic activity. The Caribbean Plate was born deep beneath the ocean some 90 million to 100 million years ago.

The formation of the Isthmus of Panama was 3 million years ago. It ultimately lost its connection to the Pacific. The earthquake that devastated Port Au Prince recently occurred along the boundary of two tectonic plates — great slabs of crust that slide past one another slowly over time.

The Caribbean plate is moving east in relation to the North American plate. Large earthquakes frequently occur on these plate boundaries. The Caribbean plate has been moving about a quarter of an inch per year, relative to the North American plate. The absolute motion of the Caribbean Plate indicates that it moves westward, not east.

The deepest part of the Atlantic Ocean (roughly 8,400 meters), lies along the northern boundary with the North American plate. The eastern boundary contains seventeen active volcanoes, most notably Soufriere Hills on Montserrat, Mount Pelée on Martinique, La Grande Soufrière on Guadeloupe, Soufrière Saint Vincent on Saint Vincent, and the submarine volcano Kick-'em-Jenny which lies about 10 km north of Grenada.

The Caribbean Plate interacts with the South American Plate forming Barbados, Trinidad and Tobago (all on the Caribbean Plate), and islands off the coast of Venezuela (including the Leeward Antilles) and Colombia. The rich Venezuelan petroleum fields possibly result from this complex plate interaction.

Martinique Earthquake Ripples across Caribbean to South America

A strong magnitude 7.4 earthquake hit near the Caribbean island of Martinique sending shock waves across the Caribbean to Dominica, Puerto Rico, Antigua, St. Lucia, Montserrat, St. Vincent, Trinidad and Tobago, Guadeloupe and Guyana. Although this quake happened deep underground, it was so huge that it was felt higher up above ground.

The powerful earthquake in the Caribbean triggered a series of false quake alarms in California. A wave of seismic energy confused computers that try to triangulate the location of earthquakes along the West Coast.

The spreading center, one of the deepest on Earth, where new material emerges from deep beneath the crust to replenish the sea floor. Some of these trigger the formation of volcanoes. It has a platelet, a kind of smaller plate within a plate, on which the island of Hispaniola, home to Haiti and the Dominican Republic rides. And it exhibits the kind of long, side-slipping faults similar to California's San Andreas Fault.

The same earthquake fault that lies under Haiti also runs through the Dominican Republic. Geologists warn that the Haiti quake – at the Enriquilla-Plantain Garden Fault – may have added strain elsewhere and more quakes are possible. Hispaniola sits squarely atop a boundary between two plates in Earth's crust: the North American Plate and the Caribbean Plate.

The Caribbean Plate is trying to slide past a particularly tough block of crust underlying the Bahamas. The two are grinding past each other, much like the motion along another plate boundary, the California's San Andreas Fault. But Hispaniola also is home to another major fault, which cuts across its northern interior and heads toward Cuba.

These two fault systems trace their origins to a broader interaction between the North American plate and the Caribbean Plate. The North American plate is plunging under the Caribbean plate north of Hispanola and Puerto Rico.

According to geologists Uri Ten Brink and Jian Lin, geologists published December 24, 2004 in the Journal of Geophysical Research from the American Geophysical Union: "A heightened earthquake risk of the Septentrional fault zone, which cuts through the highly populated region of the Cibao valley in the Dominican Republic. In addition, they caution, the geologically active offshore Puerto Rico and Hispaniola trenches are capable of producing earthquakes of magnitude 7.5 and higher.

This region is not known for frequent seismic activity, at least not the kind that is felt above ground. Although this quake happened deep underground, it was so huge that it was felt higher up above ground. And while damages to buildings were minimal and just a couple of casualties reported, it was a frightening experience for the locals living on these otherwise peaceful isles in the Caribbean and South America, including Venezuela, according to some reports.

The earthquake occurred recently about 40 km (25 miles) of Fort-De-France, Martinique at 12.00 PM MST, (3.00 PM AST in Martinique), with a preliminary magnitude of 7.4. This is according to a release by the United States Geological Survey, National Earthquake Information Center.

A bank and a building were reported to have collapsed in Martinique as a result of the tremor. One caller described his experience on local radio: "My house shook so hard I thought it was going to fall. The door, the windows, everything shook," the Associated Press reported.

In Guyana where the quake was felt, buildings shook and school children ran out of the buildings in fear. In Venezuela's capital, Caracas, 500 miles (800km) from the epicenter, some people evacuated office buildings, the Reuters news agency reported.

The powerful earthquake in the Caribbean triggered a series of false quake alarms in California. Scientists with the U.S. Geological Survey said a wave of seismic energy confused computers that try to triangulate the location of earthquakes along the West Coast.

There's a fault line in this region where the South American and the Caribbean Tectonic plates push against each other. The South American plate moves West Northwest, thrusting beneath the Caribbean plate, at a rate of about 2 cm per year.

The quake apparently occurred within the subducted South American plate which is currently active at depths of about 200km below the Lesser Antilles arc near Martinique. Large "intermediate-depth" earthquakes such as this may be felt at great distances from their epicenters even though the damages may be minimal.

Tectonic Facts

The earthquake occurred on the diffuse boundary of the Caribbean and North American plates. The Caribbean plate moves to the east with respect to the North American plate at about 2 cm/year. The plate boundary in the Dominican Republic is oriented slightly oblique to the direction of relative plate-motion. The boundary in this region includes major strike-slip faults that accommodate plate-motion that is parallel to the boundary and also dip-slip faults that accommodate plate motion that is perpendicular to the boundary. The moment-tensor solution of the September 22 earthquake implies that it occurred as the result of dip-slip faulting.

2004: Leeward Islands, magnitude of M 6.3, Fatalities 1, and damage level is unknown.

2004: Cayman Islands Region, magnitude of M 6.8, and damage level is unknown.

2006: Gulf of Mexico, magnitude of M 5.8, and damage level is unknown.

2007: A powerful earthquake rocked the eastern Caribbean on Thursday, sending office workers and shoppers on several islands fleeing into the streets. The earthquake, which struck at 2 p.m. ET with a magnitude of 7.4, was centered 42 kilometers southeast of Roseau, the capital of Dominica, where the shaking lasted for about 20 seconds. There were reports of injuries, but no deaths were immediately reported. The quake was felt hundreds of kilometers away in Puerto Rico to the west, and Venezuela and Suriname to the south.

In the neighboring island of Martinique, a government official said police and firefighters were responding to hundreds of calls for help. He said some people sustained minor injuries, but no major casualties have been reported. The official declined to give his name in accordance with government policy.

In St. Lucia, Julian Dubois, deputy director of the national emergency management organization, said the quake caused some panic and broke water lines, but did not appear to cause severe damage. The tremor triggered a series of false quake alarms in California, with computers picking up energy coming out of the Caribbean and erroneously treating it as local seismic activity.

January 8, 2009: The 2009 Costa Rica earthquake (also known as Cinchona Earthquake), occurred at 1:21:34 pm local time (19:21:34 UTC). The epicenter of the 6.1 Mw earthquake was in northern Costa Rica, 30 kilometers (19 mi) north-northwest of San José. The earthquake took at least 34 lives, including at least three children, left about 64 people missing, and injured at least 91. Hundreds of people were trapped and two villages had been cut off. The earthquake was felt all over Costa Rica as well as in southern central Nicaragua.

Note: All hours are local. M is the magnitude that reflects the energy released by the earthquake. If it is not specified that the intensity is RF (Rossi Forell), it is MM (Modified Mercalli).

Tectonic Summary

The Costa Rican earthquake of January 8th, 2009 occurred within the Caribbean plate just east of its surface boundary with the Cocos plate. The earthquake has a strike-slip mechanism and likely resulted from the release of stresses built up within the crust of the Caribbean plate as the Cocos plate subducts beneath it. The plates converge at a rate of about 75 mm/year and the Cocos subducted slab dips to the northeast at around 45° to a depth of 170 km.

Costa Rica Earthquakes

1910, May 04.
Magnitude 6.4
Unknown depth and epicenter. The earthquake general area was Cartago, Costa Rica. Fatalities of 700 were the total damage assessed. The total damage cost is unknown.

1991 April 22
Magnitude 7.6
Forty-seven people killed, 109 injured, 7,439 homeless and severe damage (IX) in the Limon-Pandora area. Intensity X was observed in some zones of liquefaction within the epicentral area. Landslides blocked roads between Limon and central Costa Rica. Twenty-eight people killed, 454 injured, 2,400 homeless and 866 buildings destroyed (VII-VIII) in the Guabito-Almirante-Bocas del Toro area, Panama. Damage in Costa Rica estimated to be about 43 million U.S. dollars.

1999 August 20
Magnitude 6.9

The depth of the earthquake was 20 KM. Damage unknown. The epicenter of the earthquake was in San Jose, Costa Rica with damage extending to Panama.

Magnitude 6.4
2004 November 20
The magnitude of the earthquake was 6.4. The depth of the earthquake was 16KM (9.9 miles). The location was about 25 miles, Southwest of San Jose, Costa Rica. Eight people killed and several injured; 526 buildings damaged or destroyed; many roads and bridges damaged; some landslides occurred in the San Jose area. Water lines broke at Parrita and power outages occurred at Quepos. Felt in much of Costa Rica.

Magnitude 6.1
2009 January 08
The earthquake distance is 30 km (20 miles) NNW of San Jose, Costa Rica. The magnitude of the earthquake's epicenter was 6.1. The depth of the earthquake was 2.8 miles. The earthquake location was about 20 miles North West from San Jose, Costa Rica. At least 20 people killed in the Cinchona-Dulce Nombre area. Many of the casualties were caused by landslides. Many people were injured, several buildings were damaged and landslides blocked roads in the area. Electricity was disrupted in parts of San Jose and adjacent areas. The earthquake was felt throughout Costa Rica and in southern and central Nicaragua.

Haiti's First Major Quake in Two Centuries

There are two major faults along Hispaniola, the island shared by Haiti and the Dominican Republic.

Aftershocks are common after large quakes, and they continue for days, weeks and even longer, though they become less frequent as time passes. Earthquakes in this region often originate at a point in the earth that's relatively shallow. The relative motion between the two tectonic plates is mostly a side-to-side slip, rather than up and down.

The earthquake triggered a tsunami with waves measured at approximately 5.5 meters (20 feet) that lashed the west coast of the island and is remembered as one of the worst natural disasters that have struck the island.

The Caribbean Plate is moving to the east while the North American Plate is moving to the west. The North American Plate is being subducted by the Caribbean Plate to the southeast of the trench.

Volcanic activity is frequent along the island arc southeast from Puerto Rico to the coast of South America. Puerto Rico, the United States Virgin Islands, British Virgin Islands and the Dominican Republic do not have active volcanoes; however they are at risk from earthquakes and tsunamis. At this trench the North American plate is being subducted by the Caribbean plate.

Possibly, the strongest earthquake that has affected Puerto Rico since the beginning of colonization occurred on May 2, 1787. This was felt strongly throughout the Island and may have been as large as magnitude 8.0 on the Richter Scale.

The Indonesian earthquake on December 26, which generated a tsunami that killed (to date) an estimated 150,000 people, came from a fault of similar structure, but was a magnitude 9.0, much larger than the recorded quakes near the Puerto Rico Trench.

The stress changes in and near the trenches after each earthquake, according to Ten Brink, researcher: "Stress has increased for the Hispaniola area, and that the potential threat of earthquakes and resulting possible tsunamis from the Puerto Rico and Hispaniola trenches is real and should be taken seriously.

Local earthquakes, such as from the fault on Hispaniola, or effects from distant earthquakes can be severe. Landslides and volcanic eruptions can also cause major earthquakes and potential tsunamis in this region. It has happened before, and it will happen again.

The 1991 Costa Rica Earthquake of 7.5 April 22, 1991, killed 53 people, injuring 198, and causing widespread damage to constructed works. Highway traffic was immediately obstructed due to widespread disruption of pavements and roadway grades and the collapse of several bridges. Most of the damage to the highway and railway systems was caused by liquefaction and consequent ground failure, primarily lateral spreading.

The 2009 Costa Rica earthquake, magnitude of 6.1. The epicenter of the 6.1 earthquake was in northern Costa Rica, 30 kilometers (19 mi) north-northwest of San José. The earthquake was felt all over Costa Rica as well as in southern central Nicaragua. The earthquake took at least 34 lives, and 158 injuries. About 2,000 aftershocks have been felt throughout Costa Rica.

Flow failures are the most catastrophic ground failure caused by liquefaction. Martinique Earthquake Ripples across Caribbean to South America: A strong magnitude 7.4 earthquake hit near the Caribbean island of Martinique sending shock waves across the Caribbean. Although this quake happened deep underground, it was so huge that it was felt higher up above ground.

The powerful earthquake in the Caribbean triggered a series of false quake alarms in California. A wave of seismic energy confused computers that try to triangulate the location of earthquakes along the West Coast.

The spreading center, one of the deepest on Earth, where new material emerges from deep beneath the crust to replenish the sea floor. Some of these trigger the formation of volcanoes. It has a platelet, a kind of smaller plate within a plate, on which the island of Hispaniola, home to Haiti and the Dominican Republic rides. And it exhibits the kind of long, side-slipping faults similar to California's San Andreas Fault.

The same earthquake fault that lies under Haiti also runs through the Dominican Republic. Geologists warn that the Haiti quake – at the Enriquilla-Plantain Garden Fault – may have added strain elsewhere and more quakes are possible.

Hispaniola sits squarely atop a boundary between two plates in Earth's crust: the North American Plate and the Caribbean Plate. The Caribbean Plate is trying to slide past a particularly tough block of crust underlying the Bahamas. The two are grinding past each other, much like the motion along another plate boundary, the California's San Andreas Fault. But Hispaniola also is home to another major fault, which cuts across its northern interior and heads toward Cuba.

These two fault systems trace their origins to a broader interaction between the North American plate and the Caribbean Plate. The North American plate is plunging under the Caribbean plate north of Hispanola and Puerto Rico.

Findings

The following is a summary of the Major Caribbean Earthquake findings:

The Caribbean is well known for earthquakes and volcanic activity. The Caribbean Plate was born deep beneath the ocean some 90 million to 100 million years ago. The formation of the Isthmus of Panama 3 million years ago, it ultimately lost its connection to the Pacific.

The earthquake that devastated Port Au Prince recently occurred along the boundary of two tectonic plates — great slabs of crust that slide past one another slowly over time. The Caribbean plate is moving east in relation to the North American plate. Large earthquakes frequently occur on these plate boundaries.

The Caribbean plate has been moving about a quarter of an inch per year, relative to the North American plate. The absolute motion of the Caribbean Plate indicates that it moves westward, not east.

The deepest part of the Atlantic Ocean (roughly 8,400 meters), lies along the northern boundary with the North American plate. The eastern boundary contains seventeen active volcanoes, most notably Soufriere Hills on Montserrat, Mount Pelée on Martinique, La Grande Soufrière on Guadeloupe, Soufrière Saint Vincent on Saint Vincent, and the submarine volcano Kick-'em-Jenny which lies about 10 km north of Grenada.

The Caribbean Plate interacts with the South American Plate forming Barbados, Trinidad and Tobago (all on the Caribbean Plate), and islands off the coast of Venezuela (including the Leeward Antilles) and Colombia. The rich Venezuelan petroleum fields possibly result from this complex plate interaction.

Coastal Waters

In twenty years, according to the climatologists, it is predicted that the coastal waters of the USA and Caribbean Islands, if the trend of the climate change continues, will raise more than 20 ft. Properties close to the beaches or close to the coast are not advisable to purchase.

Summary

The Caribbean plate is moving east in relation to the North American plate. Large earthquakes frequently occur on these plate boundaries. The Caribbean plate has been moving about a quarter of an inch per year, relative to the North American plate. But the two plates don't simply glide past one another. Strain builds up along faults at the plate boundaries, until it's released in a sudden burst of energy. This region is subject to an earthquake any time.

There are two contending theories as to the origin of the Caribbean Plate:

First Theory

One holds that it is a large igneous province that formed in the Pacific Ocean tens of millions of years ago. As the Atlantic ocean widened, North America and South America were pushed westward, separated for a time by oceanic crust. The Pacific Ocean floor is subducted under this oceanic crust between the continents.

The Caribbean Plate drifted into the same area, but as it was less dense (although thicker) than the surrounding oceanic crust. It did not subduct, but rather overrode the ocean floor, continuing to move eastward relative to North America and South America. With the formation of the Isthmus of Panama 3 million years ago, it ultimately lost its connection to the Pacific.

Part of the Puerto Rico Trench, the deepest part of the Atlantic Ocean (roughly 8,400 meters), lies along this border. The Puerto Rico trench is at a complex transition from the subduction boundary to the south and the transform boundary to the west.

Eastern Boundary
The eastern boundary is a subduction zone, but since the boundary between the North and South American Plates in the Atlantic is as yet undefined. It is unclear which one, or possibly both, is descending under the Caribbean Plate.
- The subduction forms the volcanic islands of the Lesser Antilles island arc from the Virgin Islands in the north to the islands off the coast of Venezuela in the south.
- This boundary contains seventeen active volcanoes, most notably Soufriere Hills on Montserrat, Mount Pelée on Martinique, La Grande Soufrière on Guadeloupe, Soufrière Saint Vincent on Saint Vincent, and the submarine volcano Kick-'em-Jenny which lies about 10 km north of Grenada.

South Boundary
The southern boundary (the Caribbean Plate) interacts with the South American Plate forming Barbados, Trinidad and Tobago (all on the Caribbean Plate), and islands off the coast of Venezuela (including the Leeward Antilles) and Colombia.
- This boundary is in part the result of transform faulting along with thrust faulting and some subduction.
- The rich Venezuelan petroleum fields possibly result from this complex plate interaction.

Western Boundary
The western portion of the plate is occupied by Central America. The Cocos Plate in the Pacific Ocean is subducted beneath the Caribbean Plate just off the western coast of Central America.

- This subduction forms the volcanoes of Guatemala, El Salvador, Nicaragua, and Costa Rica, also known as the Central America Volcanic Arc.

1918 Puerto Rico Earthquake

The Puerto Rico earthquake of 1918 was a major earthquake that struck the island of Puerto Rico. The magnitude for the earthquake has been reported at around 7.5 (or Level IX in the Rossi-Forel scale used at that time. The main-shock epicenter occurred off shore about 10 miles (5 km) from the northwestern coast of the island, somewhere along the Puerto Rico Trench.

The earthquake triggered a tsunami with waves measured at approximately 5.5 meters (20 feet) that lashed the west coast of the island and is remembered as one of the worst natural disasters that have struck the island. The losses resulting from the disaster were approximately 116 casualties and $4 million in property.

Puerto Rico Trench

The island of Puerto Rico lies immediately to the south of the fault zone and the trench.
The trench is 800 kilometers (500 mi) long and has a maximum depth of 8,605 meters (28,232 ft) at Milwaukee Deep, which is the deepest point in the Atlantic Ocean.
The Caribbean Plate is moving to the east while the North American Plate is moving to the west. The North American Plate is being subducted by the Caribbean Plate to the southeast of the trench. Volcanic activity is frequent along the island arc southeast from Puerto Rico to the coast of South America. The trench is 1,090 miles (1,754 km) long and about 60 miles (97 km) wide. At its deepest point (named Milwaukee Depth), it is 27,493 feet (8,380 m) deep. At this trench the North American plate is being subducted by the Caribbean plate. This subduction zone is responsible for the volcanism of the West Indies to the southeast of Puerto Rico.

Hispaniola, Puerto Rico and the U.S. Virgin Islands sit on top of small crustal blocks that are sandwiched between the North American and Caribbean plates. The island of Hispaniola faces a double risk: an earthquake from the Septentrional fault on the island itself as the plates move past each other, and an earthquake deep in the earth in the subduction zone on which the island sits.

Puerto Rico lies at the boundary between the Caribbean and North American plates.
- This means that it is currently being deformed by the tectonic stresses caused by the interaction of these plates.
- These stresses may cause earthquakes and tsunamis. These seismic events, along with landslides, represent some of the most dangerous geologic hazards in the island and in the northeastern Caribbean.
- The most recent major earthquake occurred on October 11, 1918 and had an estimated magnitude of 7.5 on the Richter scale.
- Puerto Rico in the Atlantic Ocean at the boundary between the Caribbean and North American plates is the Puerto Rico Trench, the largest and deepest trench in the Atlantic.

Volcanic activity is frequent along the island arc southeast from Puerto Rico to the coast of South America. Puerto Rico, the United States Virgin Islands, British Virgin Islands and the

Dominican Republic do not have active volcanoes; however they are at risk from earthquakes and tsunamis.

The western part of Puerto Rico lies on a fault which is said to be active.

Four strong earthquakes have affected Puerto Rico since the beginning of its colonization.

The other strong earthquake, whose magnitude has not been determined, occurred in 1670, significantly affecting the area of San German District.
Possibly, the strongest earthquake that has affected Puerto Rico since the beginning of colonization occurred on May 2, 1787. This was felt strongly throughout the Island and may have been as large as magnitude 8.0 on the Richter Scale.

Hispaniola, Puerto Rico and the U.S. Virgin Islands sit on top of small crustal blocks that are sandwiched between the North American and Caribbean plates. The island of Hispaiola faces a double risk: an earthquake from the Septentrional fault on the island itself as the plates move past each other, and an earthquake deep in the earth in the subduction zone on which the island sits.

The stress changes in and near the trenches after each earthquake, According to Ten Brink, researcher: "stress has increased for the Hispaniola area, and that the potential threat of earthquakes and resulting possible tsunamis from the Puerto Rico and Hispaniola trenches is real and should be taken seriously.

The 1991 Costa Rica Earthquake of 7.5 April 22, 1991, killed 53 people, injuring 198, and causing widespread damage to constructed works.

Highway traffic was immediately obstructed due to widespread disruption of pavements and roadway grades and the collapse of several bridges.

Most of the damage to the highway and railway systems was caused by liquefaction and consequent ground failure, primarily lateral spreading.

The 2009 Costa Rica earthquake of magnitude of 6.1. The epicenter of the 6.1 earthquake was in northern Costa Rica, 30 kilometres (19 mi) north-northwest of San José. The earthquake was felt all over Costa Rica as well as in southern central Nicaragua.

About 2,000 aftershocks have been felt throughout Costa Rica.

All earthquakes in the Caribbean emanate from the Puerto Rico trench that is located north of Puerto Rico. Puerto Rico, Dominican Republic, and Puerto Rico have asymmetric risk. So far, Sarasota, Florida seems to offer the least risk.

Earthquake Glossary

Aseismic - This term describes a fault on which no earthquakes have been observed

Asthenosphere - The asthenosphere is the ductile part of the earth just below the lithosphere, including the lower mantle. The asthenosphere is about 180 km thick.

Aftershocks - Aftershocks are earthquakes that follow the largest shock of an earthquake sequence. They are smaller than the main shock and within 1-2 rupture lengths distance from the main shock. Aftershocks can continue over a period of weeks, months, or years. In general, the larger the main shock, the larger and more numerous the aftershocks, and the longer they will continue.

Bedrock - Relatively hard, solid rock that commonly underlies softer rock, sediment, or soil; a subset of the basement.

Benioff Zon - A dipping planar (flat) zone of earthquakes that is produced by the interaction of a downgoing oceanic crustal plate with a continental plate. These earthquakes can be produced by slip along the subduction thrust fault or by slip on faults within the downgoing plate as a result of bending and extension as the plate is pulled into the mantle. Also known as the Wadati-Benioff zone.

Body Wave - A body wave is a seismic wave that moves through the interior of the earth, as opposed to surface waves that travel near the earth's surface. P and S waves are body waves. Each type of wave shakes the ground in different ways.

Brittle-Ductile Boundary - The depth in the crust where the crust changes from being brittle (tending to break) above, to being ductile (tending to bend) below. Most earthquakes occur in the brittle portion of the crust above the brittle-ductile boundary.

Core - The innermost part of the earth. The outer core extends from 2500 to 3500 miles below the earth's surface and is liquid metal. The inner core is the central 500 miles and is solid metal. The core of the earth was the first internal structural element to be identified. In 1906 R.D. Oldham discovered it from his studies of earthquake records. The inner core is solid, and the outer core is liquid and so does not transmit the shear wave energy released during an earthquake.

Crust - The crust is the outermost major layer of the earth, ranging from about 10 to 65 km in thickness worldwide. The uppermost 15-35 km of crust is brittle enough to produce earthquakes.

Deformation - Deformation is a change in the original shape of a material. When we are talking about earthquakes, deformation is due to stress and strain.

Earthquake - Earthquake is a term used to describe both a sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth.

Earthquake Risk - Earthquake risk is the probable building damage and number of people that are expected to be hurt or killed if a likely earthquake on a particular fault occurs. Earthquake risk and earthquake hazards are occasionally incorrectly used interchangeably.

Epicenter - The epicenter is the point on the earth's surface vertically above the hypocenter (or focus) point in the crust where a seismic rupture begins.

Fault - A fault is a fracture along which the blocks of crust on either side have moved relative to one another parallel to the fracture.

Fault Gouge - Fault gouge is crushed and ground-up rock produced by friction between the two sides when a fault moves.

Forearc - The forearc is the region between the subduction zone and the volcanic chain (volcanic arc).

Geodesy - Geodesy is the science of determining the size and shape of the earth and the precise location of points on its surface.

Geomorphology - Geomorphology is the study of the character and origin of landforms, such as mountains, valleys, etc

Harmonic Tremor - Harmonic tremor describes continuous rhythmic earthquakes that can be detected by seismographs. Harmonic tremors often precede or accompany volcanic eruptions.

Horst - A horst is found together with a graben in an extensional environment. The grabens are the down dropped blocks and the horsts are the upthrown blocks that lie next to the graben.

Hypocenter - The hypocenter is the point within the earth where an earthquake rupture starts. The epicenter is the point directly above it at the surface of the Earth. Also commonly termed the focus.

Intensity - The intensity is a number (written as a Roman numeral) describing the severity of an earthquake in terms of its effects on the earth's surface and on humans and their structures. Several scales exist, but the ones most commonly used in the United States are the Modified Mercalli scale and the Rossi-Forel scale. There are many intensities for an earthquake, depending on where you are, unlike the magnitude, which is one number for each earthquake.

Interplate - Pertains to processes between the earth's crustal plates.

Interplate Coupling - Interplate coupling is the ability of a fault between two plates to lock and accumulate stress. Strong interplate coupling means that the fault is locked and capable of accumulating stress, whereas weak coupling means that the fault is unlocked or only capable of accumulating low stress

Landslide - A landslide is a movement of surface material down a slope.

Liquefaction - A process by which water-saturated sediment temporarily loses strength and acts as a fluid, like when you wiggle your toes in the wet sand near the water at the beach. This effect can be caused by earthquake shaking

Lithosphere - The lithosphere is the outer solid part of the earth, including the crust and uppermost mantle. The lithosphere is about 100 km thick; although its thickness is age dependent (older lithosphere is thicker). The lithosphere below the crust is brittle enough at some locations to produce earthquakes by faulting, such as within a subducted oceanic plate.

Mid Ocean Ridge - The greatest mountain range is the Mid-Ocean Ridge, extending 64,374 km (40,000 mi) from the Arctic Ocean to the Atlantic Ocean, around Africa, Asia, and Australia, and under the Pacific Ocean to the west coast of North America. It has a greatest height of 4207m (13,800 ft) above the base ocean depth.

Oceanic Spreading Ridge - An oceanic spreading ridge is the fracture zone along the ocean bottom where molten mantle material comes to the surface, thus creating new crust. This fracture can be seen beneath the ocean as a line of ridges that form as molten rock reaches the ocean bottom and solidifies.

P-Wave - The fastest wave, and therefore the first to arrive at a given location, is called the P-wave. The P-wave, or compressional wave, alternately compresses and expands material in the same direction it is traveling.

Plate Tectonics - Plate Tectonics is the theory supported by a wide range of evidence that considers the earth's crust and upper mantle to be composed of several large, thin, relatively rigid plates that move relative to one another. Slip on faults that define the plate boundaries commonly results in earthquakes. Several styles of faults bound the plates, including thrust faults along which plate material is subducted or consumed in the mantle, oceanic spreading ridges along which new crustal material is produced, and transform faults that accommodate horizontal slip (strike slip) between adjoining plates. (See also "This Dynamic Earth: The Story of Plate Tectonics.")

Pleistocene - The Pleistocene is the time period between about 10,000 years before present and about 1,650,000 years before present. As a descriptive term applied to rocks or faults, it marks the period of rock formation or the time of most recent fault slip, respectively. Faults of Pleistocene age may be considered active though their activity rates are commonly lower than younger faults.

Richter Scale - The Richter magnitude scale was developed in 1935 by Charles F. Richter of the California Institute of Technology as a mathematical device to compare the size of earthquakes. The magnitude of an earthquake is determined from the logarithm of the amplitude of waves recorded by seismographs. Adjustments are included for the variation in the distance between the various seismographs and the epicenter of the earthquakes. On the Richter Scale, magnitude is expressed in whole numbers and decimal fractions.

For example, a magnitude 5.3 might be computed for a moderate earthquake, and a strong earthquake might be rated as magnitude 6.3. Because of the logarithmic basis of the scale, each whole number increase in magnitude represents a tenfold increase in measured amplitude. As an estimate of energy, each whole number step in the magnitude scale corresponds to the release of about 31 times more energy than the amount associated with the preceding whole number value.

Ring of Fire - The "Ring of Fire," also called the Circum-Pacific belt, is the zone of earthquakes surrounding the Pacific Ocean — about 90% of the world's earthquakes occur there. The next most seismic region (5-6% of earthquakes) is the Alpide belt (extends from Mediterranean region, eastward through Turkey, Iran, and northern India. The next most seismic region (5-6% of earthquakes) is the Alpide belt (extends from Mediterranean region, eastward through Turkey, Iran, and northern India.

Rupture Front - The rupture front is the instantaneous boundary between the slipping and locked parts of a fault during an earthquake. Rupture in one direction on the fault is referred to as unilateral. Rupture may radiate outward in a circular manner or it may radiate toward the two ends of the fault from an interior point, behavior referred to as bilateral.

Rupture Velocity - The speed at which a rupture front moves across the surface of the fault during an earthquake.

S-Wave - An S-wave, or shear wave, is a seismic body wave that shakes the ground back and forth perpendicular to the direction the wave is moving.

San Andreas Fault - It is NOT a single, continuous fault, but rather is actually a fault zone made up of many segments. Movement may occur along any of the many fault segments along the zone at any time. The San Andreas Fault system is more that 1300 km (800 miles) long, and in some spots is as much as 16 km (10 miles) deep. The origin of the name of the San Andreas Fault is often cited as the San Andreas Lake. However, based on some 1895 and 1908 reports by geologist A.C. Lawson, who named the fault, the name was actually taken from the San Andreas Valley. He likely did not realize at the time that the fault ran almost the entire length of California!

Sea-Floor Spreading - Sea-floor spreading is what happens at the mid-oceanic ridge where a divergent boundary is causing two plates to move away from one another resulting in spreading of the sea floor. As the plates move apart, new material wells up and cools onto the edge of the plates.

Seiche - A seiche is the sloshing of a closed body of water from earthquake shaking. Swimming pools often have seiches during earthquakes.

Seismic Gap - A seismic gap is a section of a fault that has produced earthquakes in the past but is now quiet. For some seismic gaps, no earthquakes have been observed historically, but it is believed that the fault segment is capable of producing earthquakes on some other basis, such as plate-motion information or strain measurements

Seismic Wave - A seismic wave is an elastic wave generated by an impulse such as an earthquake or an explosion. Seismic waves may travel either along or near the earth's surface (Rayleigh and Love waves) or through the earth's interior (P and S-waves).

Seismic Zone - A seismic zone is an area of seismicity probably sharing a common cause. Example: "The New Madrid Seismic Zone."

Seismogram - A seismogram is a record written by a seismograph in response to ground motions produced by an earthquake, explosion, or other ground-motion sources
Seismograph - A seismograph, or seismometer, is an instrument used to detect and record earthquakes. Generally, it consists of a mass attached to a fixed base. During an earthquake, the base moves and the mass does not. The motion of the base with respect to the mass is commonly transformed into an electrical voltage. The electrical voltage is recorded on paper, magnetic tape, or another recording medium. This record is proportional to the motion of the seismometer mass relative to the earth, but it can be mathematically converted to a record of the absolute motion of the ground. Seismograph generally refers to the seismometer and its recording device as a single unit.

Shear Stress - Shear stress is the stress component parallel to a given surface, such as a fault plane, that results from forces applied parallel to the surface or from remote forces transmitted through the surrounding rock.

Subduction Zone - The subduction zone is the place where two lithospheric plates come together, one riding over the other. Most volcanoes on land occur parallel to and inland from the boundary between the two plates.

Tectonic - Tectonic refers to rock-deforming processes and resulting structures that occur over large sections of the lithosphere.

Tectonic Plates - The tectonic plates are the large, thin, relatively rigid plates that move relative to one another on the outer surface of the Earth.

Tensional Stress - Tensional stress is the stress that tends to pull something apart. It is the stress component perpendicular to a given surface, such as a fault plane, that results from forces applied perpendicular to the surface or from remote forces transmitted through the surrounding rock.

Tidal Wave- A tidal wave is a shallow water wave caused by the gravitational interactions between the Sun, Moon, and Earth.

Tsunami - A tsunami is a sea wave of local or distant origin that results from large-scale seafloor displacements associated with large earthquakes, major submarine slides, or exploding volcanic islands.

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