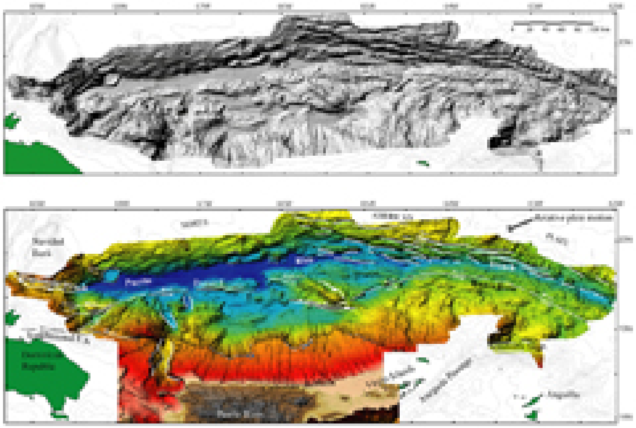
US Geological Survey - Woods Hole Science Center

Caribbean tsunami and earthquake hazard studies

SUMMARY:

Puerto Rico and the Virgin Islands are located at an active plate boundary between the North American plate and the northeast corner of the Caribbean plate where the plate movements have caused large magnitude earthquakes and devastating tsunamis. Scientists have so far failed to explain the deformation of this complex region in a coherent and predictable picture and this has hampered their ability to assess the seismic and tsunami hazard. The objective of this project is to provide the understanding needed to approach the problem of assessment, education and mitigation of tectonic hazards in Puerto Rico and the Virgin Islands.



map of study area

INVESTIGATORS:

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DESCRIPTION:

In the twentieth century alone there have been six very large earthquakes (Ms 7.8 on 7/29/1943; Ms 8.0 on 8/4/1946 followed by four major aftershocks of Ms 7.6, 7.0, 7.3, 7.1 between 1946 and 1953). Large tsunamis have also hit Puerto Rico and Hispaniola, reportedly killing 1800 people in 1946 and 40 people in 1918. USGS GLORIA images of the slope north of Puerto Rico disclose massive slide scars, as much as 50 km across, that probably generated tsunamis along the north shore of the island. The northern margin of Puerto Rico has collapsed as much as 4.0 km. The island is also surrounded by massive tectonic features on the other sides. The risk to life and economic infrastructure is high, because 4 million U.S. citizens live along the coastlines of Puerto Rico and the Virgin Islands. Scientists have so far failed to explain the deformation of this complex region in a coherent and predictable picture and this has hampered their ability to assess the seismic and tsunami hazard. It is as if we would try to assess earthquake hazards in California without knowing of the existence of the San Andreas Fault system and its rate of motion. Impact of this work is intended to improve the safety of residents and to protect coastal resources in the Puerto Rico/Virgin Islands region with regard to earthquakes and tsunamis. By determining the likely hazards and their causative mechanisms and providing this information to government agencies and the public we may aid in such activities as improvement of building codes, encouraging safer zoning, and assisting public education for response to hazards.

START DATE OF PROJECT:

01-OCT-2002

END DATE OF PROJECT:

30-SEP-2005

LOCATION:

Caribbean

APPROACH:

Data acquisition

NOAA Office of Ocean Exploration provided funding and 32 days of ship time to carry out a comprehensive seafloor mapping of an 800 km by 120 km area north of Puerto Rico. This area is considered by NOAA to be an exploration frontier, because of the paucity of modern data there. The SHOALS Lidar data set covering the near shore around Puerto Rico was

collected with FEMA funds and was integrated into this data set.
In cooperation with the Universidad Complutense de Madrid, and the University of Puerto Rico, and using the USGS ocean bottom seismometers (OBS), we will collect seismic reflection and refraction data north and south of Puerto Rico. The southern margin of Puerto Rico has been rarely surveyed (and that was done more than 30 years ago) despite its potential for tectonic activity. The OBS will be left on the sea floor to record local earthquakes and help the Puerto Rico Seismic Network locate earthquakes with its instruments.

Analysis and modeling

A comprehensive analysis of local earthquake records from the Puerto Rico Seismic network with an emphasis on accurate relocation of earthquakes using the double-differencing method will take place. Finite-element modeling of tsunami run-up on the shores of Puerto Rico and the Virgin Islands using detailed multibeam bathymetry and SHOALS Lidar data, will help identify areas of potential tsunami hazards. Modeling studies of fault interactions has provided theoretical framework to assess the hazard to Puerto Rico from secondary near-shore faults.

RESULTS:

New sea floor map of the Puerto Rico Trench:

Detailed seafloor mapping of complete geological provinces provide critical perspective on their origin and development and provide base maps for studies in other disciplines. The data were collected using the SeaBeam 2112 multibeam system aboard the NOAA ship Ron Brown with sufficient swath overlap and proper line orientation for hydrographic survey. The data were gridded at 150 m grid size following resolution tests. Vertical resolution is estimated to be 0.5-1% of the water depth. Backscatter mosaic images derived from the multibeam bathymetry data aided in interpretation. The total mapped area is 100,000 km2, slightly smaller than the area of the State of Virginia. The maps have been used to investigate the causes for the subsidence and deformation of this unusually deep part of the Atlantic Ocean and to identify earthquake and tsunami hazards. Earthquake hazard from strike-slip motion in the forearc may be small, although other potential sources of earthquakes in the region may exist. Tsunami hazard to the northern coast of Puerto Rico and the Virgin Islands from submarine slope failures appears to be high.

Stress interaction between subduction earthquakes and forearc strike-slip faults:

Strike-slip faults in the forearc often present significant seismic hazard because of their proximity to population centers. The interaction between thrust events on the subduction interface and strike-slip faults within the forearc has been explored using 3-D models of static Coulomb stress change. Model results reveal that subduction earthquakes with slip vectors making high oblique angles to the trench axis enhance the Coulomb stress on strike-slip faults adjacent to the trench, but reduce the stress on faults farther back in the forearc. In contrast, subduction events with slip vectors perpendicular to the trench axis enhance the Coulomb stress on strike-slip faults farther back in the forearc, while reducing the stress adjacent to the trench. A significant contribution to Coulomb stress increase on strike-slip faults in the back of the forearc comes from "unclamping" of the fault, i.e., reduction in normal stress, due to thrust motion on the subduction interface, whereas shear stress increases the Coulomb stress near the trench. We argue that although Coulomb stress changes are ephemeral, they exert significant influence on the pattern of deformation.

We use the models to explain the contrasting deformation pattern between two adjacent segments of oblique subduction of the North American (NOAM) plate under the northern Caribbean. Dip-slip reverse motion is dominant in the Hispaniola segment, where the strike-slip faults are more than 60 km inland from the trench. In contrast, subduction slip motion is very oblique near Puerto Rico, where the strike-slip fault is less than 15 km from the trench. The jump from a strike-slip fault near the trench in the Puerto Rico segment to inland faults in Hispaniola is explained by different distributions of Coulomb stress in the forearc of the two segments, as a result of the change from oblique slip on the Puerto Rico subduction interface to more perpendicular subduction slip beneath Hispaniola. The observations and modeling suggest that subduction-induced strike-slip seismic hazard to Puerto Rico may be smaller than previously assumed, but the hazard to Hispaniola remains high.

Submarine slope failures north of Puerto Rico and their tsunami potential:

New multibeam bathymetry and coincident acoustic backscatter images of the 770-km long Puerto Rico trench reveal numerous slope failures at various sizes north of Puerto Rico and the Virgin Islands. At the edge of the carbonate platform a few tens of km north of Puerto Rico, the failed material comprises carbonate blocks, which slid, at least initially, as coherent rock masses. The style of failure (rock falls and slide blocks vs. debris avalanche and debris flow) appears to be correlated with the thickness of the carbonate layers at the headwall of the slide. Extensional fissures, discovered in the ocean floor near the edge of the platform, suggest that the slope failure process is expected to continue in the future. The displacement of large coherent blocks and the steep slope (up to 45°) at the failure point at the edge of the carbonate platform would imply higher slide velocity, and therefore a higher potential for tsunami runup than along many other U.S. coasts that are covered with clastic sediments. One of the identified failure scars at the edge of the platform, the Arecibo amphitheater, previously thought to represent a single giant slide with a volume of 900-1500 cu. km, appears instead to comprise multiple failures. Simulations of one of the slope failures within the Arecibo Amphitheater predict a maximum runup less than 20 m on the northern coast of Puerto Rico. A minimum recurrence time for slope failures along the edge of the carbonate platform can be estimated assuming that the failure process has continued since the tilting of the platform about 3.5 m.y. ago, that the failures have a characteristic area and thickness similar to those observed and assuming that the edge of the platform was initially straight. Elsewhere along the northwestern margin of the island, a 22-km wide slide scarp was discovered in the Upper Mona rift and could be associated with the 1918 tsunami and earthquake that hit northwestern Puerto Rico. Other large submarine slides were discovered for the first time on the northern side of the Puerto Rico trench on the downgoing North American plate. Because these slides occur in deep water (6000 m), have large horizontal and vertical (20 x 1.5 km) dimensions, and the tsunamis emanating from these slides are directed toward Puerto Rico, they are of particular concern and necessitate further study.

Model for the subsidence of the Puerto Rico trench and the rise of the island of Puerto Rico:

A coherent explanation to many observations in the NE Caribbean, which puzzled scientists for the past 40 years, is proposed. These observations include the unusually great depth of part of the PRT, the lowest Free-air gravity anomaly on Earth, and a tilted Oligo-Pliocene carbonate platform whose northern edge is a depth of 4000 m b.s.l. and its reconstructed southern depth is at an elevation of 1300 m a.s.l. The platform is uniformly tilted along 250 km long section of the trench, and the duration of the tilting event is estimated at between 15-40 ky. We propose that these large vertical movements were generated during a short geological time in the middle Pliocene, when the descending NOAM slab partially or completely tore. On the basis of gravity, topography, seismic activity, focal mechanism, and deformation of the seafloor, we locate the tear along a diagonal trend extending from the trench north of the Virgin Islands southwestward toward the northeastern edge of Puerto Rico. As a result of the tear, the descending segment to the west of the tear increased its dip. The increased dip could arise from either the loss of the "suction force", which balances the gravitational pull on the slab due to sideways asthenospheric flow through the tear, or because this segment lost the support of the rest of the descending rigid slab. The increased descent angle caused the trench and the proximal forearc to subside. It also caused the upper plate under the arc to detach from the descending slab. This allowed the arc to rise, which created the island of Puerto Rico. Two processes might have caused the slab to tear 3.5 m.y. ago. Counterclockwise rotation of the PRVI block during the Late Miocene probably increased the trench curvature, which raised the trench-parallel tensile stresses in the slab. Into this tighter curvature entered a large seamount about 3.5 m.y. ago and focused the necessary stresses to tear the slab at this location. The proposed model provides a tectonic framework for the NE Caribbean plate boundary, which will help in the assessment of earthquake and tsunami hazards for Puerto Rico, and the British and U.S. Virgin Islands. Beyond the regional interest, it shows that geological phenomena of the scale observed here can arise from local crustal interactions through coupling between lithosphere and asthenosphere and between horizontal and vertical tectonic forces. Finally, the contrast between the collapsed trench and uplifted island in the Puerto Rico section of the subduction zone, and the adjacent more normal subduction zone of the Virgin Islands, provides constraints on dynamic models of subduction zones and the rheological properties of the slab and its surrounding asthenosphere. A more detailed study of the history of the collapse of the carbonate platform may help constrain the rates of reef and platform growth during sea level rise.

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