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New Seafloor Map of the Puerto Rico Trench Helps Assess Earthquake and Tsunami Hazards

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The Puerto Rico Trench, the deepest part of the Atlantic Ocean, is located where the North American (NOAM) plate is subducting under the Caribbean plate (Figure 1). The trench region may pose significant seismic and tsunami hazards to Puerto Rico and the U.S. Virgin Islands, where 4 million U.S. citizens reside. Widespread damage in Puerto Rico and Hispaniola from an earthquake in 1787 was estimated to be the result of a magnitude 8 earthquake north of the islands [*McCann et al.*, 2004]. A tsunami killed 40 people in NW Puerto Rico following a magnitude 7.3 earthquake in 1918 [*Mercado and McCann*, 1998]. Large landslide escarpments have been mapped on the seafloor north of Puerto Rico [*Mercado et al.*, 2002; *Schwab et al.*, 1991], although their ages are unknown.

The Puerto Rico Trench is atypical of oceanic trenches. Subduction is highly oblique (10°–20°) to the trench axis with a large component of left-lateral strike-slip motion. Similar convergence geometry is observed at the Challenger Deep in the Mariana Trench, the deepest point on Earth. In addition to its extremely deep seafloor, the Puerto Rico Trench is also characterized by the most negative free-air gravity anomaly on Earth, -380 mGal, located 50 km south of the trench, where water depth is 7950 m (Figure 2). A tilted carbonate platform provides evidence for extreme vertical tectonism in the region. This platform was horizontally deposited over Cretaceous to Paleocene arc rocks starting in the Late Oligocene. Then, at 3.5 Ma, the carbonate platform was tilted by 4° toward the trench over a time period of less than 40 kyr, (U. S. ten Brink et al., manuscript in preparation, 2004) such that its northern edge is at a depth of 4000 m and its reconstructed elevation on land in Puerto Rico is at +1300 m (Figures 1 and 2).

To help understand the origin of the unusual bathymetry, gravity, and vertical tectonics of the plate boundary and to provide constraints for hazard assessment, the morphology of the entire 770-km-long trench from the Dominican Republic in the west to Anguilla in the east was mapped with multibeam echosounder during three cruises in 2002 and 2003. Parts of the Puerto Rico Trench were previously surveyed with side-scan sonar [*Grindlay et al.*, 1997] and multibeam echosounder [*Dillon et al.*, 1998; *Grindlay et al.*, 1997], often at lower resolution and with line orientation and spacing that did not provide complete bathymetric coverage.

The data presented here were collected using the SeaBeam 2112 multibeam system aboard the National Oceanic and Atmospheric Administration (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 (10–80 m; L. Mayer, oral communication, 2003). Backscatter mosaic images derived from the multibeam bathymetry data aided in interpretation. The total mapped area is 100,000 km^2, slightly smaller than the area of the state of Virginia.

Subsidence of the Trench

The trench can be divided into two parts at about 65°–66°W. The western part includes the deepest sector of the trench, and is associated with the most oblique convergence. This sector is 10–15 km wide and 8300–8340 m deep relative to mean sea level (Figure 1). It is remarkably flat and is covered by nonreflective pelagic sediments. Seismic profiles show it to be underlain by rotated blocks of the NOAM plate that indicate trench subsidence. The unusual depth extends southward over parts of the forearc. The trench floor narrows to the west and abruptly shallows to 4700 m as it turns into the Hispaniola Trench, where convergence is more perpendicular. The eastern part of the trench is shallower by 700 m and more rugged than the deep western part. The subducting NOAM plate is observed in seismic lines to be broken into blocks, but the descending blocks are not rotated.

Deformation of the Subducting Plate

The trench wall north of the eastern part of the trench is cut by a series of normal faults with vertical throw up to 1500 m. Deformation cuts across remnant abyssal-hill lineaments that were presumably created near the spreading ridge, and is probably related to the bending of the NOAM plate around and under the curved subduction zone. Submarine slide scarps and slide toes were observed for the first time on the northern trench wall, the largest of which (at 68°W) is 20 km wide. The areas to the north and the west of that slide, including the steep slopes of Navidad Bank, show numerous submarine slide scarps.

Strain Partitioning in the Forearc

A 535-km-long fault is located 10–15 km south of the trench and passes through rounded hills that form the accretionary prism (Figure 1). The fault is interpreted to accommodate left-lateral motion because it is offset around a pull-apart depression (Figures 1 and 2). Seismic reflection data show the steeply dipping fault to penetrate 5 km through the accretionary sediments before terminating in the subduction interface [ten Brink and Lin, Stress interaction between subduction earthquakes and forearc strike-slip faults: modeling and applications, submitted to *J. Geophys. Res. Solid Earth*, 2004]. Part of this fault trace was first identified as a weak lineament on a Gloria backscatter image [*Masson and Scanlon*, 1991] and was named the Northern Puerto Rico Slope Fault Zone [*Grindlay et al.*, 1997]. The authors propose renaming this distinct regional fault the "Bunce fault" after the late Elizabeth Bunce, a pioneer marine geophysicist who explored the Puerto Rico Trench in the 1950s [*Bunce and Fahlquist*, 1962].

Bunce fault ends at the western end of the Puerto Rico Trench in several splays, typical of distributed deformation at the end of large strike-slip faults, such as the Alpine fault of New Zealand. The fault appears to be the only active strike-slip fault along most of this highly oblique subduction zone. Its proximity to the trench suggests that slip along the subduction interface is effectively oblique, which is in agreement with GPS measurements and earthquake focal mechanisms [ten Brink and Lin, Stress interaction between subduction earthquakes and forearc strike-slip faults: modeling and applications, submitted to *J. Geophys. Res. Solid Earth*, 2004]. Another fault closer to Puerto Rico (the South Puerto Rico Slope Fault Zone

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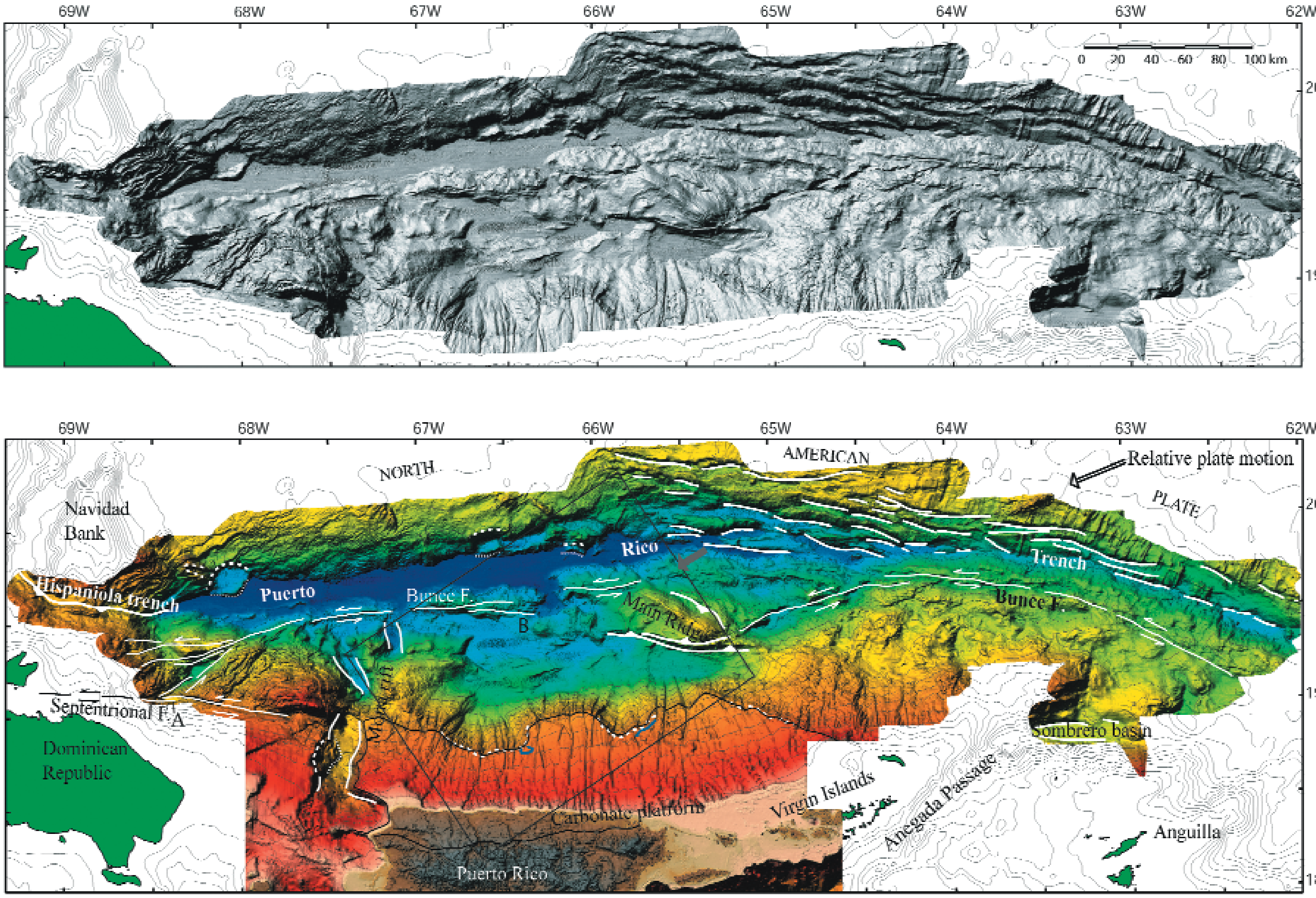

Fig. 1. (top) Shaded relief of the new multibeam bathymetry along the Puerto Rico Trench illuminated from the northwest. Thin contours indicate bathymetry from ETOPO2 at 500-m intervals. (bottom) Combined bathymetry map of the multibeam bathymetry data, single-beam bathymetry compilation around Puerto Rico, Lidar data near shore, and topography of Puerto Rico. Contour interval is 500 m. Thick barbed white lines denote thrust faults; thick white lines denote normal faults; thin white lines denote strike-slip fault; thin black lines denote northern edge of tilted carbonate platform and southern edge on land; dashed lines indicate head scarp of slope failures; dotted line indicates debris toe; blue lines indicate fissures in the seafloor; A, pull-apart basin; B, location of probable extinct mud volcano observed on backscatter images. Large black box and adjacent grey arrow show location and viewing direction of Figure 2.

(SPRSFZ) [*Grindlay et al.*, 1997]), which was previously proposed to be active, has no clear expression in the bathymetry (Figure 2). Therefore, earthquake hazard to Puerto Rico from strike-slip faults in the forearc appears low, because only the Bunce fault appears active; it is located ~110 km away, it is ~5 km deep, and it offsets partially consolidated sediments.

Bunce fault is deflected southward at 65°W, perhaps because this section was perturbed by the oblique subduction of Main Ridge. Main Ridge is interpreted to be underlain by a subducted ridge of seamounts because its axis is perpendicular to the observed abyssal-hill grain of the subducting NOAM plate (Figure 1). The subduction of the ridge has generated SW trending strike-slip fault in its wake, thrust faults with opposing dips on both sides of the ridge, and a reentrant in the trench axis, as predicted by sandbox models of subducting seamounts. Earthquake focal mechanisms and crossing seismic profiles indicate that these thrust faults are active and may present some seismic hazard.

A fault trace at the SW edge of the image is interpreted to be the eastern end of Septentrional fault, a major active fault in Hispaniola. Left-lateral motion is inferred from the existence of a small pull-apart basin along the fault (A in Figure 1). The fault ends abruptly in a 1000-m-deep circular depression 25 km west of Mona Rift, contrary to previous suggestions that it continues eastward across Mona Rift and along the base of the Puerto Rico slope.

Rifts in the Forearc and the Subduction Zone

Mona Rift NW of Puerto Rico consists of three en-echelon depressions (5000, 7800, and 8150 m), which cut the carbonate platform and extend almost to the Bunce fault (Figure 1). The rift probably accommodates minor E-W extension between Hispaniola and Puerto Rico. A large slump failure along the western wall of the upper rift basin may be related to the 1918 earthquake and tsunami.

The Anegada Passage south of the Virgin Islands is a series of deep depressions that were probably formed by a mixture of normal and strike-slip motion. Several reconstructions and tectonic analyses of the northeast Caribbean show the trough to be a crustal boundary between a block comprising Puerto Rico and the Virgin Islands and the Lesser Antilles Arc and, as such, extended the boundary to the trench [e.g., *Masson and Scanlon*, 1991]. This map shows that the Anegada Passage probably ends in the Sombrero Basin and does not connect to the trench.

Active Submarine Slides at the Edge of the Carbonate Platform

Two semicircular escarpments, 30–50 km across, are mapped along the northern edge of the carbonate platform at a distance of 35–50 km north of Puerto Rico (Figure 2). Our bathymetry and side-scan images indicate that the semicircular scarps were not formed each by a single catastrophic failure, as previously suggested [*Mercado et al.*, 2002; *Schwab et al.*, 1991], but were shaped by continuous retrograde slumping of smaller segments. Fissures near the edge of the carbonate platform indicate that the slumping process is ongoing (Figure 2). At the platform margin, the slope of the seafloor reaches 45°, and the water depth increases by 4000 m. Therefore, there may be significant

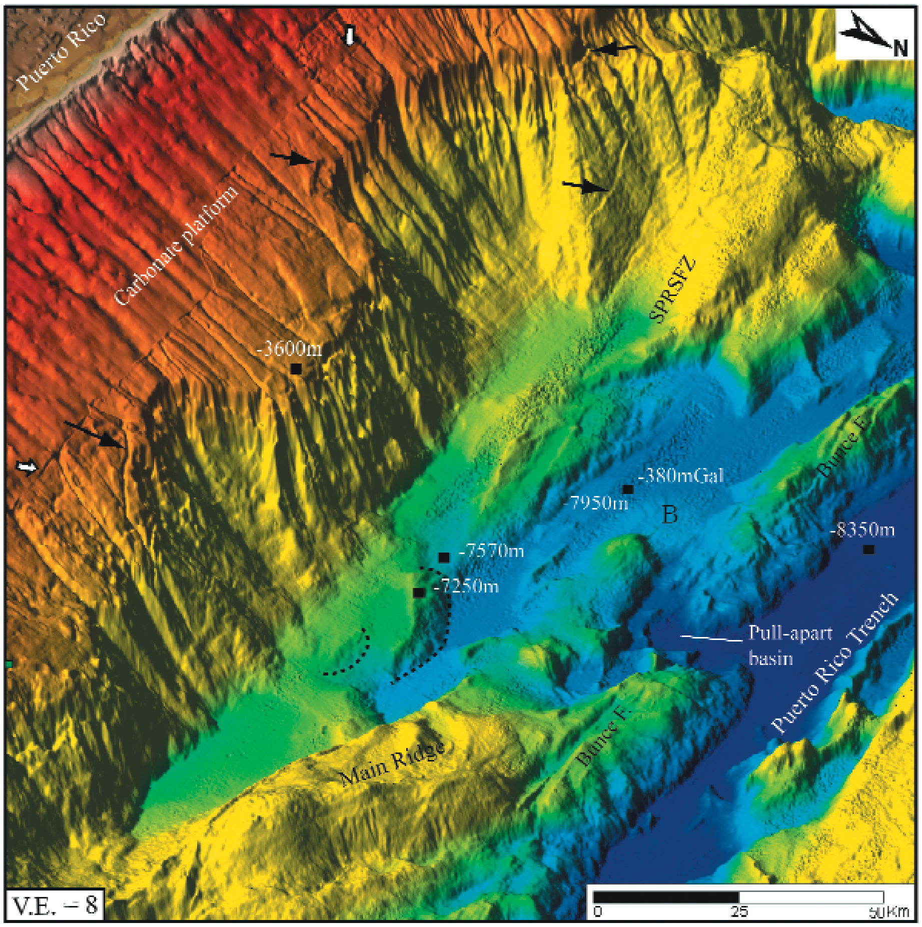

Fig. 2. Perspective view of the boxed region in Figure 1. Viewing direction is from the NE to the SW (grey arrow in Figure 1). White arrows point to the boundary between multibeam bathymetry and single-beam bathymetry. Black arrows point to fissures in the seafloor. Dotted lines are debris toes. The debris field reaching the larger toe appears to have been crossed by the debris ending at the smaller toe, indicating several generations of slope failure. The locations of a previously suggested strike-slip fault (SPRSFZ) and the largest free-air gravity anomaly on Earth (-380 mGal) are shown. Stippled textures (e.g., near SPRSFZ) are multibeam acquisition artifacts. B is as in Figure 1.

tsunami hazard to the northern coast of Puerto Rico from submarine slope failures. Such failures can be triggered either spontaneously or by small earthquakes.

Implications to Hazard Assessment

Detailed seafloor mapping of complete geological provinces, such as the one reported here, provide critical perspective on their origin and development and provide base maps for studies in other disciplines. Here and in related publications, the maps are used to investigate the causes of 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.

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