EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 85 NUMBER 8
24 FEBRUARY 2004
PAGES 77–88

Earthquake Shakes "Big Bend" Region of North America-Caribbean Boundary Zone

PAGES 77, 83

At 12:45 pm on 22 September, a M6.5 earthquake severely shook the northern Dominican Republic on the island of Hispaniola. The earthquake caused extensive damage to buildings in the major cities of Puerto Plata and Santiago, along with landslides in outlying areas. The main shock was followed by a large aftershock of M5.1 1 hr and 45 min later. Unfortunately, one person died due to collapse of a building during the main shock, two elderly people died of heart attacks, and one person jumped out of a building and later died of injuries. Fortunately, two partially collapsed school buildings and several office buildings in Puerto Plata that were severely damaged were unoccupied at the time of the early morning main shock.

Aftershocks ranging up to nearly M5 continued for over a month, alarming local inhabitants. The M6.5 earthquake is the strongest shock to affect the northern Dominican Republic since a series of thrust events ranging from M6.1–8.1 occurred offshore and northeast of the Dominican Republic between 1943 and 1953 [*Dolan and Wald*, 1998]. This article summarizes the tectonic setting of the recent earthquake, its focal mechanism and inferred fault plane, damage, and ongoing research.

Plate Tectonic Setting

The island of Hispaniola (Dominican Republic and Haiti) occupies a trans-pressional or restraining bend in the 3200-km-long, left-lateral North America-Caribbean plate boundary zone (Figure 1a). Global Positioning System (GPS) studies have shown that the Caribbean plate is moving east-northeastward at a rate of 18–20 ± 3 mm/yr relative to North America. This direction implies maximum oblique convergence between Hispaniola on the Caribbean plate, and the 22–27-km-thick crust of the Bahama carbonate platform on the adjacent North America plate (Figure 1a). This plate motion is partitioned into strike-slip displacement across the onshore Septentrional and Enriquillo faults and convergence across the offshore north Hispaniola fault zone [*Dolan and Wald*, 1998], and reflected by high elevations on the island (3000 m) and shortening structures within late Neogene sedimentary rocks [*Mann et al.*, 2002] (Figures 1 and 2).

The GPS velocity field in the northern Dominican Republic is compatible with the model of strain partitioning and elastic strain accumulation along a roughly west-northwest-striking, left-lateral strike-slip fault accommodating east-west plate motion (Septentrional) and a sub-parallel, submarine, low-angle thrust fault accommodating southwestward underthrusting [*Calais et al.*, 2002] (Figures 1b and 2). GPS vectors show a characteristic pattern of strain partitioning: slip directions along the Septentrional microplate are at a high angle to the plate boundary, and reflect thrusting along the North Hispaniola fault zone (Figure 1b). To the south, GPS vectors in central Hispaniola are more parallel to the Septentrional fault and reflect strike-slip motion parallel to this fault. The strain partitioning process gives rise to earthquakes with diverse focal mechanisms that suggest strike-slip, thrust, and oblique-slip displacements as shown in Figure 1b.

Pre-historic, Historical Seismicity of Major Faults of Northern Dominican Republic

The Septentrional fault zone is a left-lateral strike-slip fault marked by prominent scarps in alluvium in the densely populated, 320-km-long Cibao Valley in the Dominican Republic [*Mann et al.*, 1998] (Figure 1b). Paleoseismic studies of the central Septentrional fault have shown that the most recent ground-rupturing earthquake occurred between A.D. 1040 and A.D. 1230, and involved a minimum of ~4 m of left-lateral strike slip and 2.3 m of normal slip [*Prentice et al.*, 2003]. Paleoliquefaction studies suggest the fault rupture associated with this event may have involved the eastern as well as the central sections of the Septentrional fault, and produced four earthquakes of M 7–8 [*Tuttle et al.*, 2003]. The large historical earthquake of 1842 is inferred by many to have been caused by rupture of the Septentrional fault zone in the western Cibao Valley and along the north coast of Haiti (Figure 1b). At least two additional prehistoric earthquakes are known to have caused liquefaction in the western Cibao Valley during the past 1600 years [*Tuttle et al.*, 2003].

Stream terraces offset by the central Septentrional fault in the densely populated area northeast of Santiago provide late Holocene slip rate estimates of 6–9 mm/yr and a maximum of 11–12 mm/yr. Combining these estimates gives a best estimate of 6–12 mm/yr for the slip rate of the central Septentrional fault. Combining a slip rate of 6–12 mm/yr with the 800-yr interval since the most recent large earthquake on this fault implies an accumulation of at least 4.8 m of slip available to be released in the next large earthquake. The value of predicted slip is similar to the amount of slip released in the event 800 years ago. The current slip deficit suggests the possibility of a large, future event greater than M7. If the slip rate is as high as 12 mm/yr, then twice the amount of slip may be available, or around 10 m, suggesting the possibility of an even larger earthquake.

Because the north Hispaniola fault lies offshore, we have no quantitative data on its prehistoric activity and must rely instead on the record of historical earthquakes. *Dolan and Wald* [1998] have attributed a series of large (M6.2–M8.1) thrust earthquakes from 1943–1953 to oblique subduction of the North America plate and Bahama platform beneath the Septentrional microplate (Figure 2). These events began in 1943 in the Mona Passage area between the Dominican Republic and Puerto Rico, and moved westward to the position of the 1953 event (Figure 1b). A large earthquake in 1564 that severely damaged towns in the central Cibao Valley may have been related to thrusting on the Hispaniola fault zone, because trenching studies of the Septentrional have revealed no events younger than 1200 A.D.

Location, Focal Mechanism of September 2003 Earthquake

The 2003 event occurred immediately west of the epicenter of the 1953 oblique thrust event [*Dolan and Wald,* 1998]. Main shock locations vary by 30 km between the USGS and Harvard CMT (Figure 1b). Estimates of the depth of the event have ranged from 10 to 15 km, and are consistent with the lack of reported surface breaks in the epicentral area. The concentration of aftershocks recorded by

BY P. MANN, E. CALAIS, AND V. HUERFANO

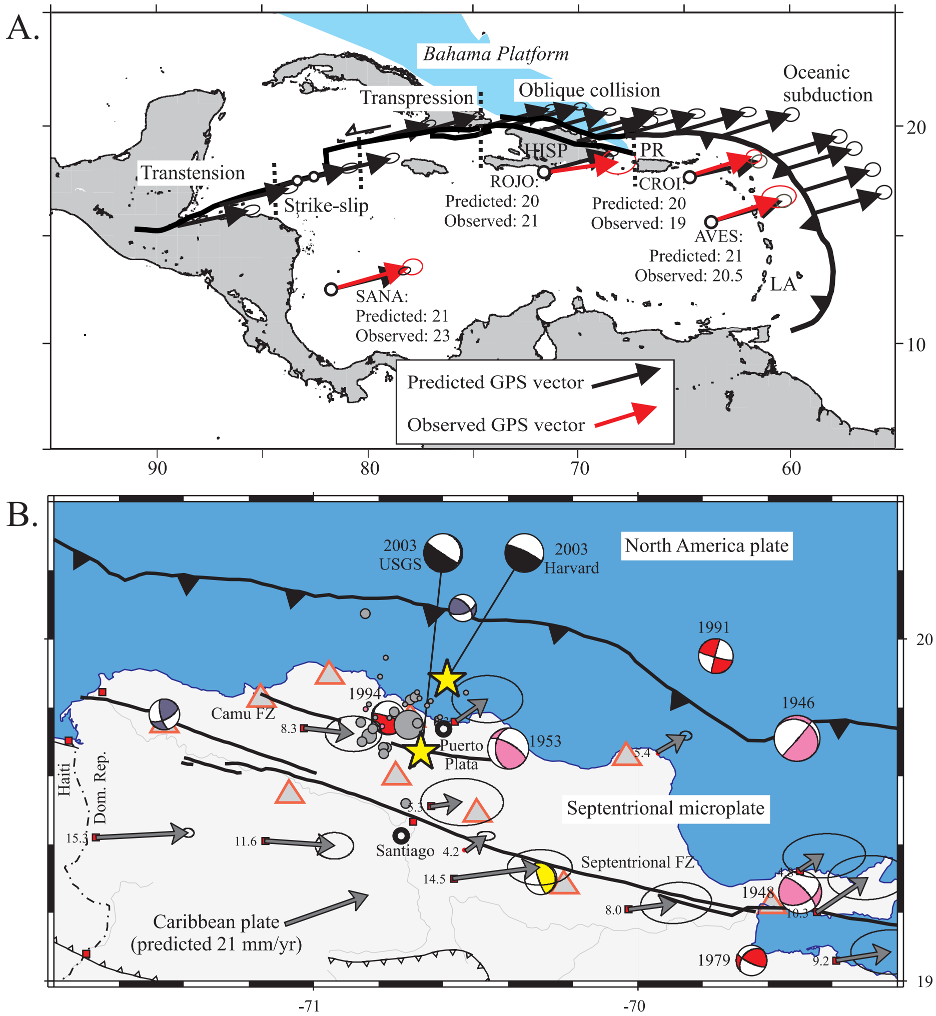

Fig. 1 (a) Caribbean-North America plate velocity predictions of DeMets et al. *[2000] (black arrows) are based on GPS velocities at four sites in the stable interior of the plate (red vectors) and two fault strike measurements in the strike-slip component of the North America-Caribbean plate-boundary zone. The predicted velocities are consistent with the along-strike transition in structural styles from trans-tension in the northwestern corner of the Caribbean plate to oblique convergence between the Caribbean plate and the Bahama carbonate platform in Hispaniola (Dominican Republic and Haiti). (b) This tectonic map of the northern Dominican Republic shows USGS and Harvard locations (yellow stars) and focal mechanisms (black) for the 22 September 2003 earthquake. Aftershock locations and relative sizes are shown by gray circles and are provided by the short period network operated by L. Odenel of the Water Resources Agency (INDRHI) of the Dominican Republic. Harvard CMT solutions are shown in red, focal mechanisms from* Dolan and Wald *[1998] are shown in pink,* Molnar and Sykes *[1969] are in yellow, and* Calais et al. *[1992] are in blue. GPS vectors and their error ellipses are from* Calais et al *[2002]; the total predicted GPS rate is from* DeMets et al. *[2000].*

the Water Resources Agency of the Dominican Republic (INDHRI) favors the U.S. Geological Survey main shock location, roughly 10 km south of Puerto Plata (Figure 1b). The focal mechanism indicates a high-angle, sub-vertical reverse fault plane aligned roughly parallel to both the north Hispaniola and Septentrional faults or, alternatively, a low-angle thrust fault (Figure 1b). A northwest-striking thrust or reverse fault plane is consistent with the GPS motion vector from the city of Puerto Plata.

Earthquake-Related Damage

The Dominican Society of Engineers, Architects, and Agronomists (CODIA) has compiled maps and photos of damaged structures in Puerto Plata and Santiago. These are available online at http://www.ig.utexas.edu/outreach/dr_earthquake/index.htm. In both cities, damaged buildings, including two collapsed school buildings in Puerto Plata, are concentrated in alluvial sedimentary deposits. No liquefaction features were found during field reconnaissance.

Research Conducted in Response to Earthquake

Responses by members of an informal working group included the establishment of a 2-month temporary network of 10 broadband seismometers kindly made available by the IRIS Consortium to the Puerto Rico Seismic Network. The instruments are deployed in the epicentral region and along the Septentrional fault zone (Figure 1b). The objective is to record aftershocks to better define the fault plane to be a low-angle thrust fault, as shown schematically in Figure 2. Efforts are underway to better integrate results from local, short-period networks operated by INDHRI and the Autonomous University of Santo Domingo, and the new broadband data.

Another group re-surveyed 12 GPS sites in the northern Dominican Republic shown in Figure 1b to better constrain crustal motions during and after the earthquake. The goal is to make all of these data available online for use by interested researchers.

It is possible that the 2003 earthquake may have reduced the normal stress across the Septentrional fault zone, and thus advanced it toward failure. Because it has a slip rate of 6–12 mm/yr and has not produced a large earthquake in over 800 years, the Septentrional fault may already be close to failure (Figure 1b). U.S. and Dominican scientists presented background information and preliminary results of their studies of the earthquake at a press conference organized by CODIA in Santiago in October. The same group released a list of recommendations to the press and Dominican government in three areas: earthquake research, earthquake engineering, and public education and earthquake preparedness. The Web site mentioned above contains all presentations made, damage maps and other information related to the earthquake, and a complete list of all scientists involved in ongoing research.

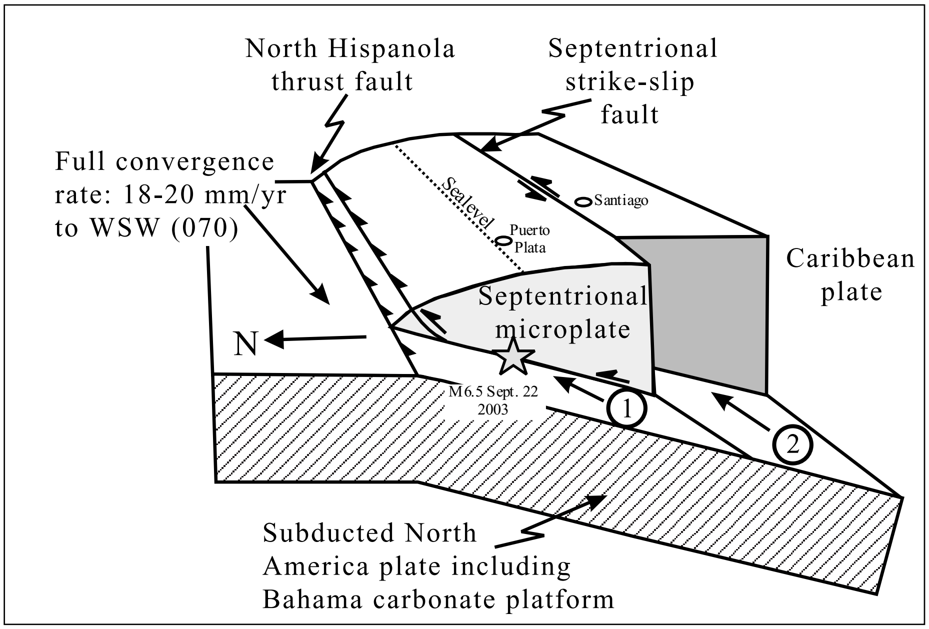

Fig. 2. This schematic block diagram shows the wedge-shaped Septentrional microplate of the northern Dominican Republic bounded by the sub-vertical Septentrional fault zone to the south and the low-angle North Hispaniola thrust fault to the north. The Septentrional fault has not ruptured for more than 800 years and has the potential for producing an M7 earthquake. Therefore, the potential change in normal stress across the Septentrional fault due to the occurrence of the 22 September 2003 earthquake is of concern. Epicenter is shown by star. Diagram modified from Dolan and Mann *[1998].*

References

Calais, E., N. Bethoux, and B. Mercier de Lepinay, (1992), From transcurrent faulting to frontal subduction: a seismotectonic study of the northern Caribbean plate boundary from Cuba to Puerto Rico, *Tectonics, 11,* 114–123.

Calais, E., Y. Mazabraud, B. M. de Lepinay, P. Mann, G. Mattioli, and P. Jansma, (2002), Strain partitioning and fault slip rates in the northeastern Caribbean from GPS measurements, *Geophys. Res. Lett., 29,* 1856, doi:10:1029/2002GL015397.

DeMets, C., P. Jansma, G. Mattioli, T. Dixon, F. Farina, R. Bilham, E. Calais, and P. Mann, (2000), GPS geodetic constraints on Caribbean-North American plate motion, *Geophys. Res. Lett., 27,* 437–440.

Dolan, J. and P. Mann (eds.), (1998), Active Strike-slip and Collisional Tectonics of the Northern Caribbean Plate Boundary Zone, Geol. Soc. Am. Spec. Pap. 326, 174 pp., Geological Society of America, Boulder.

Dolan, J., and D. Wald, (1998), The 1943–1953 north-central Caribbean earthquakes: Active tectonic setting, seismic hazards, and implications for Caribbean-North America plate motions, in *Active Strike-slip and Collisional Tectonics of the Northern Caribbean Plate Boundary Zone,* edited by J. Dolan and P. Mann, Geol. Soc. Am. Spec. Pap. 326, pp. 143–169, Geological Society of America, Boulder.

Mann, P., C. Prentice, G. Burr, L. Pena, and F. Taylor, (1998), Tectonic geomorphology and paleoseismology of the Septentrional fault system, Dominican Republic, in *Active Strike-slip and Collisional Tectonics of the Northern Caribbean Plate Boundary Zone*, edited by J. Dolan and P., Mann, Geol. Soc. Am. Spec. Pap. 326, pp. 63–123, Geological Society of America, Boulder.

Mann, P., E. Calais, J. C. Ruegg, C. DeMets, T. Dixon, P. Jansma, and G. Mattioli, (2002), Oblique collision in the northeastern Caribbean from GPS measurements and geological observations, *Tectonics, 21*, 1057, doi:10.1029/2001TC001304.

Molnar, P. and L. Sykes, (1969), Tectonics of the Caribbean and middle America regions from focal mechanisms and seismicity, *Bull. Geol. Soc. America, 80*, 1639–1684.

Prentice, C., P. Mann, L. Pena, and G. Burr, (2003), Slip rate and earthquake recurrence along the central Septentrional fault, North American-Caribbean plate boundary, Dominican Republic, *J. Geophys. Res.*, *108,* 2149, doi:10.1029/2001JB000442.

Tuttle, M. P., C. S. Prentice, K. Dyer-Williams, L. R. Pena, and G. Burr, (2003), Late Holocene liquefaction features in the Dominican Republic: A powerful tool for earthquake hazard assessment in the northeastern Caribbean, *Seismol. Soc. Am. Bull., 93*, 27–46.

Author Information

Paul Mann, University of Texas at Austin; Eric Calais, Purdue University, West Lafayette, Ind.; and Victor Huerfano, University of Puerto Rico, Mayaguez

For additional information, contact Paul Mann, Institute for Geophysics, University of Texas, Austin; E-mail: paulm@ig.utexas.edu.